A data-driven and simulation approach for understanding thermal performance of slum redevelopment in Mumbai, India

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Abstract

Over 54% of the world's population reside in informal settlements like slums. Thus, any meaningful strategy for transitioning the world toward a more sustainable urban built environment must address the redevelopment of slum communities. This study aims to take a first-step towards the design optimization of slum redevelopment by evaluating the thermal performance of various urban slum redevelopment morphologies in Mumbai, India. We propose a data-driven and simulation based approach to understand how slum redevelopment morphologies impact thermal performance and validate our approach using real data collected from a field site in the Dharavi slum, Mumbai, India. Results indicate that the existing horizontal form outperforms proposed vertical redevelopment forms in terms of maintaining lower operating temperatures. In other words, vertical redevelopment could worsen thermal comfort conditions for existing residents. Given the current push towards vertical housing structures by the Indian government, our results have substantial implications for the design and redevelopment of such informal settlements and lays the groundwork for establishing design guidelines and processes that ensure more sustainable and inclusive redevelopment.

Introduction

Slums or informal settlements are the manifestation of two major challenges facing humanity: rapid urbanization and the proliferation of poverty. In 2014 nearly 54% of the world's population were estimated to live in slums (United Nations, 2016). Slums represent an unsustainable form of habitation due to a lack of basic services like sanitation, water, electricity and healthcare, overcrowding, unsafe building structures, higher concentrations of poverty and unemployment (Bardhan, Sarkar, Jana, & Velaga, 2015). However, because they provide low-cost housing near central business districts of cities slums are often the first stopping point for migrants coming from rural areas.

Asia's largest slum is Dharavi, India. Dharavi is in the centre of the city of Mumbai (formerly known as Bombay), the financial and economic capital of India. Of Mumbai's 12 million plus inhabitants more than half are slum dwellers (Bardhan et al., 2015). Given Dharavi's strategic location, it is an epicentre of a large thriving economy of informal business with an annual turnover of more than $1billion USD (Jana, Bardhan, Sarkar, & Kumar, 2016) and as a result is an integral part of Mumbai's economy. The UN characterizes slums as the areas of 'concentrated disadvantages' that grossly affects the quality of life in the city. Dharavi has a huge impact on the disease burden of the city with regular outbreaks of diarrheal diseases, leptospirosis, malaria, dengue and respiratory diseases (Unger & Riley, 2007). The poor housing conditions with no ventilation and sunlight, also makes Dharavi an epicentre for sick building related diseases (Ezeh et al., 2016). Thus, transitioning to more a sustainable Mumbai will require tackling the environmental, human and building challenges associated with Dharavi and other urban slums.

As part of their report *The Challenges of Slums-Global Report on Human Settlement*, UN-Habitant highlighted the need for slum redevelopment policies and design that drive such informal settlements towards sustainability. Such policies and design guidelines should be integrated within the broader, people-centric urban poverty reduction policies, which address the energy, health and environmental sustainability of the habitat (UN-Habitat, 2003). In this purview, this study represents a first-step approach towards the design optimization of slum redevelopment using an Urban Building Energy Modelling (UBEM) framework. Specifically, we utilize a combined data-driven and simulation based approach to analyse and assess the thermal performance of two proposed slum redevelopment vertical morphologies against the current horizontal form. Our findings aim to lay the groundwork for more informed policies and guidelines of slum redevelopment across India and the world.

Background

A comfortable indoor environment is integral to the sustainability of a community as it directly impacts health and the well-being among of occupants. Moreover, for a country like India with a large low-income group (LIG) and middle-income group (MIG), a healthy indoor environment can have significant impacts as women and children spend most of their time indoors (Bardhan & Debnath, 2016).

Current practice relies on the use of simulation software (e.g., EnergyPlus, Revit) to analyse, understand and optimize the future design of buildings. Previous work has utilized such simulation software to analyse the impact of building geometry and morphology of

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communities on thermal performance in great detail (Lin, Lin, & Hwang, 2017). However, this body of work has largely been focused on buildings in countries of the developed world (Pisello, Castaldo, Taylor, & Cotana, 2016; Sokol, Cerezo, & Reinhart, 2016).

Several challenges exist to extending such work to redevelopment of slum communities in developing countries like India. First, as-built information for slum communities is not readily available since most construction was done in an informal manner. The development of as-built models requires extensive field work to understand geometries and building materials utilized in such informal settlements. Second, redevelopment strategies of slum communities are expected to be low-cost and therefore have limited capacities to employ active cooling strategies. As a result, the morphology of buildings must be optimized to maximize the use of passive cooling strategies.

Additionally, a main constraint of simulation based analysis of building thermal performance is the need for strong assumptions related to occupancy dynamics (i.e., schedules). Default schedules in most simulation programs are deterministic in nature and are represented by a set of static events that occur regardless of environmental influences of which are stochastic in nature (Kalvelage & Dorneich, 2016; Klein et al., 2012). Recent work (Kalvelage & Dorneich, 2016) has highlighted the need for more realistic representation of occupant dynamics as it can dramatically impact the prediction and the assessment of the building performance during the design phase.

Previous studies that have focused on interaction between buildings and occupant dynamics have largely been focused on the energy sustainability of office buildings (Huang & Niu, 2015; I & Dear, 1998; Lee & Yik, 2004; Ruparathna, Hewage, & Sadiq, 2016). This work has limited applicability to a developing nation like India, due to large scale heterogeneity in the living and working patterns of building occupants (Bardhan & Debnath, 2016). Specifically, socio-economic structures of the slums are often associated with have very high levels of dynamic occupancy patterns, which can contribute to variations in comfort signatures and energy use outcomes (Langevin, Wen, & Gurian, 2015; Steemers & Yun, 2009).

We aim to address these gaps in current literature and extend previous work by utilizing a combined data-driven and simulation based method. We utilize data from on-site surveys and in-situ sensors to calibrate our simulation models and evaluate the thermal performance of two vertical redevelopment design morphologies against the current horizontal morphology of the Dharavi slum in Mumbai, India.

Methodology and Data

Our methodological framework for this study is comprised of three steps. First, we conducted on-site surveys to obtain the physical dimensions and features of a typical slum dwelling and constructed an as-built model of the dwelling and the current community's morphology. This step was required due to the informal nature of our slum communities and the lack of city-wide Geographical Information Systems (GIS) databases as well as open semantic formats such as CityGML (OGC, 2012). Second, we deployed in-situ sensors to obtain data on indoor temperature and relative humidity of the slum dwelling and utilized this data to calibrate an energy simulation of the slum dwelling and validate the underlying assumptions on occupancy dynamics. Third, we employed this calibrated simulation validated assumptions on occupancy dynamics to model the thermal performance of two proposed vertical redevelopment morphologies against the current horizontal slum outlay of Dharavi, Mumbai India.

The vertical morphologies are derived from proposed designs put forth by the Mumbai government (Government of India, 2016). The horizontal slum form was physically surveyed and the dimensions of the existing houses that represent a typical horizontal slum house were measured. The geometric input data consisted of building envelope shapes, window opening rations as well as terrain data. The dynamic energy simulations were performed using EnergyPlus v8.7 with DesignBuilder v4.7 as the front-end GUI.

To acquire data on the thermal comfort indicators of the horizontal slums, in-situ environmental sensors HOBO Onset UX100-011 for temperature and relative humidity (RH) sensors were used to record data in a typical horizontal slum household. The sensors were installed for a period of two weeks in a typical summer month from August 10, 2016 to August 23, 2016.

Here, we have used operative temperature as a surrogate for the uncertainties involved in the air temperature data points measured in the slum built-environment. The operative temperature is used as the thermal comfort parameter. The operative temperature is widely referred to as 'environmental temperature', which is a cumulative quantity involving air temperature, the effect of internal reflection and refractions of heat radiations and also the effect of human clothing, activity and metabolism, as per the *Adaptive* ASHRAE Standards 55 (R. de Dear, 2011; R. J. De Dear & G.S. Brager, 2002; Indraganti, 2010). The operative temperatures are assumed to be the aggregate of individual units, as the model calibration was done considering one unit of slum housing. This method was employed owing to the methodological need of manual iterative calibration (Agami Reddy, 2006).

Study area

Dharavi, Asia's largest slum, was chosen as the study area. It is estimated that there are more than 60,000 slum houses, informally accommodating one million population with a density of 600 to 2,000 people per acre (Yardley, 2010) in Dharavi (see Figure 1). Dharavi also hosts a thriving informal business network with an annual turnover of $1billion USD. Hence, its existence is integral to Mumbai's and the surrounding region's economy. Recently, the Central Indian Government and State Government of Maharashtra of which Mumbai is part of, is pushing for Dharavi's redevelopment making the creation of early design guidelines that embody sustainability metrics extremely pertinent and timely.

The Central Indian Government and the State Government of Maharashtra had launched several schemes like the Slum Redevelopment Scheme of 1995, Rajiv Awas Yojna (RAY) 2012-2022 and the Cluster Redevelopment Scheme of 2014, with the common objective of improving the quality of life of such low income group communities (LIG), by providing them quality and affordable housing (Bardhan et al., 2015). The government plans to re-cluster the existing horizontal slums into vertical redevelopments (in the form of high-rises). However, the energy sustainability of such morphological transition from horizontal forms to vertical forms has yet to be studied and further underscores the relevancy of this work.

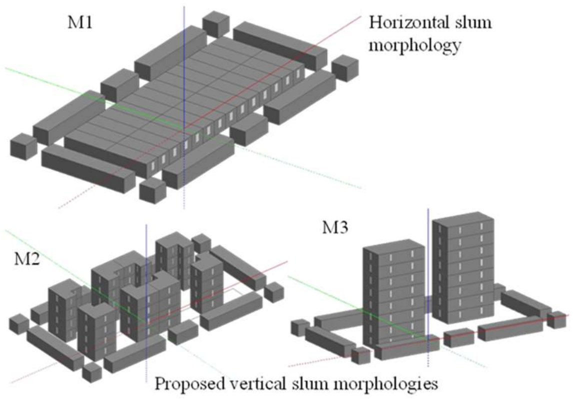

Figure 1: Slum morphologies in Mumbai: Horizontal (M1) and Vertical (M2 and M3).

Morphology generation of slum community

Figure 2 illustrates the urban slum morphologies of Mumbai, where the horizontal slums (M1) is being redeveloped to proposed vertical structures (M2 and M3). The vertical redevelopment designs (M2, M3) are based on the Dharavi Redevelopment Project, by the Central Indian Government (Government of India, 2016). This redevelopment project, commonly known as Dharavi Redevelopment Project or DRP, is headed by the Slum Rehabilitation Authority (SRA). New vertical housing constructed by the SRA are public-private partnership that provide low-cost small apartments to slum residents free of cost. These apartments are approximately 21m^2 (255 sq. ft), and constructed with the motive to maximize occupancy by removing the horizontal slums without paying much attention to ventilation, sanitation, hygiene and access to daylight. Moreover, the private builders who get to build the SRA vertical housing have the right to build other premium apartments and commercial sites on the remaining land that has been "freed up" by removing the horizontal slums and sell them at higher market prices with an obligation to build SRA homes free of cost (Bardhan et al., 2015; Jana et al., 2016). As a result, units in newly developed vertical housing tend to follow a similar pattern of existing horizontal units of having one door and one window.

Built environment characteristics: field study

A field study was conducted for a period of two weeks (August 10, 2016 to August 23, 2016) where the temperature and RH sensors were installed in a residential slum house in Dharavi. The overall built environment in Dharavi is characterised by deep, narrow alleys that lacked access to sunlight and fresh air exchanges. Figure 3 illustrates the built environment conditions of the study area. The houses were observed to be devoid of fresh air and sunlight. The indoor temperature was high due to the ultra-compact nature of the building form (see Figure 3).

Figure 4 represents the indoor configuration of a typical slum house with a length of 5.2 meters, width of 2.1 meters and a height of 2.1 meters. The house has no windows or access to sunlight and thus artificial lights are kept 'on' for about 18 hours per day along with a ceiling fan to regulate indoor temperature.

The logged sensor data is illustrated in Figure 4 and indicates that the indoor temperature is largely constant through the day and night, without any significant peaks or dips. This occurs even as the outdoor temperature fluctuates throughout the day, with significant local maxima and minima (see Figure 4). The mean indoor temperature throughout the day was approximately 30.5° C, which is approximately 1.6 degree higher than the mean outside temperature.

Figure 2: The built environment of the houses in Dharavi.

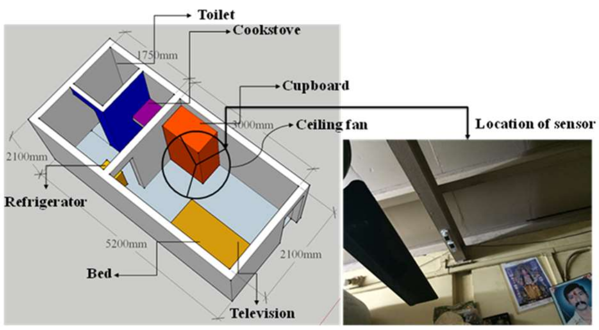

Figure 3: Sensor setup in the surveyed slum house.

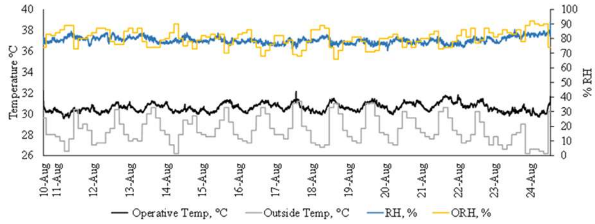

Figure 4: Sensor data for the study period (August 10, 2016 – August 23, 2016).
(Note: ORH%= outside relative humidity, the outside weather data was imported from http://rp5.ru/)

Modelling and simulation of the slum dwelling

The surveyed slum house was modelled using Design Builder v4.7. It uses Energy Plus v8.3 as its core engine to carry out climate based dynamic simulations. The data-logger (HOBO Onset UX100-011) collected data continuously for the two-week study period. The climatic pattern of Mumbai during this period is hot and humid. The weather data file for simulation was imported from the ISHRAE, Mumbai, 2016. The initial phase of the simulation portion of our study involved modelling the surveyed slum dwelling to choose the appropriate built materials and boundary conditions.

The simulation parameters are listed in the Table 1. We assumed the circulation of air inside the room was through the constant use of a ceiling fan with 10 air exchanges per hour (ach) (Zhu, Srebric, Rudnick, Vincent, & Nardell, 2014) based on our on-site observations. The building material database was imported from the commonly available low cost building materials in the low income housing database (BMTPC, 2015; FAO, 2011; Gradillas, 2015; UNIDO, 2007). These building materials were also chosen based on our on-site observations. The primary activity in the room was assumed to be sitting, reading and cooking. Natural ventilation was observed to be the only source of fresh air exchanges in the house. The occupants' density (person/m^2) in the simulated zone (Zone 1, see Figure 5) was estimated to be around 0.64 based on our on-site field observations.

This typical slum dwelling formed the general archetype employed as a template for all three slum morphologies. This decision was driven by the present-conditions of the typical SRA housing structures already constructed. The ultra-compact sprawling of these vertical structures, revert the living conditions to that of the horizontal slums. Thus, even though the vertical forms M2 and M3 can accommodate more windows and doors by the virtue of their forms, their operating conditions can be derived from the archetype in horizontal slums.

Table 1: Simulation parameters.

#	Parameters			
		Material	Thickness (mm)	U-value (W/m2-K)
1	Wall	Brick wall	250	0.464
2	Roof	Metal sheet-Duraluminium	50	1.386
3	Ceiling	Plywood	12.7	1.612
4	Internal Partitions	Brick cavity with 50mm air-gap	115	1.28
5	Floor	Concrete slab, unheated with insulation	1200; Floor factor= 0.88 W/m-K	
6	Air infiltration	Through cracks		
7	Openings	Only Doors, no windows		
8	HVAC	Absent; natural ventilation only		
9	Mechanical ventilation	Ceiling fan with a constant air change rate of 10ach		
10	Lighting system	Fluorescent lighting T8, operated for 18 hours a day		

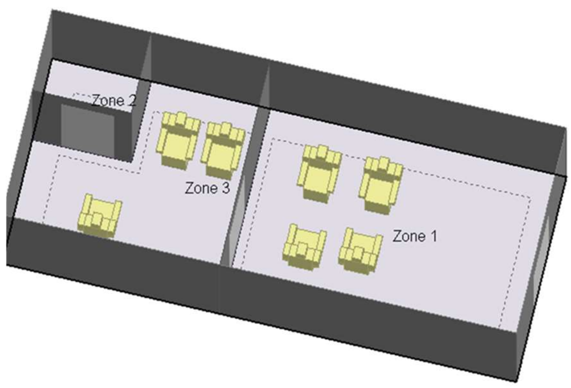

Figure 5: CAD model of the surveyed house with the occupants in Dharavi slums, Mumbai.

Validation and calibration

It is never possible to determine the exact source of uncertainness in a building simulation problem, as the calibration solution requires dynamic matching between the computed and the measured values, rather than a static time values. These elements make calibration and validation of building simulations challenging, and with the increase in the scale of the simulation i.e. from a single building model to the community scale, these complexities increase many-folds (Mustafaraj, Marini, Costa, & Keane, 2014). We utilized a data-driven manual iterative calibration (Agami Reddy, 2006) technique that involves adjustment of inputs and parameters on a trial-and-error basis until the program output matches the known data (Mustafaraj et al., 2014). This method was coupled with the graphical method of calibration to the orient the calibration process graphically (Agami Reddy, 2006).

The calibration accuracy was evaluated using MBE and CV(RMSE), which was calculated on a half-hourly basis for the year 2016 (based on the available weather file used for simulation) (Mustafaraj et al., 2014).

$$MBE = \frac{\sum_{i=1}^{N_p}(M_i - S_i)}{\sum_{i=1}^{N_p} M_i} \quad (1)$$

$$CV(RMSE)_p = \frac{\sqrt{\sum_{i=1}^{N_p}((M_i - S_i)^2/N_p)}}{\overline{M_p}} \quad (2)$$

$$M_p = \frac{\sum_{i=1}^{N_p} M_i}{N_p} \quad (3)$$

where, M_i and S_i are the measured and simulated data at instance *i*, respectively; p is the interval (e.g. monthly, weekly, daily & hourly); N_p is the number of values at interval p (i.e $N_{mont} = 12, N_{days} = 365, N_{hour} = 8670$) and M_p is the average of the measured data.

ASHRAE Guidelines 14, specifies the acceptable limits for calibration of hourly data as $-10\% \leq MBE_{hou} \leq 10\%$ and $CV(RMSE)_{hourl} \leq 30\%$ and monthly data as $5\% \leq MBE_{month} \leq 5\%$ and $CV(RMSE)_{month} \leq 15\%$ (ASHRAE, 2002).

Results and discussion

Energy simulations of the slum morphologies (M1, M2 and M3), were performed to assess the thermal performance of both the current horizontal slum and proposed redevelopment vertical forms.

We utilized the aggregate temperature of the space as the operative temperature as this enabled us capture and represent the overall thermal-dynamics of each slum morphology. Both the simulated and the measured data displayed similar trends for the typical slum dwelling as shown in Figure 6, with an acceptable hourly MBE of -1.07% and CV(RMSE) of 2.26%. As such, our occupant dynamics and other simulation assumptions were validated by the measured data. The single building simulation of the surveyed slum house, represented an almost constant indoor temperature of 30.5 °C. Field observations confirmed that a lack of ventilation and high occupant density were primary drivers of such constant temperature levels.

Figure 6 illustrates the trend of the measured and the simulated data of the surveyed slum house.

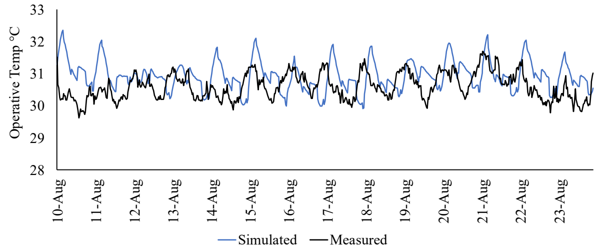

Figure 6: Simulated vs. measured temperature for the surveyed single slum home

The simulation results of the slum morphologies showed that the horizontal form (M1) outperformed the vertical forms (M2, M3) in respect to maintaining a suitable thermal comfort throughout the year (see Figure 7). This result was surprising given the current trend towards vertical redevelopment. We postulate that this could be attributed to the fact that the building envelope of the vertical forms are more exposed to the full impact of the outdoor temperature and solar radiation compared to low rises which often receive mutual shading (Taib, Abdullah, Syed Fadzil, & Yeok, 2010). However, we note that this finding should be further corroborated with further investigation that considers orientation and the exposure envelope in greater detail.

The compact nature of the horizontal slum exaggerates the cooling effect from shading. However, it was observed that among the vertical forms M2 and M3, M2 had relatively better capability in maintaining lower temperatures. This can be attributed to the irregular corrugated form of M2 in comparison to the slender form of M3. The irregular form of M2, promotes air flow turbulence by building pressure laterally on the irregular corrugated façade thus facilitating cooling through cross ventilation. The irregular shape also helps to reduce the thermal mass exposure to solar radiation which creates mutual shading that in turn drives lower indoor temperature in comparison to the regular rectangular form of M3.

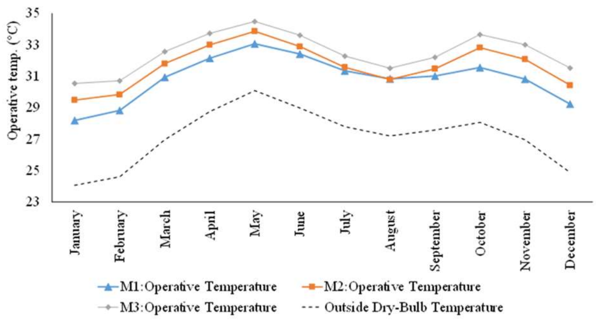

Figure 7: Comparison of operative temperatures of the vertical vs. horizontal slum forms of Mumbai, India.

The comparison of the operative temperatures among the slum typologies also indicates that indoor temperatures were at least 4 degrees higher than the outside temperature. Given that the latent gains of these houses are relatively similar across the morphologies, we hypothesize that the variation that arises in the thermal stress is from the arrangement of the houses and their relative position with respect to mutual shading from neighbouring houses. The space between the buildings plays a significant role in modulating the airflow that contributes to the cooling effect through natural ventilation (He, Liu, Kvan, & Peng, 2017). Hence, it is evident that apart from material and occupancy, the spatial arrangement of the buildings with respect to its surrounding also plays a significant role in thermal comfort of the buildings. The average indoor temperatures of M2 ranged between 29-32°C, which is higher than the considered comfort temperatures. However, this temperature range corresponds to an acceptable level of thermal comfort in most Indian cities in similar climate zones (Indraganti, 2011). In this context, M2 yields acceptable comfort levels and is the preferred vertical form option over M3.

The objective of this study was to create a way-forward for a sustainable slum habitat design toolkit that involves data-driven design heuristics for a UBEM calibrated to characteristics of informal slum communities. Field surveys coupled with human-space interaction data collection, formed the basis for slum morphology generation and its simulation. The thermal performance of various slum morphologies (M1, M2 and M3), demonstrated the appropriateness of one form over the other.

We found that the M1 morphology has consistently lower operating temperatures for the entire year and therefore would provide higher thermal comfort outcomes to occupants. Based on such results, the horizontal form should be retained. However, the government of India has found it imperative that the current morphology be removed and redeveloped (M1) into vertical forms, due to safety, health and land efficiency concerns of the current horizontal forms. As a result, from a policy perspective it is important to explore how better thermal comfort could be achieved in vertical forms. Currently, the two proposed vertical forms are advocated by the government in an ad-hoc manner without much consideration on the thermal comfort or health implications of natural ventilation and could cause slum dwellers to be worse off despite significant investment by the government in redevelopment. Specifically, optimizing for lower operative temperatures can lead to energy efficiency and sustainability on a larger scale as occupants will not turn to energy intensive air conditioners if acceptable levels of thermal comfort can be achieved passively.

This study aims to demonstrate the need for further exploration of the benefits of one urban form over another and hopes to spawn discussion on how redevelopment can occur without increasing the comfort, energy and sustainability burdens of current residents. Our results indicated that simply following current top-down design and planning practices for redevelopment in proposed vertical forms (M2, M3) would have grave consequences for occupants. Overall, this paper aims to be a first-step in a whole new genre of urban building energy research that would involve data-driven low-income built environment modelling and simulations and initiate new paradigms for informed and inclusive policy-making in slum redevelopment schemes. We note the strong socio-political context of slum redevelopment as governments across the world are pushing for more high-rise vertical forms to maximize occupancy and reclaim premium land for private development. In the case of Dharavi, it is located on extremely valuable land due to its proximity to Mumbai's new central business district (i.e., Bandra-Kurla Complex) and thus further exacerbates challenges associated with sustainable slum redevelopment.

Limitations and future work

This study is limited to a partial UBEM using survey data collected from a single dwelling and utilized as a slum archetype for a small neighbourhood of 32 families. The lack of region specific GIS datasets or CityGML libraries demanded a manual data input methods for the slum morphologies modelling and as a result the thermal evaluation was limited to the variation of the thermal masses in the horizontal and vertical forms.

Future works aims to address this limitation by conducting sensitivity analysis to identify critical built-parameters for low-income built environments along with the socio-cultural variables. Additionally, a limitation of this work is the use of a single aggregated operating temperature for the entire building as means of assessment. Future works aims to individually model each individual unit to understand how thermal performance varies across units in a building with differing exposures. Moreover, future work also aims to develop a more detailed UBEM for the entire slum of Dharavi through parametrization of built-components like window to wall ratio and floor area index, and their effect on thermal comfort. Such a detailed UBEM for slums would enable deeper modelling of building-occupant dynamics such that a more holistic low-income habitat design toolkit could be established that encompasses health and economic outcomes such as disability adjusted life years (DALYs) in the design process.

Conclusion

Overall, this paper aimed to be a first-step approach towards the design optimization of slum redevelopment using an Urban Building Energy Modelling (UBEM) framework. We utilized a combined data-driven and simulation based approach to analyse and assess the thermal performance of two proposed slum redevelopment vertical morphologies against the current horizontal form. Our findings indicated that the current horizontal form provides better thermal comfort outcomes to occupants than either of the proposed vertical forms. Implications of these results demonstrated the need for further exploration of the benefits of one urban form over another and the creation of more inclusive slum redevelopment schemes to ensure that redevelopment doesn not increase the comfort, energy and sustainability burdens of current residents.

Bottom-up design strategies for slum redevelopment that utilize data from field surveys and environmental sensors as done in this study will prove to be integral in understanding the impacts development plans and help embed socio-cultural, economic and environmental elements into the design process. As the government of India races towards its goal of providing housing for all by 2022, results from data-driven and simulation studies of slum communities could have substantial impacts for generations to come.

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