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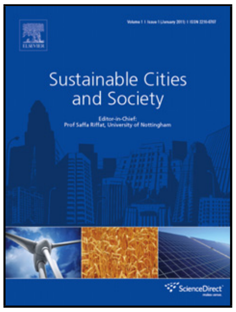

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Low-income housing layouts under socio-architectural complexities: A parametric study for sustainable slum rehabilitation

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Highlights:

- Quantifying low-income group housing forms using socio-architectural and geometric parameters.
- A novel socio-architectural analysis for sustainable slum rehabilitation policy.
- Efficient geometric and spatial arrangement can improve the quality of life in low-income settlements.
- Use of computational fluid dynamics to investigate form-based wind flow characteristics for improved indoor environment.

Abstract

Lack of sustainable slum redevelopment guidelines in India is a policy gap that needs immediate attention. A rational design and planning route is necessary to ensure sustainability of the upcoming low-income (LIG) housing stocks. In this study, we performed a cross-sectional evaluation of LIG housing layouts through a socio-architectural and site-based wind-flow analysis route. We hypothesise that a better indoor environment in the LIG housing can be achieved through a better wind driven natural-ventilation in the living spaces, which is a function of the housing layout. Specific objectives of this study were: i) to investigate the influence of socio-architectural and geometric parameters on the LIG housing layouts; ii) to examine the effect of site-wind flow on LIG housing layouts using CFD simulations. BDD chawls of Mumbai were adopted as the case study. Results show that the current form of the LIG houses had a poor indoor environment and social interaction spaces, while the hypothesised iterated layout 'Form A' performed better in all the socio-architectural and wind-flow metrics that can promote relatively better quality of life. This study is a first-step approach for the development of regulatory guidelines in LIG housing design that is coherent to the context of the space.

Keywords: Slum redevelopment; Urban renewal; Socio-architectural; Low-income; Housing policy; Planning

1. Introduction

The concept of smart and sustainable cities has gained importance due to rapid global urbanisation and the need for sustainability in all aspects of the city (Ibrahim, Adams, El-zaart, Ibrahim, & El-zaart, 2016). Sustainable Development Goal 3 and 11 has further promoted the development of sustainable cities with an aim at improving the living conditions of the citizens to provide them with a better quality of life (Bardhan, Kurisu, & Hanaki, 2011, 2015). However, due to the challenges at policy and social levels, the extent to which the local governments can address sustainability issues within a city remains unanswered (Bulkeley & Betsill, 2005).

UN-Habitat characterises slums as lack of durable housing, insufficient living spaces, lack of access to safe water at an affordable price, inadequate sanitation regarding access to private or shared public toilets and insecure tenure that entitles force evictions (UN-Habitat, 2007). In India, slums have been defined as those residential areas where dwellings are unfit for human habitation implicating in an inferior quality of life (QoL), as per Section-3 of the Slum Area Improvement and Clearance Act 1956 (Bardhan, Sarkar, Jana, & Velaga, 2015). National Urban Housing and Habitat Policy 2007 (MHUPA, 2007b) states mismatch between demand and supply of affordable housing units for the Economically Weaker Sections (EWS) and Low Income Groups (LIG) sectors and is a significant issue of sustainable development in India. This lack of affordable housing under the urbanisation pressure transforms cities into the hyper-dense agglomeration of EWS and LIG settlements in the form of urban slums. Nearly, 13.7 million households of urban India lives in slums (Census, 2011). The Government of India (GoI) has been trying hard to contain and transform such rapid expansion of slums in cities, since the introduction of the National Housing Policy (NHP) in 1994. However, such 'slum-free city' policy measures remain ineffective even today.

The National Urban Housing and Habitat Policy 2007 emphasises on earmarking land for EWS/LIG groups in the new housing projects, and ascertains the role of government in social housing through affordable housing programs like 'Housing for All-2022'(MHUPA, 2015); 'National Slum Development Program (NSDP) 1996-2006' (MHUPA, 2007a); 'Swarna Jayanti Shahari Rozgar Yojana (SJSRY) 1997' (MUAE, 1997); 'Valmiki Ambedkar Awas Yojana (VAMBAY) 2001' (MoUD, 2001), etc. These policies and programs have yielded positive results in providing housing and habitat for the EWS and LIG, but its efficacy in the long run, remains a planning challenge (Bardhan, Sarkar, et al., 2015). Additionally, there are no standardised methodologies for such efficacy studies in housing and habitat sector and remains a blind spot in India's habitat policy (Bardhan, Debnath, Jana, & Norford, 2018; Debnath, Bardhan, & Jain, 2017). It is estimated that 80% of the housing stock is yet to be constructed in the coming 20 years (Bardhan & Debnath, 2016), out of which one-third of the shares would be exclusive for the EWS/LIG sections (MHUPA, 2015). Sustainable habitat guidelines for these settlements become a vital necessity to ensure the inclusive growth of the country. Besides, sustainable LIG habitats would provide energy efficiency in the residential sector, health security among the most vulnerable population groups and improve resiliency to climate change (Debnath, Bardhan, & Jain, 2016, 2017; Jana, Bardhan, Sarkar, & Kumar, 2016).

The novelty of this study lies in the cross-sectional approach of LIG housing policy determination under constraints (in this case, the LIG housing design was fixed). Here, the housing layout was parametrically studied by varying socio-architectural and geometric elements and was further coupled with site-based airflow analysis to investigate the suitability of a housing layout under socio-technical complexities. We hypothesise that 'a better indoor air quality through cross-ventilation would ensure a better quality of life in low-income tenement housing, which is a function of the site-layout'. Hence, our methodology transverse across socio-architectural and geometric metrics, along with a computational fluid dynamics (CFD) analysis of the site-based wind flow pattern around the housing layouts, for determining the most suitable LIG layout under design constraints. Specific objectives of this study were: i) to investigate the influence of socio-architectural and geometric parameters on the LIG housing layouts; ii) to examine the effect of site-wind flow on LIG housing layouts using computational fluid dynamic simulations. The more significant goal is to imbibe sustainability in urban renewal and rejuvenation program of the GoI, by generating a process-flow for LIG habitat design through data-driven design heuristics of the people and places. It would ensure that older LIG housing stocks of a city are not just reconstructed (MoUD, 2017). Instead, a retrofitting and re-designing route of urban rejuvenation is adopted to ensure sustainability in the process of LIG habitat development.

2. Background

The acknowledgment of 'adequate housing' concerning poverty alleviation and socio-economic progress led to the concept of social housing in international discourse since the 1970s. Historically, international housing policy has witnessed the emergence of two distinct approaches towards securing of low-income housing provision, namely ‘provider paradigm’ and ‘support paradigm’ (Ehebrecht, 2014). While ‘provider paradigm’ fosters the idea of technical provision of shelter, the ‘support paradigm’ cultivates the social aspects within the broader concept of housing. The provider model is quantitatively biased and hence has been criticised for being too consumerist-orientated, contributing to profit-maximisation, while neglecting endorsement of the human needs. On the other hand, the support paradigm provides efficient resource management for societal well-being. Arresting of slum proliferation in developing countries like India has mostly followed the ‘provider’ regime with less consideration to the socio-cultural aspects of informal life (Bardhan et al., 2018; Bardhan, Sarkar, et al., 2015; Jana et al., 2016).

Rapid industrialisation leads to the construction of mass social housing to compensate for the housing backlogs. However, such housing units were designed primarily for maximising occupancy and severely compromised on the socio-cultural aspects of the communities. These units were plagued with insufficient open spaces that did not allow for extensions in case of changes in family composition, thus, inhibiting future socio-economic upliftment of the inhabitants. Such practices led ‘urbanisation into poverty’, creating a socio-economic and spatial exclusion in the form of informal settlements and ‘slums’. These substandard dwelling units, often connoted as ‘slums of despair’ were destined to eradication, elimination or clearance. In global policy discourse, slums have been tackled either through the ‘direct approach’ of repressive measures or ‘indirect approach’ of upgrading the informal settlements. While the direct approach focused on forced evictions and relocations, the indirect approach dealt with vertical upliftment through rehabilitation (Ehebrecht, 2014; Huchzermeyer, 2011). Realignment of these existing policies led to the formation of Basic Needs and Redistribution with Growth (RWG) strategy, which shifted the concept of slum redevelopment to economic growth coupled with social justice. The idea was to develop a model in which users become the principal actor in the housing activity. Housing was viewed more as a process than a commodity. The principle of in-situ’ and ‘aided self-help’ approach became a central theme for low-income rehabilitation. The terms linked to this strategy like ‘slum resettlement’, ‘slum rehabilitation’ and ‘slum improvement’ may have multiple meanings ranging from in situ upgradation to resettlement depending on local, city and national level drivers of change. A study by Bardhan, Sarkar, et al., (2015) on the fate of Mumbai slums since independence in 1947, found that Mumbai also witnessed a similar linear trend of slum eviction to slum rehabilitation (see Fig. 1).

The UN-Habitat (2016) states that one in every three urbanites of the developing world stays in slums and other informal settlements, thus making slum urbanism a reality. Literature has established a strong and inherent connection between built-environment and well-being that implicates on the quality of life. However, discrete slum redevelopment guidelines with a focus on built environment and its design remains an under-researched area. Hence, preparation of urban-built plans that link SDG 11 and 3, i.e. healthy sustainable communities is of utmost importance and will stand out to be more proactive than a reactive approach (Debnath & Bardhan, 2018; Debnath, Bardhan, & Banerjee, 2017).

The LIG settlements, particularly in Mumbai, are characterised by lack of airflow path in the living spaces leading to poor indoor air quality, higher indoor temperature and lack of sanitation and hygiene (Debnath, Bardhan, & Jain, 2017). The development controls of Mumbai's low-income rehabilitation settlements have been modified significantly over the years to maximise occupancy, with little or no consideration towards the quality of spaces which in turn deteriorated the quality of indoor built-environment. In Mumbai, the city building is regulated through General Development Control Regulation (GDCR) and National Building Code (NBC) of India. A separate set of guidelines were drafted for the slum rehabilitation housing, named as Slum Rehabilitation Development Control Regulation (DCR) (see section 33(10) of Municipal Corporation of Greater Mumbai (MCGM), 2016). When compared to the GDCR and NBC, DCR guidelines are relatively relaxed. There is no prescribed limit for the maximum housing density in the DCR, which sometimes leads to hyper-densification, up to1300 dwelling units per hectare (du/ha). The minimum prescribed density for the slum rehabilitation in the DCR is 650 du/ha as against 200 du/ha in the GDCR, and it further creates a hyper-dense situation. The recommended minimum distance between the buildings of 32 m height in DCR is six meters, whereas the GDCR and the NBC prescribe this distance to be at least one-third of the building height. Table 1 illustrates the modifications and relaxations prescribed in the Development Control Regulation of Mumbai for Slum Rehabilitation colonies from 1995 till 2016. Some of the modifications that can be adapted and translated to better built-environment are the housing unit sizes and, the floor area ratio (FAR). The unit sizes have been increased from 20.9 m^2 to 25 m^2 while the FAR has seen an increase from 2.5 to 4. On the contrary, the minimum density has been increased from 500 du/ha to 650 du/ha indicating the stress to accommodate more people. Though these policy revisions allow building taller structures, the inter-building distances remain the same.

The quality of life is aggravated by the lack of LIG habitat planning tools and methodologies available with the city planning department. At present, the Mumbai City Development Plan 2005-2025 (M-CDP) recommends strategies for housing and slum improvement in the city and stresses on corrective measures for regulatory problems (MCGM, 2017a) (see Table 2).

Table 2 illustrates the current gap in the CDP regarding planning for LIG/EWS settlement redevelopment, which redeems such projects ineffective in substantially improving quality of life and leaves a large environmental footprint. Here, we are investigating the impact of these gaps in policy and planning through a socio-architectural form-based analysis of privacy and social spaces, coupled with a site-based airflow analysis of the LIG tenement housing layout (commonly known as ‘chawls’).

Physical privacy provided by a spatial territory becomes a prerequisite for social behaviours. If a jointly owned space with clear boundaries has privacy such that it does not create seclusion through avoidance of contact, then it encourages social interaction among the users of the space (Ramezani & Hamidi, 2010). The need for social space is critical to these LIG/EWS households, as these spaces are utilised for both formal and informal economic activities mediated through the strong social ties among the inhabitants (Bardhan, Sarkar, et al., 2015). Debnath et al. (2017) discussed this paradigm between horizontal slum structures and vertical slum redevelopment structures, where the state government is propagating vertical structures through Mumbai City Development Plans, whereas occupants prefer horizontal structures as it provides a community shared spaces for informal businesses. It was found that the vertical building form had higher indoor air temperature range than the horizontal form during the summer months (Debnath, Bardhan, & Jain, 2017). The occupants find advantageous to live in the horizontal form than the vertical type, and they often tend to sublet these vertical LIG units and shift back to the horizontal slums. Thus, a systemic approach to space design that can ensure comfortable and liveable conditions within these vertical units while considering the contextual social setting is much-needed.

In this study, we investigate the relative importance of the various site layout of the vertical structures, proposed in slum redevelopment planning that provides variation in form and social interaction spaces, warranting liveable conditions. Presently, a prototype linear design of the vertical building is widely accepted by the slum redevelopment authority and is replicated in almost all the slum redevelopment sites (see Fig. 4). Hence, the only degree of freedom available is varying the site layout to modulate active site air-flow which in turn promotes better indoor air quality, and thermal comfort ranges through wind-driven natural ventilation.

Housing layout and its impact on the wind-velocity

The spatial configuration of buildings and its agglomerated urban forms are critical to the local building-energy performance that influences outdoor and indoor thermal comfort, site-airflow characteristics and the indoor air exchanges in natural ventilation (nat-vent) conditions (Y. Chen, Li, Zheng, Guan, & Liu, 2011). Additionally, site-airflow around buildings has a direct effect on the indoor and outdoor thermal comfort, indoor air quality and energy use of buildings (Sanaieian, Tenpierik, Linden, Mehdizadeh Seraj, & Mofidi Shemrani, 2014), making a form-based arrangement an essential parameter for improved airflow in the indoor spaces (Sanaieian et al., 2014). It becomes more critical for LIG/EWS housing, as natural ventilation is the primary mode of ventilation in such housing stocks, implicating the need for robust design and planning measures for improved indoor air quality (Debnath, Bardhan, & Banerjee, 2016). It, in turn, affects the health and well-being of the entire LIG housing stock. For example, in a recent study by Bardhan et al., (2018), it was observed that the occupants living in lower-floors in the tenement housing (BDD chawls) in Mumbai had more healthcare related visits than the occupants living in the upper floors in the same building. It indicates there exists a critical relationship between housing layout and occupant's health outcomes.

Housing layout affects the airflow pattern and ventilation rates, in which building arrangements are the most crucial design/planning variables (R. Ramponi & Blocken, 2012; Srifuengfung, 2012; Yuan & Ng, 2012). Wirén (1983) in his study of a Swedish single-family building in a neighbourhood of identical buildings observed that the density of the surrounding buildings affects the distribution and the magnitude of the wind pressure on the building surface. A similar study by Yuan & Ng (2012) for Hong Kong showed that densely spaced buildings increase the wind resistances and obstruct the ventilation flow in the neighbourhood. Srifuengfung (2012) corroborated this through an empirical and CFD analysis using parameters like the block size; the floor-area ratio; the open-space ratio; the ratio of total skin surface area of an urban block to lot area; the building density and the building surface roughness. The building orientation and height were found to be significant factors that affect urban ventilation in Bangkok. Urban density, mutual arrangements of buildings, the shape and dimensions strongly modulates the urban wind flow and that the shape and dimensions of the streets contribute significantly to this modulation (Rubina Ramponi, Blocken, de Coo, & Janssen, 2015).

Literature also emphasises that plan area density (λ_P) and frontal area density (λ_F) are relevant variables that can contribute to the aerodynamic properties of a particular housing layout (Kent et al., 2017; R. Ramponi & Blocken, 2012; Wicht, Wicht, & Osińska-Skotak, 2017). Empirical evidence of the effect of the frontal area density, the building orientation and the building height on local meteorology and air quality were reported by Edussuriya, Chan, & Ye (2011); Hang, Sandberg, & Li (2009); Taseiko, Mikhailuta, Pitt, Lezhenin, & Zakharov (2009); and Lu & Liu, (2016). Therefore, it is evident that the wind field in the urban boundary layer is dramatically changed by urban geometry because buildings produce greater frictional drag than other surface roughness elements in a natural environment (Yuan & Ng, 2012).

Literature records various method that has been used to quantify the effect of housing layout on thermal comfort and ventilation. For example, Huang, Lu, & Sellers (2007) compared various urban layouts based on porosity and compactness of urban space. Porosity measures the ratio of open space compared to the total site area and is commonly termed as the ratio of open space (ROS). Compactness index provides numerical representation describing how far an object deviates from a standard shape. Grimmond C.S.B & & Oke T.R. (1999) studied the aerodynamic characteristics of cities to forecast the behaviour of urban-wind and turbulence by considering surface-area ratio indices like plan area index, frontal-area index, complete-area index and aspect ratio.

Another important housing layout indicator is the fractal dimension, which describes the distribution of structures in the plane of observation (ground plane or elevation). Any housing layout has an inherent fractal order, which takes in to account the spatial complexity, which is often failed by the Euclidean geometry of spaces (Terzi & Kaya, 2011). The fractal geometry of an urban space describes the space-filling process owing to rapid urbanisation (like the hyper-dense LIG/EWS settlement case of Mumbai). In a two-dimensional plane, a fractal dimension can be anything between 0 (a point) and 2 (the plane itself) (Gleick, 1997; Lu & Liu, 2016). Researchers have attempted to measure the fractal dimensions for enclosed urban spaces with varied building layouts in the developed world which have led to values between 1.40 and 1.80 (Batty & Longley, 1994; Batty & Xie, 1996; Moon, 2002).

In this study, we chose an array of geometric metrics to describe three different forms of housing layout, using the prototype vertical building design, regarding its urban geometry and social interaction space availability. A classic case of a LIG settlement in Mumbai was considered, which emulates a ‘slum-like’ living conditions in a vertical building form. Natural ventilation is the primary driver for addressing cooling demands in these settlements, which makes it necessary to address the morphological basis of the layout of the buildings in enabling better wind-driven natural ventilation (Debnath, Bardhan, & Jain, 2017). Studies have shown that acceptable thermal comfort ranges in warm and humid climate like Mumbai, can be achieved when the outdoor air velocity is in the range of 1 – 5 m/s, where values below 1 m/s is a calm-zone, not strong enough to facilitate wind driven natural-ventilation in indoor living spaces and vice-versa (Blocken, Janssen, & van Hooff, 2012; Cheng & Ng, 2006; Indraganti, Ooka, & Rijal, 2012). Here, we have adopted a cross-sectional methodology to calculate the impact of LIG housing layout on site-based airflow analysis computed using 3D steady-state Reynolds Averaged Navier Stokes (RANS) set of equations along with standard k-ε turbulence model in uniform-hexahedral CFD grids.

3. Methodology

In this study, a cross-sectional methodology was adopted to evaluate the suitability of a housing layout for LIG settlements using socio-architectural, geometric metrics and site-based airflow simulations. This method was designed based on two tracks, first to address the socio-architectural needs of the LIG space; the second is the parametric analysis of the housing layouts for site-based airflow calculations using an external CFD analysis to investigate the most suitable housing layout for the studies LIG houses. To understand the efficacy of housing layout, a parametric estimation was adopted on three housing layouts: the base-case (i.e. the current orientation of BDD chawls) and two hypothetical iterated urban forms (A and B). The socio-architectural and geometric estimation of the LIG spaces was performed to evaluate the structural variation among the parametric layouts of the vertical structures by i) availability of social interaction space and privacy degree of the outdoor open space, ii) varied site geometry. Fig. 2 illustrates the three housing layouts considered in this study.

These three layouts were developed such that they had a similar floor-space index, and built parameters like the form factor, the built-up area, the distance between each building and height. The arrangement of spaces within the building blocks was iterated while keeping the inter-element distance same (i.e.15m away from each other) in all the cases. This iteration generated variation in the social space available within each layout. For example, layout A and B (see Fig. 2) have a reasonable (six houses share one social space) and a high (four houses share one social space) amount of social interaction space respectively, in comparison to the base case scenario where 20 blocks share one social space. These three layouts were compared using geometric metrics and their variation in site-based airflow characteristics. The utilisation of such site-based physical parameters for effective ventilation can provide an optimal design strategy for better indoor air quality while providing needed social interaction spaces, at a cluster level. The methodology adopted in this study is illustrated in Fig. 3.

3.1 Geometric metrics used in this study

The variation in socio-architectural characteristics of the three LIG housing layouts was quantified using 12 form and space-based metrics. The conceptualisation of the relationship of these metrics with the quality of the LIG housing layouts was done following the socio-cultural, and architectural needs of such low-income housing. Table 3 describes the geometric metrics and their conceptualised relationship with the LIG housing layouts (Grimmond, King, Roth, & Oke, 1998; Millward-Hopkins, Tomlin, Ma, Ingham, & Pourkashanian, 2013). These metrics can be modulated through existing policy variables like FAR, density and provision for open space that are used in DCR. Table 3 provides the corresponding policy variable for each metric.

Nomenclature

H	Height of the building (in m)
W_{canyon}	Canyon width (in m)
A_T	Plot area (in m^2)
P	Perimeter of the urban form (in m)
W	Maximum width of the plot (in m)
Pop_{UB}	Total population of the urban block
P_i	Perimeter of the shape/profile (in m)
A_F	Frontal plane façade area (in m^2)
$A_{positive}$	Total area of positive space (in m^2)
$A_{negative}$	Total area of negative space (in m^2)
S	Surface area of building (in m^2)
V	Volume of the building plot (in m^3)
e_{ij}	Connectivity of an edge in a space graph $G\ (V, E)$, where, V is the set of nodes defining places $\{vi \mid i = 1, 2, \ldots, n\}$ and E is the set of edges or links connecting them $\{vi, vj \mid eij, i,j = 1, 2, \ldots, n\}$
C_{ij}	Number of edges *(E)* to which a node *i* is directly connected

3.2 Study Area

The British-era-Bombay Development Department (BDD) chawls in the central and south-central Mumbai was chosen as the study area. Spread spatially across four regions, namely, Worli (120), NM Joshi Marg (32), Sewri (12), Naigam (42) within the city. Here, residents of the BDD chawls in the Worli region were surveyed. A typical building form in the Worli chawl is shown in Fig 4. These LIG/EWS housing units have one or two-room units not more than 20 m^2 attached to a common corridor with shared toilets on each floor (Bardhan, Sarkar, et al., 2015). The BDD-chawls under consideration in this study is vertical structures with four floors, measuring to a height of 12 m. The living conditions of these places are like that of the slums with lack of airflow across the living spaces having an integrated cooking space within the living unit. The cooking fuel comprises of both cleaner cooking fuel like LPG and dirtier fuels like kerosene and biomass, which contributes to a higher level of household air pollution (Debnath, Bardhan, & Banerjee, 2017; Debnath, Bardhan, & Jain, 2017). The living spaces are entirely ventilated through natural ventilation, with a ceiling fan in each of the housing units as the indoor air circulation device (Bardhan et al., 2018). Each floor of a BDD-chawl hosts 20 household unit, with a total occupancy of 80 households in a single housing unit. The area consists of 206 such tenement units. Here, the study area consists of a block of 20 chawl buildings (see Fig. 4), which accommodates at least 1600 households with an approximate population size of 8000.

3.3 Airflow modelling and simulation

External airflow characteristics around the study buildings were calculated using CFD simulations computed using DesignBuilder v4.7 and EnergyPlus v8.3. The climate-based modelling of the study site was conducted using the nearest weather station data, situated at Santacruz airport (10 km away). Mumbai is characterised by hot and humid climate, with prevalent South-western (SW) wind directions. The average wind velocity during the month of the survey was approximately 3.66 m/s (13 km/h) at 10 m height. A temperature and a relative humidity sensor (HOBO Onset UX100-011) was installed in one of the tenement houses for the model validation purpose. The building properties of the model-input were imported from the 'Assembly U-factor Calculator Tool' for Indian conditions available at www.carbse.org/resource/tools_(CARBSE, 2017). The airflow modelling was predominantly natural ventilation with a ceiling fan in the living spaces (modelled as a mechanical ventilation system, see Table 4. The simulation models also incorporated actual occupancy and window-operating schedules, as per specifications of Debnath, Bardhan, & Jain (2017), and Bardhan et al., (2018). The uncertainties associated with the natural ventilation modelling, that include the stochastic state of local weather, hindrance to the air-flow due to high agglomeration of buildings in high density cities and user-behaviour in the opening and closing of the windows were addressed by adopting a deterministic approach in calculating the airflow in the building zones with steady-state time step of two hours (Debnath, Bardhan, & Banerjee, 2016, 2017). Table 4 illustrates the physical input parameters of the simulation.

Steady-state RANS governing equations were chosen for the CFD simulation, which was solved using the standard k-ε turbulence model (see Debnath, Bardhan, & Banerjee, (2016) for mathematical background). The second-order UPWIND discretisation scheme, was chosen for excellent accuracy and robust delivery of numerical solutions (Zhang, Zhang, Zhai, & Chen, 2007). Uniform hexahedral grids were chosen for the mesh modelling of the study unit (see Fig 3). Hexahedral cells were used owing to its high stability and convergence ratio for rectangular geometries (Gowreesunker, Tassou, & Kolokotroni, 2013). The grid topology details are illustrated in Table 5.

Grid independence tests were conducted, and medium-size grids were found to be most suitable regarding solution convergence and computation time. The solutions were assumed to be reasonably converged using the criteria of 0.01% of the root mean square residuals for mass and momentum equations, 1% of the energy conservation targets and numerical results to the point that no longer change with additional iterations (i.e. <5,000 iterations), as per the best practise CFD guidelines (Hajdukiewicz, Geron, & Keane, 2013; Toparlar et al., 2015). The external CFD boundary conditions were imported from the monthly EnergyPlus simulation results, through a manual coupling.

The energy simulation models were validated using the data acquired through the indoor air temperature and humidity data logger installed in one of the surveyed units. The metric of operative temperature (OT) was used to validate the energy simulation model. It is a function of mean radiant temperature and the air temperature, indicating the *'environmental temperature'* of space (R. de Dear, 2011; R. J. De Dear & G.S. Brager, 2002). The data acquired through the installed sensor was assumed to represent OT, owing to the compact nature of the built-form of the surveyed units as the surface temperature are approximately same as the air temperature (Bardhan et al., 2018; Debnath, Bardhan, & Jain, 2017). Model calibration was performed using the method of *manual iterative calibration* (Agami Reddy, 2006). Additionally, the simulated results were also compared with the energy simulation calibration data for the model mentioned in (Bardhan et al., 2018) (see Fig. 5). The calibration accuracy was evaluated using MBE and CV(RMSE) (Mustafaraj, Marini, Costa, & Keane, 2014), which were calculated on a half-hourly basis for August 2016 (Bardhan et al., 2018).

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

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

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 $N_{month} = 12, N_{days} = 365, N_{hour} = 8670$) and M_p is the average of the measured data. ASHRAE Guideline 14, specifies the acceptable limits for calibration of hourly data as -10% ≤ MBE_hourly ≤ 10% and CV(RMSE)_hourly ≤30% and monthly data as 5%≤ MBE_monthly ≤5% and CV(RMSE)_monthly ≤15% (ASHRAE, 2002).

4. Results

The validation data projected an acceptable range of MBE and CV(RMSE) of 0.34% and 2.88%, respectively. The average indoor diurnal temperature was observed to be around 30.13 °C, with a minimum of 29.36 °C and a maximum value of 31.74 °C. The MBE and CV(RMSE) values were as per ASHRAE Guidelines-14 specified limits. The current model comparison values to Debnath, Bardhan, & Jain (2017), is illustrated in Table 6.

4.1 Geometric metrices of the parametric LIG urban housing layouts

Comparison of different geometric parameters between the three parametric layouts enabled a detailed view of the variations in the three housing layouts. The calculated geometric metrics for the three typologies are presented in Table 7. The results showed that Form A was significantly less compact concerning the base-case and Form B. Base case form was found to be densest followed by Form B while Form A was observed to be relatively less dense when density was calculated for all three layouts. It indicates that Form A being less compact and dense than other two forms provides more sustainable living conditions than the other two layouts.

Form A was observed to be the most irregular with a fractal value of 1.41 followed by similar fractal expressions of base case (1.28) and Form B (1.3). However, base case was most fragmented in comparison to the other two forms, when brokenness was considered. The degree of the brokenness of a form was quantified based on the amount of jaggedness or broken the perimeter of the form was, i.e. how much it deviated from the straight line. The significantly high value of frontal area index in Form A (0.082) denotes higher roughness length, which represents the aerodynamic property of the layout that facilitates better airflow.

On comparing the socio-architectural parameters, it can be inferred that Form A provided the significantly higher amount of social interaction space (49%) in comparison to the Form B (20%) and base case (28%). Moreover, in Form A six houses shared one social space (see Fig. 2b), in Form B four houses shared one social space (see Fig. 2c), whereas 20 houses shared one social space in the base-case scenario (see Fig. 2a). Thus, implying a relatively higher level of community interaction in case of the Form A. Form A comprised of the highest amount of positive open spaces to undefined and service related negative spaces (ratio- 2.17:1). The other two alternatives (base-case and Form B) had more of unused negative spaces than positive ones (see Table 7). Similarly, the privacy gradient of open space in Form A was highest followed by Form B with the base-case having the least privacy.

Although, the three forms revealed moderate variations in the geometric metrics, the social interaction spaces among the forms varied significantly. Among the three forms Form A performed better than the base-case and Form B, in all the metrics.

4.2 Site-based airflow analysis

The site-based airflow pattern around the buildings is illustrated in Fig. 6. The 'blue' colour bands represent low wind-velocity zones (~ 0.00-1.85 m/s), the 'yellow-orange' colour bands represent the medium wind-velocity zones (~2.00-4.00 m/s), and the 'dark orange-red' zones represents higher wind-velocity zones (~ 4.50 – 7.00 m/s). Subjectively, the 'blue' zone refers that the natural ventilation alone will be insufficient to promote thermal comfort in the living spaces through cross-ventilation. The 'yellow-orange' zones infer natural ventilation may provide thermal comfort and improved air quality through active air exchanges in the living spaces, although a mechanical device like an exhaust fan or a pedestal wind-fan, may be required intermittently to maintain constant air-exchange levels in the indoor spaces. Moreover, the 'dark orange-red' zones infer that the wind-velocity is high enough to promote thermal comfort and cross-ventilation without the need of any external mechanical devices (Blocken et al., 2012; Indraganti et al., 2012).

Fig. 6 indicates a lower range of wind-velocity (blue colour bands) across the varying heights in Form A and Form B. The higher occurrence of yellow bands was distinct in the second floor (9.50 m) and the third floor (11.50 m), for Form A and B (see Fig 5). It infers the possibility of better air exchange through cross-ventilation. However, in the Base-case scenario, the blue colour bands remain consistent across the building irrespective of the height, indicating the design itself restricts the wind-flow across the building. Subjective interpretation of these layouts reveals that the current orientation of the chawl, inherently obstructs wind-flows across the structures, whereas Form A and Form B allows the required turbulence within the spaces, which create zones of low-pressure across the window. Thus, retrofits like a low-cost extract fan can improve the cross-ventilation conditions in these two layouts. Fig. 7 illustrates the change in the local wind-velocity contours for the ground floor (2.50 m) and the top floor (11.50 m). The wind flow remains low across the windows in the base-case scenario, whereas Form A shows more yellow zones around the windows than Form B at the top floor level (see Fig 7). Thus, concerning airflow across the building, Form A can be considered as a more suitable form for LIG housing layout that can promote better indoor air quality.

5. Discussion

We performed a cross-sectional study of the slum redevelopment policy for the city of Mumbai, as stated in the City Development Plan (CDP) 2005-2025. The proposed strategy in the CDP involves community participation in slum redevelopment of the LIG/EWS housing stocks and improving access to primary urban services. However, lack of sustainable design guidelines was observed in the current policy for urban renewal and rejuvenation missions in the city. Here, we investigated this paradigm of urban design for LIG/EWS social housing, through a socio-architectural geometric estimation using 12 parameters (see Table 7). These parameters were investigated based on three LIG housing layouts (see Fig. 2). Additionally, a site-based airflow analysis was conducted using CFD simulations, such that the airflow patterns can help in determining the socio-architectural geometry that can improve the indoor air quality and thermal comfort conditions through wind-driven natural-ventilation. The intent behind these cross-sectional analyses was to arrive at reasonable design heuristics for the urban rejuvenation and renewal of the tenement housing in Mumbai, such that relatively better housing conditions can be provided in the upcoming LIG housing stocks, just by modulating the site-characteristics and socio-architectural variables.

Fig. 6 and Fig. 7 illustrates the site-based airflow characteristics of the three layouts, and it is evident that Form A had higher air-velocity near the windows. It can be attributed to the lower aspect ratio (see Table 7), that provides a profound canyon effect, modulating the local wind flows that facilitates natural ventilation (Tong & Leung, 2012). Additionally, the compactness ratio and shape index of Form A was also lowest in comparison to the base-case scenario and Form B (see Table 7). A lower compactness ratio infers a higher quality of building layout, especially in these LIG housing (see Table 3). Although this may seem counterintuitive, given the typical hyper-dense nature of the LIG settlement, lower compactness would mean that there are more per capita allowable liveable spaces. Similarly, Form A reported a higher fractal value than the other two forms, which physically represents the degree of continuity of the housing layouts, indicating that Form A would signify a more socially inclusive housing structure. It forms the core aspect of social housing for LIG population. Moreover, increased fractalness increases the form roughness, which stimulates higher wind flow.

Social interaction space was found to be highest in the Form A (0.49) than the base-case (0.28) and Form B (0.20), indicating that the Form A can provide better community spaces, that would enable more space for business and social gathering. It is one of the critical attributes that horizontal slum housing offers for the current vertical structures (Debnath, Bardhan, & Jain, 2017). With higher social interaction space in Form A, occupants might find it more liveable as this form provides continuous space for conducting their economic activities. For example, a typical economic activity in the horizontal slums is tailoring. The tailor shop owners require the regular flow of customers, visibility and ease of access, however, when these occupants are shifted to a vertical structure, the foot-fall of the customers on higher floor reduces, which in turn affects their household economics. The fall in the customer base due to shifting from horizontal to a vertical structure is a significant reason for the occupants' reluctance to shift to a vertical LIG housing. In addition to the social interaction space, Form A has more frontal area index (see Table 7), indicating that more façade is exposed to site wind flow. It could also be interpreted regarding having more surface area exposed to higher wind-velocity (see Fig 5), thus, enabling better conditions for the installation of extract fans as a retrofit. Installing extract fans in the windward side would improve cross-ventilation in the living spaces, translating into better indoor air quality and thermal comfort. Thus, fulfilling the requirements of a better LIG/EWS housing design (see *policy gap* in Table 2).

Another critical socio-cultural element of LIG housing is occupant privacy. This parameter needs to be imbibed in sustainable low-income housing policies so that occupants do not shift back to compact horizontal and more impoverished slum forms. We have found that Form A offers a better amount of privacy (0.37) due to the alternative staggered arrangement of the housing structures. Additionally, Form B had similar privacy values (0.34). The base-case scenario had the lowest privacy quotient (0.25), which physically translate into the operating schedules of the doors and windows of the occupants. It means base-case building design compels the occupants to keep their windows and doors closed for a longer duration, which in-turn affects the indoor air quality and indoor air temperature by restricting wind-driven cross ventilation.

Cumulatively, Form A qualifies as the relatively suitable LIG housing design that can fill the gap in this low-income sustainable habitat regulatory crisis in India. With the given constraint of space and policy, Form A offers better privacy, community spaces for business and canyon width for inducing higher wind velocity across the buildings (see Fig 5 and Fig 6). Additionally, Form A shows larger frontal area index, i.e. more exposed façade, which could be utilised for retrofitting of installation of solar photovoltaic panels for enhanced energy efficiency in the structures. Thus, with the given constraints of developmental guidelines as per the Mumbai City Development Plan 2005-2025 (see Table 2), the Form A serves as a relatively better design for upcoming LIG/EWS housing stocks under the slum redevelopment program.

6. Conclusion

Quality of life of the citizens is an essential aspect while planning for smart and sustainable cities. Due to rapid urbanisation, many cities of the developing countries witnessed slum proliferation characterised by a reduced quality of life. With the challenges associated with the phenomenon of slum formation and rapid urbanisation, many slum redevelopment and rehabilitation policies came into existence. However, these policies focus on maximising occupancy and often overlooks the need for improving the built-environment which can significantly improve the quality of life of the inhabitants. It is due to the lack of process-driven slum redevelopment guidelines, there remains a blind spot in the current housing policies in India, and around the world. The low-income group population has specific socio-cultural characteristics that cannot be addressed through a standard 'urban-design' template. Addressing these needs would require a deeper involvement of socio-architectural elements of such space into the design process, to ensure sustainability of the future low-income housing stocks. In India, these housing stocks are yet to be constructed under the 'Housing-for-all- program. However, the current low-income housing stocks have deteriorated into slum-like living conditions, implicating negatively on the health and well-being of the occupants.

In this study, a similar low-income housing of Mumbai called the ‘chawls’ were cross-sectionally investigated to derive planning and design elements that would orchestrate with the specific needs of sustainable slum-redevelopment. The cross-sectional study included geometric computation of three low-income housing form-based layouts, with the steady-state wind flow simulations of the housing sites using computational fluid dynamics. This study enabled in identifying the critical socio-architectural and geometric parameters of LIG housing layouts that can promote better indoor air quality and thermal comfort. Improving these space-based parameters would impart a relatively better quality of life in the rehabilitated occupants. Our findings indicate that the current housing layout (i.e. the base case scenario) is unable to provide adequate quality of life and just a rearrangement of the space (as in Form A) can render space more 'livable'. The third hypothetical form, Form B, was found to perform like the base-case layout. It shows that not all iterations of housing layout can produce the desired effect, hence the sensitivity of socio-architectural parameters needs to be critically analysed. This analysis can pave a pathway to development of regulatory guidelines for low-income housing design that is also coherent with the context of the space.

The next step would be to investigate the avenues for actively engaging the stakeholders in the design-process, such that the slum-rehabilitation process remains sustainability with the changing patterns of urbanisation. At present, we are actively working with the mainstream media to sensitise citizens and policy-makers about this issue, and the public pleasantly acknowledges our attempt to improve such built-environment through engineering-based approaches (see the media coverage links: https://tinyurl.com/yan7plfu; https://tinyurl.com/yacl9w96; https://tinyurl.com/yagxne4x).

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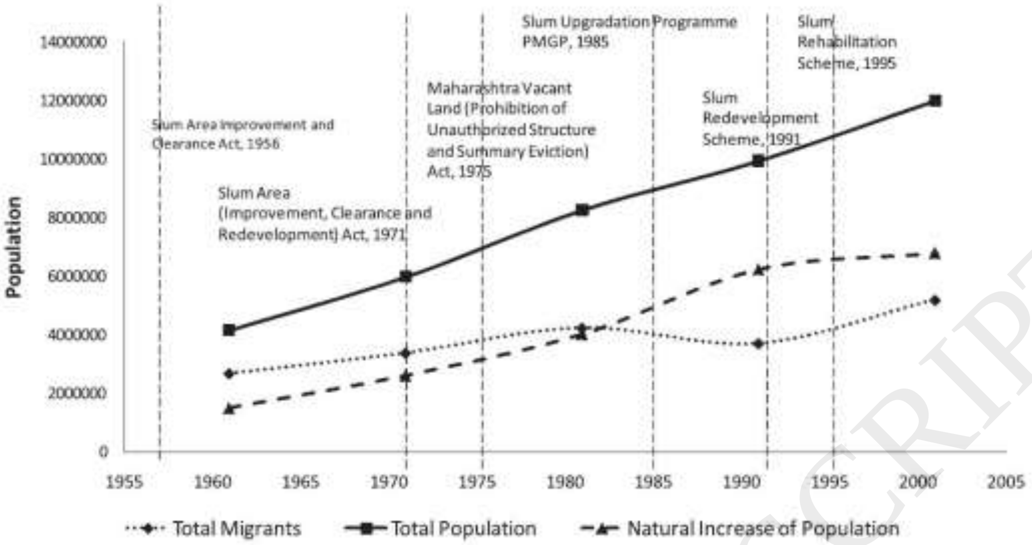
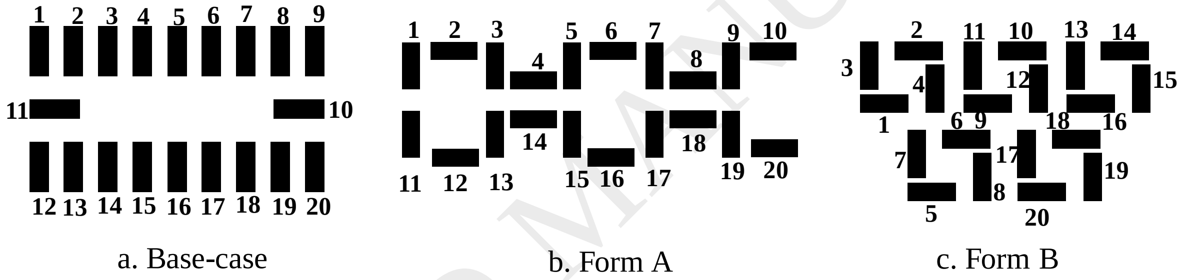


Fig. 1 Evolution of Slum policy in Mumbai, India since independence in 1947 (Bardhan, Sarkar, et al., 2015).



a. Base-case

b. Form A

c. Form B

Fig. 2 The urban-forms of LIG houses considered in the study.
(Note: Base-case is the current scenario, Form A and B are the hypothetical cases)

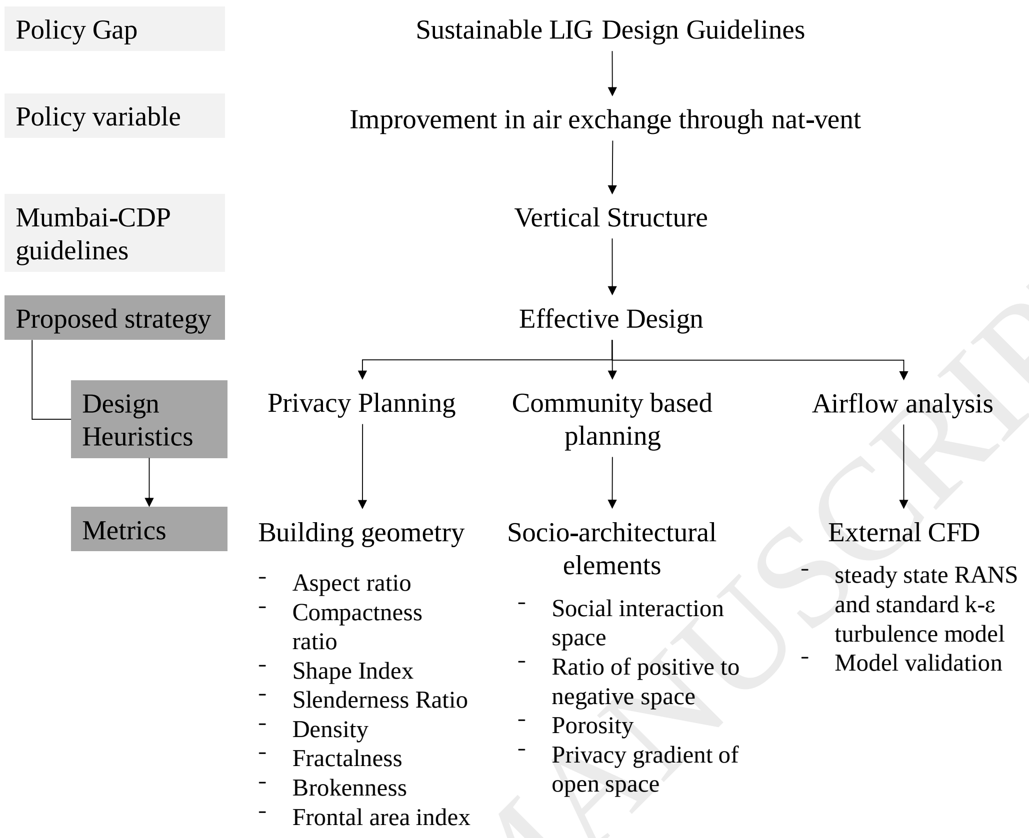
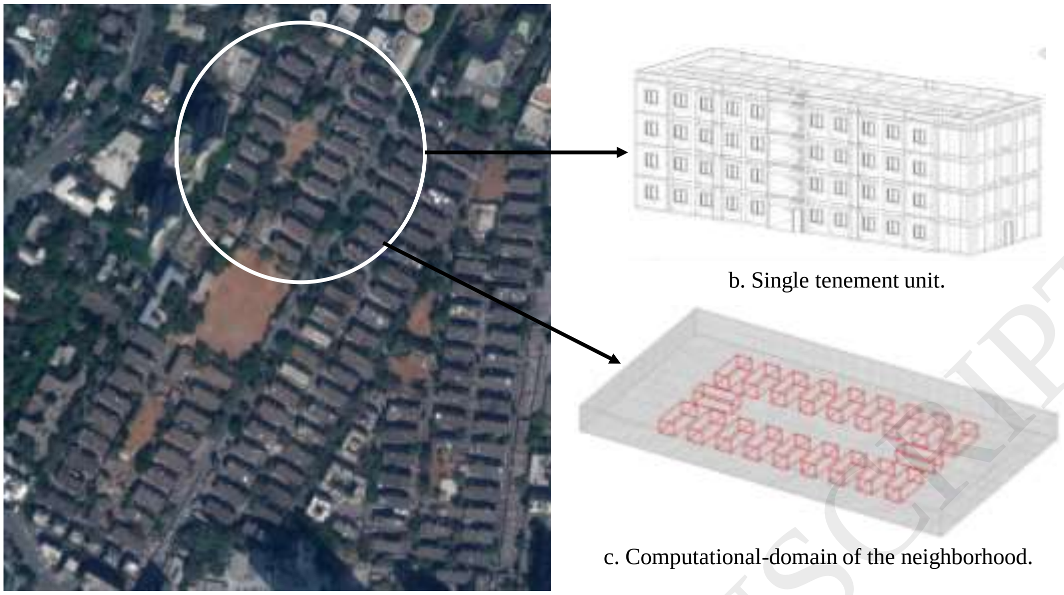


Fig. 3 Methodology adopted



b. Single tenement unit.

c. Computational-domain of the neighborhood.

a. Site-layout of the BDD chawl community.
(Source: Google Earth)

Fig. 4 Building layout of BDD chawl, Mumbai.

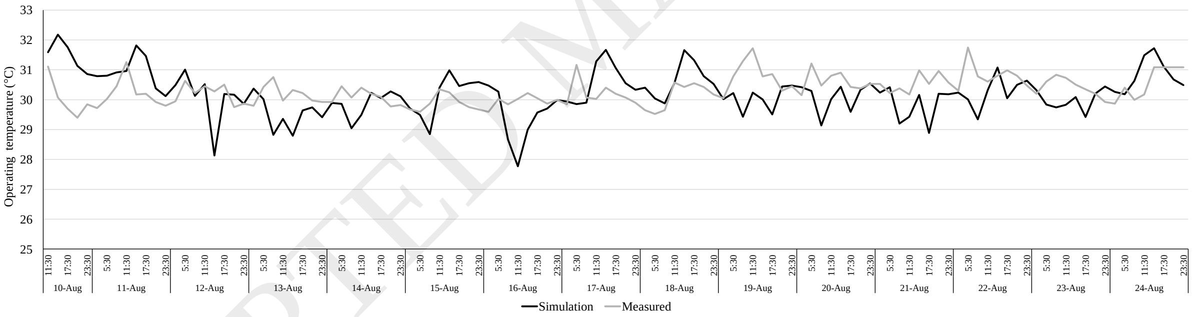


Fig. 5 Measured vs. simulated data of the energy model.

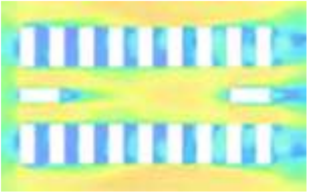
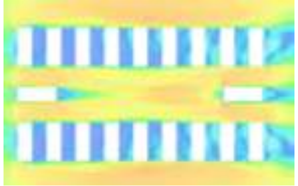
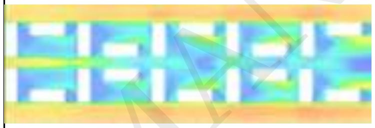
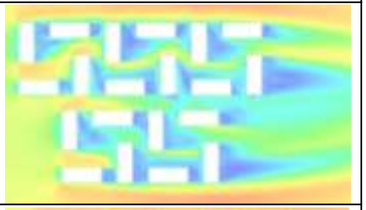
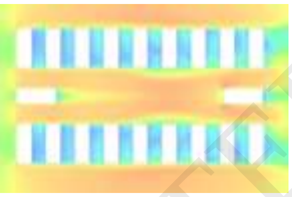
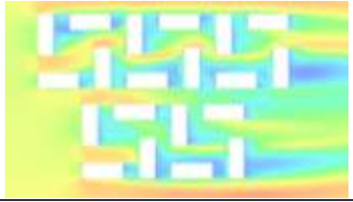
Height	Base-case	Form A	Form B
2.50			
5.50			
7.50			
9.50			
11.50			
	Wind velocity (m/s) 🟦 0.00 🟦 0.61 🟦 1.22 🟦 1.83 🟩 2.44 🟩 3.05 🟩 3.66 🟨 4.28 🟨 4.88 🟧 5.50 🟧 6.10 🟥 6.71	Wind velocity (m/s) 🟦 0.00 🟦 0.53 🟦 1.05 🟦 1.58 🟩 2.10 🟩 2.63 🟩 3.15 🟨 3.68 🟨 4.20 🟧 4.73 🟧 5.25 🟥 5.78	Wind velocity (m/s) 🟦 0.00 🟦 0.45 🟦 0.90 🟦 1.35 🟩 1.80 🟩 2.25 🟩 2.70 🟨 3.15 🟨 3.60 🟧 4.05 🟧 4.50 🟥 4.95

Fig. 6 Airflow pattern around the forms at different heights in the *xy* plane.

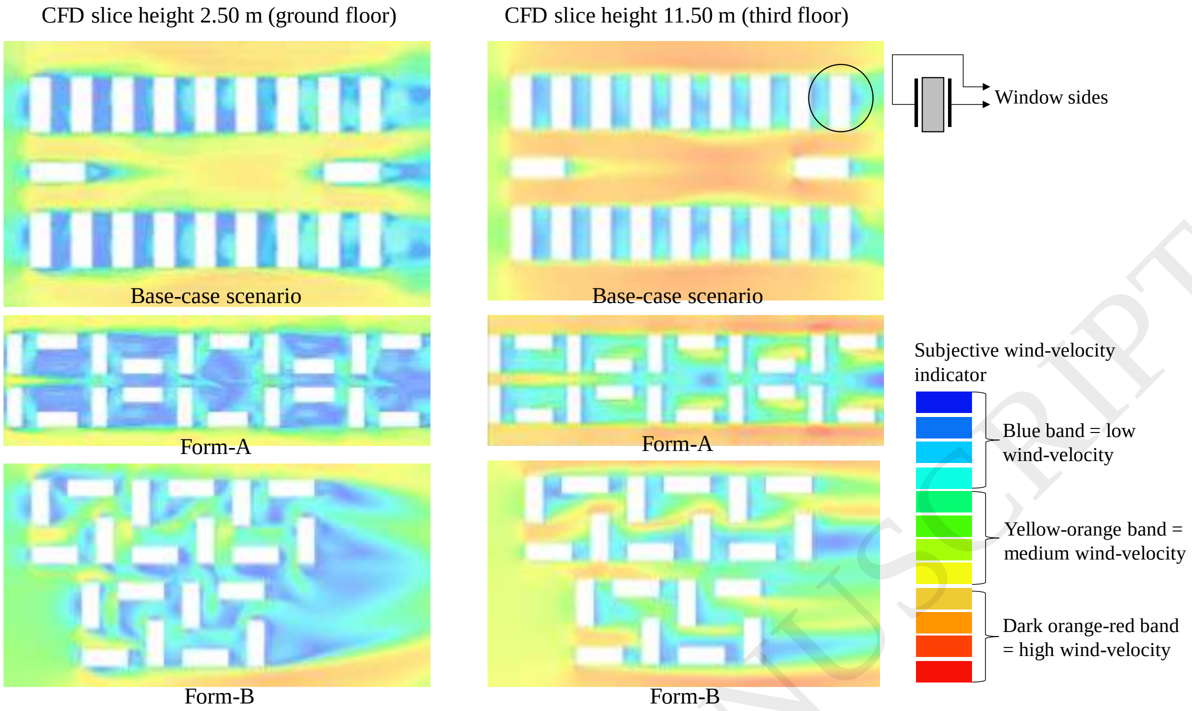


Fig. 7 Case-wise variation in the air-flow pattern across the buildings.

Table 1: Modification to Development Control Regulations (DCR), Mumbai for Rehabilitated Colonies over the years

Year	1995	2002	2008	2016 (proposed by MCGM, 2016)
Unit Size	20.90 m^2	25 m^2	25 m^2	25 m^2
Sanctioned FAR	May exceed 2.5	May exceed 3	May exceed 3 or 4	May exceed 4
Minimum Density	500 du/ha		500 du/ha 650 du/ha for Dharavi	650 du/ha
Distance between buildings	Not less than 3 meters			6 meters
Open Space	Minimum 8% of the plot area			

Table 2 Strategy for LIG housing and slum improvement (MCGM, 2017b), with authors' assessment of the gap in policy and planning.

	Enlisted strategies (MCGM, 2017)	Key features	Gap in policy and planning (Authors' assessment)
Strategy for Housing	Actions for housing access to slums	Redevelopment through participatory appraisal; Tenure grant for housing unit size < 20 m^2; Cross-subsidisation through TDR and increased FSI; Public rental and temporary shelters	Lack of *process-driven methodology* in redevelopment planning of slum settlements.
	Actions for increasing housing stocks	Variable FSI according to infrastructure need and environmental limits; Redevelopment of unused government lands/ old mill areas;	No consideration of *the building-form based socio-technical design heuristics* for slum improvement such that occupants' privacy and the informal businesses of such settlements can be sustained.
	Actions for improving dilapidated buildings	Redevelopment of dilapidated buildings especially the tenement (chawl) housing	
	Policy level measures	Improving the planning and environmental review capabilities at the municipal level	
Strategy for slum improvement	Well-developed slums (< 33 m^2 of floor space)	These slums should be converted into formal housing by granting tenure to the residents	Absence of consideration on indoor *liveability parameters* like indoor air quality, thermal comfort and building energy efficiency. It indicates the lack of sensitivity of the authority towards the notion of well-being in such built environment.
	Slum dwellers living in acceptable areas	In-situ development of these slums with cross-subsidisation	
	Slum dwellers living in important public areas like parks, railways and airports	The slum dwellers can be moved to unused governmental lands, including saltpan lands and current No Development Zones (NDZs); allowing the slums to form their own societies	
	Access to urban basic services	Greater focus on the water supply system, sanitation program, solid waste management, construction of concrete roads lines with storm water drains, auditing the municipal health and education facilities.	

Table 3 Geometric metrics for measuring urban forms.

Indicators	Formula used	Description	Conceptualization of relationship with quality of LIG housing layouts (Q_L) (see Fig 1)	Association to existing policy variable	Reference
Aspect ratio	$\frac{H}{W_{canyon}}$	The ratio of building height and canyon width. Higher the value of canyon width, lesser will be the value of aspect ratio. It ranges from 0 to 1.	$Q_L \propto \frac{1}{Aspect\ ratio}$	FAR	
Compactness ratio	$\frac{4A_T}{P^2}$	The ratio of area and perimeter of an urban form, with different nomenclatures. Higher the value of the parameters, higher is the compactness. the compactness ratio ranges from 0 to 1.	$Q_L \propto \frac{1}{Compactness\ ratio}$	FAR	(Batistella, 2001)
Shape Index	$\frac{P}{2\sqrt{\pi A_T}}$		$Q_L \propto \frac{1}{Shape\ Index}$		
Slenderness Ratio	$\frac{H}{W}$	The ratio of height and width of the shape. As the height of all the buildings are same, the slenderness ratio increases as the site width decreases. It ranges from 0 to 1.	$Q_L \propto \frac{1}{Slenderness\ ratio}$	FAR	
Density	$\frac{Pop_{UB}}{A_T}$	Density is calculated by comparing the total population of an urban agglomeration to the total urban area. Each building considered in the study area has four floors with 20 apartments per floor. Thus, the total population of the urban block consisting of 20 chawl units was calculated to be 8400 taking a household size to be five as the average household size. Density ranges from 0 to 1.	$Q_L \propto \frac{1}{Density}$	Density	
Fractalness	$\frac{2lnP_i}{lnA_T}$	Fractalness reflects the measures the degree of self-similar repetitiveness of an element in the housing layout form. Higher values indicate more complex boundaries and spatial structures; fractal	$Q_L \propto Fractalness$	Provision for open space	(Md Rian, Park, Uk Ahn, & Chang, 2007).

Indicators	Formula used	Description	Conceptualization of relationship with quality of LIG housing layouts (Q_L) (see Fig 1)	Association to existing policy variable	Reference
		dimension index range from 1 –2.			
Brokenness	$\frac{P_i}{P}$	Measures the degree to which the form or shape is fragmented. It is the ratio of the actual perimeter of the profile/shape of the urban form and the enclosed perimeter of the plot. Brokenness ranges from 0 to 1.	$Q_L \propto Brokenness$	Provision for open space	(Authors' computation)
Frontal area index	$\frac{A_F}{A_T}$	Measured as the ratio of façade area (projected onto a vertical/frontal plane normal to the wind direction) to the area of a grid plane on which buildings are located.	$Q_L \propto \frac{1}{Frontal\ area\ Index}$		(K. Chen & Norford, 2017) (Wong & Nichol, 2013)
Social interaction space	$\frac{A_{positive}}{A_T}$	The quantity of open spaces improves behaviour, social interaction among citizens and useful airflow characteristics from the environment point of view Hence, the amount of social interaction space for all three forms were examined as the ratio of positive/socially interactive area within the plot to the whole plot area.	$Q_L \propto Social\ intercation\ space$	Provision for open space	(Katzschner, 2003) (Prajongsan & Sharples, 2012)
Ratio of positive to negative space	$\frac{A_{positive}}{A_{negative}}$	An increase in the net amount of open space within a built environment does not necessarily signify that space has a practical use, i.e. has a positive impact or a function one. There are spaces within a site which remains devoid of any function and cannot always be used for any activity. These are spaces left over after planning	$Q_L \propto positive\ space$	Provision for open space	(Carmona, 2010).

Indicators	Formula used	Description	Conceptualization of relationship with quality of LIG housing layouts (Q_L) (see Fig 1)	Association to existing policy variable	Reference
		(SLOAP). These negative spaces reduce the socio-architectural efficacy of the form as the cannot be used for social interaction.			
Porosity	$\frac{A_{void}}{A_T}$	The open spaces in a built form can be conceptualised as “holes” or “pores” in the urban area. This parameter measures the proportion of these “pores” within the entire urbanised space.	$Q_L \propto Porosity$	Provision for open space	(Huang et al., 2007).
Privacy	$e_{ij} = \begin{matrix} 1, if\ v_i v_j \in E \\ 0, Otherwise \end{matrix}$ $C_{ij} = \sum_j e_{ij}$	Privacy gradient of space is measured using two indices (i) isovist graph, and (ii) connectivity degree of space syntax. If a space with joint ownership having clear boundaries is visible and connected, then it incites more social interaction and stabilises social contacts.	$Q_L \propto Privacy$		(Ramezani & Hamidi, 2010) (Batty, 2001) (Alitajer & Molavi Nojoumi, 2016)
Form factor	$\frac{S}{V}$	The ratio of surface area to the volume	$Q_L \propto Form\ factor$	FAR	

Table 4 Simulation input parameters

Sl. No.	Element	Materials	Thickness (mm)	Overall U-Value (W/m^2-K)	Surface to Surface U-factor (W/m^2-K)	Conductivity (W/m-K)	Specific Heat (MJ/m^{3}K)	Density (Kg/m^3)	Reference
1	Walls	Brick-Kiln Fired	250	1.8	2.6	0.59	0.27	1660	(CARBSE, 2017)
2	Roof	Concrete 25/50	150	3.6	9.3	1.4	0.48	2427	
3	Floor	Concrete 25/50	150	3.6	9.3	1.4	0.48	2427	
4	Air Infiltration	Through minor cracks and openings (Moderate Infiltration).							
5	Ventilation system	Wind driven natural ventilation. With one ceiling fan in each of the surveyed units, operating with a constant air change rate of 10 ACH (Zhu, Srebric, Rudnick, Vincent, & Nardell, 2014)							
6	Exhaust system	Not available in the surveyed units							
7	Lighting system	Fluorescent lighting T8, operated for 18 hour a day (One fluorescent light per unit)							
8	Other HH equipment	One television, one refrigerator							
9	Operating Schedules	Occupancy: 5:00 AM to 10:00 PM Mon - Sun, All week days; Window Schedule: Windows are kept open throughout, with 90% glazing area							
10	Window to wall ratio	<5%, with single-glazing windowpane. The windows are kept open throughout the day and are usually closed in the night time (based on the HH survey).							

Table 5 Mesh details

Cell type	Uniform Hexahedral
Total no. of cells	188*344*24 = 1,552,128
Aspect ratio	1.379
Grid tolerance limit	0.5000 m
Site domain factor (length/ width/ height)	1.50/1.50/2.00

Table 6 Comparison of the validation parameters between this study and Debnath, Bardhan & Jain, (2017).

Verification parameter	This study	Debnath, Bardhan, & Jain (2017)	Standard Deviation
MBE (%)	0.34	1.07	0.49
CV(RMSE) (%)	2.88	2.26	0.43
Avg. indoor temp. (°C)	30.13	30.50	0.26
Min. indoor temp. (°C)	29.36	29.90	0.38
Max. indoor temp. (°C)	31.74	32.75	0.71

Table 7. Parametric results of the urban geometric analysis of the LIG housing layouts.

Parameters	Base case	Form A	Form B
Aspect Ratio	0.24	0.19	0.32
Compactness Ratio	0.22	0.06	0.19
Shape Index	1.19	0.73	1.28
Slenderness Ratio	0.05	0.03	0.05
Density	0.25	0.21	0.23
Fractalness	1.28	1.41	1.30
Brokenness	2.75	1.78	2.20
Frontal Area Index	0.05	0.08	0.05
Social Interaction Space	0.28	0.49	0.20
Ratio of positive to negative space	0.80	2.17	0.96
Porosity	0.64	0.69	0.69
Amount of Privacy	0.25	0.37	0.34