A simulation based framework to optimize the interior design parameters for effective Indoor Environmental Quality (IEQ) experience in affordable residential units: Cases from Mumbai, India

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Abstract. This study intends to optimise the interior layout of two low-income multi-rise tenement designs that would provide effective indoor environmental quality (IEQ) over the breathing zone. A variety of interior layouts were generated for both space constrained tenement units by introducing and varying interior architectural parameters and their respective design variables such as partition wall, cook-stove and furniture location. The study initiated with in-situ sensor development coupled with a stepwise simulation based framework involving sampling based parametric modelling followed by CFD simulations and multi-objective optimisation. Air velocity, temperature, and pollutant concentrations were considered as surrogate measures of IEQ. The research finally delivered two varying interior design layout with optimised design variables that would deliver indoor air quality within comfort range over the breathing zone in nat-vent conditions. Dearth of sustainable design strategies is a major dead-spot in habitat planning policies of India and needs urgent attention. This data driven research heuristics if applied through building design guidelines would help the architects, building engineers and urban planners to design and rejuvenate slum and low-income habitats by imbibing the environmental sustainability aspect in habit design policies.

1. Introduction

Literature has cited strong and reliable connection between public health and built environment (BE). The nexus of health-space interconnections evolve over a lifetime that essentially links human-space interaction at different stages of urbanization [1]. The unprecedented levels of urbanization impose greater challenges in the aspect of environmental sustainability with air pollution, unsustainable energy use on one hand and degradation of global sustainability, health, livability and human well-being on other hand. In a response to this context, the urbanization pressure in the developing nations with poor
socio-economic conditions would lead the urbanites face challenges including ecological depletion, reduced green open spaces, housing shortage and resource depletion leading to diminishing quality of urban life (QoUL) [2].

With the paradigm shift in the concept of urbanization, and most of people moving indoor, Indoor environmental quality (IEQ) has come to the forefront of public domain especially among the researchers by being a major means of sustainable development [3]. It is well established in literature that IEQ has crucial links to occupant health and well-being [4]. Public health risks resulting from inferior IEQ are observed to be higher in women and children especially the poor owing to their maximum exposure to indoor pollution, which considerably influences the societal cost. A study on the association between IEQ and Sick Building Syndrome (SBS) in Hong Kong concluded that people working in offices with poor IEQ have less productivity [5]. The statistical analysis also elucidated that samples with SBS were more dissatisfied with IEQ than those without. Another study had investigated the association of green buildings of Singapore with quantitative and qualitative IEQ performance parameters to find that there was statistically significant reduction in risk of occupants having unusual fatigue, headache etc. in green buildings with improved IEQ with respect to conventionally designed buildings [6]. Hence, IEQ being a latent but challenging issue, the excavation of epistemology of this less-explored subject of IEQ-BE nexus becomes necessary.

Optimal built-environment (BE) with improved or at least comfortable IEQ is henceforth necessary for sustainable development. Passive building designs with ventilation effective building strategies improve the thermal comfort and indoor air quality (IAQ) of a space along with saving energy consumption. According to ASHRAE standard 55 report, an indoor air speed of 0.8m/sec would reduce the operative temperature by 2.6°C, provided the air temperature is equal to radiant temperature [7]. Research by Kubota et al. [8] cite reduction in energy consumption and greenhouse gas emissions as potential benefits of integrating natural ventilation strategies in the built environment. Entwining natural ventilation approaches in building design increases the thermal comfort degree in indoor besides outdoor conditions. Enhanced IEQ and greater occupant control have been observed in higher percentage in naturally ventilated buildings than that of mechanically ventilated buildings. Application of natural ventilation strategies and passive cooling systems is also expected to reduce 18% savings in health costs[9] and 2.35% reduction in world energy requirements [10]. A study by Fisk [11] unveils that fresh air introduction and higher indoor air exchange rates can hugely reduce SBS symptoms.

Airflow characteristics and air movement path is the governing prerequisite in the ventilation process when integrating and designing building facade, building form, apertures and building orientation [12]. Literature that have elucidated the effect architectural design parameters have on indoor wind motion have focused on community level parameters like building arrangement [13] building orientation[14], boundary wall [15], aspect ratio [14], building voids [16] and courtyards [17], building envelope level parameters like size type and position of window [18], shading devices [19], balcony [20] ceiling [7]. However, limited studies have focused on the relationship between indoor air velocity and interior design parameters [21]. Thus, appropriate natural ventilation sensitive building design with optimized interior design parameters should be utilized to improve indoor micro-climates and thermal comfort in buildings.

There have also been huge research on scientific methods like optimization of building design parameters in order to satisfy user defined objectives. However, till date most of the applications of building design optimization have been performed in the field of cost-management and energy efficiency [22], [23]. Furthermore, design optimization has only considered building design parameters at community and envelope level.

The study, by adopting a transverse research methodology tries to unearth the process of building design optimization with focus on interior design parameters for delivering improved indoor air quality and thermal comfort conditions. We hypothesize that ‘better indoor air quality can be achieved through efficient building design, which is a function of interior design’. Indoor air velocity, temperature and pollutant concentrations were accounted as the major surrogate measures of IEQ in this study. The research methodology involving in-situ environmental sensor deployment coupled with computational
simulations and numerical analysis tries to optimize the interior design parameters of two different low-income tenement units by improving indoor air quality in natural ventilation conditions. Objectively, this study explores into the interior architectural parameters with aerodynamic potential and their design variables to investigate their effect on indoor natural ventilation characteristics. Owing to the lack of literature regarding aerodynamically efficient interior design parameters and their optimized design for obtaining better indoor environmental conditions, this study is of its first kind to deal with interior design optimization for better IEQ in natural ventilation condition in tropical climate of India with a focus on low-income habitats, which consists 50% of Indian population.

2. Background
The UN-Habitat reports that one in every three urbanites of developing world stays in slums and other informal settlements, thus making slum urbanism a truth [24]. The deficiency of ‘affordable housing’ has been accounted in India as a major impediment for urbanization. In response to this context, the government housing group authorities have delivered housing to socially-driven class of population. This avowal of ‘adequate housing’ regarding poverty mitigation and socio-economic development became the underlying cause behind the concept of social mass housing since 1970s[25]. These houses, commonly connoted as ‘chawls’ in Mumbai, consist of single-dwelling units housing male-centric migrant industrial workers [26]. The one room tenement apartments of 18.58m² area, attached to a common corridor with shared toilets continued to degrade to ‘slum-like’ living conditions, adversely affecting the health, well-being and quality of life of inhabitants. The poor QoL within the ‘chawls’ are indicated by consumption of unclean fuels for cooking purpose combustion of which emits smoke and pollutants, lack of appropriate hygiene and sanitation facilities, extreme levels of indoor air pollution etc. [1]. Government housing authorities seek to resettle these populations as well as traditional slum dwellers to permanent multistorey structures to mitigate land scarcity and provide security of tenure under Slum Rehabilitation (SRA) Development Control Regulation (DCR). However, arresting of slum proliferation in Mumbai through these techniques have majorly followed the ‘provider’ regime which is quantifiably biased and has been criticized for being extremely consumerist-orientated, contributing to profit-maximization, occupancy-maximization while overlooking commendation of the human needs [27].

The recently built hyper-dense multistoried low-income SRA colonies, like traditional slums and ‘chawls’ in Mumbai are characterized by airflow deficiency in living zones leading to inferior air quality, extremely high temperature trapped zones, high pollution levels and lack of hygiene. These high rise tenement housings, built without any prescribed design guidelines, lead to hyper-densification with inadequate inter-block spaces and tremendously high densities (approximately 1300du/ha). The QoL is further aggravated by the lack of low-income habitat design tools and guidelines. Overcrowding and deficient ventilation increase indoor moisture levels within these tenement units, thus leading to incidence of respiratory diseases within inhabitants. The lack of cross ventilation strategies within these ‘pigeon-hole’ like tenement apartments often leads to the failure of attaining effective ventilation thresholds [21]. This phenomenon inhibits the efficient disposal of indoor stale air, leading to high levels of indoor pollution with extreme indoor contaminant concentration. Indoor temperature levels fluctuating from comfort ranges within these tenement units cause SBS syndrome. Additionally, the proximity of these buildings to heavy vehicular roads was found to contribute significantly to the deteriorated IAQ.

However, the dearth of aetiological evidence of the BE-IEQ nexus especially in low-income housings of Mumbai acts as an impediment for sustainable low-income urban planning measures in Mumbai, advertently leading to poor QoUL, environmental pollution etc. Furthermore, the linkages between health determinants of low-income housing population and environmental measures are not well-demonstrated in existing literature. Thus, this study intends to investigate for low-income populations.
3. Methodology

3.1. Study Area

This study examines the human-space inter-linkages of the occupants of low-income housing of Mumbai, India. Two typologies of low-income multi-storey housing was selected here based on their design variations. Owing to the single male-centric labour force specific in-migration during 19th century in Mumbai for cotton textile mills and petrochemical industries, housing complexes comprising of one-room tenement units also connotated as ‘chawls’ were evolved. The British-era Bombay Development Directorate (BDD) ‘chawls’ of central and south-central Mumbai was selected here as one case study. Later, in response to extreme urbanisation pressure, affordable housing group authorities tend to resettle the socially-driven class of population to permanent hyper-dense multi-rise apartments under Slum Rehabilitation Development Control Regulations (DCR) and through Project Affected People (PAP). Lalubhai slum rehabilitation colony, a compound of sixty-five buildings in Munkhurd, Mumbai was chosen as the second case study area. The regional setting of the ‘BDD chawls’ and ‘Lalubhai compound’ is illustrated in Figure 1.

![Figure 1 Regional setting with housing layouts of Lalubhai compound (top) and BDD chawl (down)](source: geohacker.in (google images))

The housing of BDD chawls consists of one room apartment of 13.23m² area, connected to a shared corridor with common toilets on each floor (see Figure 2). On contrary, although the tenement units of Lalubhai compound are one room unit (21.42sq.m) with common corridor, each unit is provided with attached bath (2.47sq.m) and water closet. Typically, the interior space consists of two undivided zones: cooking and multi-purpose living zone. Both the multipurpose tenement units contained one window (1.5m x 1.2m) and a door (0.9m x 2.1m) on the opposite wall. An item of furniture (bed: 1.9m x 1.0m x 0.635m) was placed in the room to recognize its most favorable position for availing the maximum
experiential IEQ. A cook-stove (0.4m x 0.4m x 0.4m) was placed below the window (as observed from field survey), which was the chief indoor source of heat and pollutant other than ambient traffic sources.

| BDD Chawl | Lalubhai compound |
|-----------|-------------------|
| Housing layout |  |
| Number of tenement units per floor | 20 | 13 |
| Room layout |  |
| 3D view of tenement unit |  |
| Attached Toilet | No | Yes (2.47 sq.m) |
| Kitchen (segregated) | No | No |
| Number of windows in living space | 1 | 1 |
| Number of doors | 1 | 1 |
| Room area | 13.23 sq.m | 21.42 sq.m |

Figure 2 Tenement unit layout, 3D view and one iterated scenarios of BDD chawl and Lalubhai compound

3.2. Design optimization procedure

Literature has concluded that ventilation effective passive building design with improved indoor air quality is the most economic and effectual approach for decreasing thermal load as well as public health degradation in buildings. Building design with natural ventilation encompasses multiple factors such as local weather conditions, building arrangement and building interior design. The design may also need to consider for stochastic variables like occupant behaviour. The optimal design for efficient natural ventilation and improved indoor air quality consists of a three stage step-wise procedure as shown in Figure 3: (1) Generation of interior hypothetical iterated design scenarios, (2) CFD simulations and numerical calculations of the design scenarios and (3) Multi-objective based design optimization.
3.2.1. **Stage 1.** A number of random sampling algorithms are commercially available like Monte Carlo Sampling technique etc. Latin Hypercube sampling (LHS) technique, a simulation based reliability evaluation method was selected in this study to generate design scenarios by introducing and varying interior design parameters. In LHS technique, the domain of each random variable decomposed into interval; and same probability is assigned to all the intervals [28], [29]. The maximum number of combinations for a Latin Hypercube of M divisions and N variables can be computed following the relation in Equation (1)

\[
\binom{M-1}{\sum_{n=0}^{N-1}(M-n)} = (M!)^{N-1}
\]

The advantage of using LHS algorithm is its improved space filling technique than other random sampling methods [30]. The LHS maximin scheme maximises the minimal distance between sampling points. The design variables of architectural parameters were sampled, algorithms inbuilt in MATLAB were utilised to formulate a Hypercube, with uniform distributions between 0 and 1. Further permutations were executed until the mean and standard deviation of the generated samples vary by 1%.

3.2.2. **Stage 2.** A number of numerical and simulation tools are available for investigating the natural ventilation performance of the design such as, computational fluid dynamics (CFD) models, zonal models, multi-zone network models etc. The accuracy of the CFD models is highly appreciated in spite of their high computation time and detailed input boundary conditions. Owing to specialized numerical technique driven process of design optimization, where accuracy and precision are key concerns, CFD was selected for performing building simulations. A commercial CFD software programme ANSYS Fluent was used to simulate the air velocity, temperature and indoor pollutant concentrations for the sampling algorithm generated different design cases. A detailed description of CFD simulations are described subsequently.

3.2.2.1. **Field measurements.** CFD simulations can deliver accurate and very detailed three dimensional information regarding the airflow, temperature and contaminant levels and distributions within each point of the room. For evaluation of natural ventilation and IEQ performance of the iterated units, the in-situ measurements of the distributions are infeasible. Since indoor air velocity, temperature and pollutant levels are the most significant parameters for measuring natural ventilation and IEQ, this study performed on-site sensor based measurements for three consecutive days in August 2018 in order to supplement input boundary conditions to CFD models. Testo 480® vane-anemometer was deployed to measure the outdoor airspeed data at window-pane (air inlet) along with a Kestrel 5400 which was used in order to gather ambient room temperature data. A DustTrak 8532 handheld sensor was utilised to measure pollutant point measurements in existing tenement units near window inlet as well as cook-
Apart from these, ibutton stove temperature sensors were also installed at the surface of cook-stove for recording the temperature of indoor heat source during active hours. This study however, did not consider other environmental attributes like relative humidity.

3.2.2.2. CFD simulations. Three dimensional actual size physical models for the tenement units were generated in DesignModeler of ANSYS Fluent. Considering the geometric shapes of most of the architectural elements and objects within the room, unstructured tetrahedral mesh was applied in all the geometric models; whilst the grids were refined at opening positions (both inlet and outlet) as large velocity gradient may occur there. The steady RANS standard K-ℇ turbulence model was used to simulate the steady state natural ventilation of the unit, and the airflow transport can be calculated by the Equation (2) explained in [31]. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling algorithm was utilised to discretize the governing equations in Fluent. The solution was considered converged when the residuals or RMS values of flow and energy were less than or equal to their specific convergence criteria, $10^{-3}$ and $10^{-6}$ respectively [32].

Boundary conditions were set according to the on-site measurement results, e.g. wind was coming from the south-west, with an average velocity magnitude of 0.989m/sec at the window inlet. Owing to negligible indoor-outdoor temperature difference, the air stream was considered isothermal in natural ventilation conditions. Therefore, the energy conservation equation was not solved in the simulation to save the computing time and capacity, which can aid in improving the efficiency of solving other equations. The average temperature at the surface of stove was recorded 35°C during cooking conditions, while Kestrel measured 26.85°C as ambient room temperature. The mass flow rate of pollutant (PM$_{2.5}$ in this case) was numerically calculated following the Equation (2)

$$m = \rho \cdot a \cdot v \tag{2}$$

Where $m$ is the mass flow rate of the element (kg/sec), $\rho$ is the density of the element and $v$ is the velocity at which the element is traversing. In this case, $a$ (area) is perpendicular to the velocity component. The boundary conditions of the CFD models are explained in Table 1.
Table 1 CFD boundary conditions for air velocity, temperature and pollutant concentration models

| Computational Domain | Air Velocity | Boundary Conditions | Pollutant concentration |
|----------------------|--------------|---------------------|-------------------------|
| Model Used           | Stand K-ԑ RANS turbulence model | Euler Lagrange Model (Discrete Phase Model) | - |
| Window (Velocity inlet) (Primary particle inlet source) | Gauge pressure = 0; T = 300K (26.85°C); Turbulence intensity = 5 percent, Velocity = 0.989 m/sec | Gauge pressure = 0; T = 300K (26.85°C); Turbulence intensity = 5 percent, Air velocity = 0.989 m/sec; Mass flow rate= 1e-07 kg/sec; Pollutant velocity (x, y, z directions) = 1.53e-08 m/sec; material type= inert carbon, particle size diameter= 2.5e-06m. | - |
| Ventilator (Pressure outlet) | Gauge pressure = 0; T = 300K (26.85°C); Turbulence intensity = 10 percent | Gauge pressure = 0; T = 300K (26.85°C); Turbulence intensity = 5 percent DPM Boundary condition: Escape type | - |
| Cook-stove Surface (Velocity inlet) (Secondary particle inlet source) | - | Gauge pressure = 0 ; T = 308.15K (from sensor data); Hydraulic diameter= 0.15 (authors’ computation); Turbulence intensity = 5 percent | Gauge pressure = 0; T = 300K (26.85°C); Turbulence intensity = 10 percent, Air velocity = 1 m/sec; Mass flow rate= 1.46e-06 kg/sec; Pollutant velocity (x, y, z directions) = 7.48e-08 m/sec; material type= inert carbon, particle size diameter= 2.5e-06m. |
| Wall-room (Wall surface) | Stationary wall; No slip | Stationary wall; No slip; T = 300K (26.85°C) DPM Boundary condition: Trap type | - |

For the pollutant concentration model, Euler Lagrange approach in Discrete Phase Model (DPM) in ANSYS Fluent was executed to simulate the indoor pollution for generated scenarios. In this model, air, considered as continuum phase is solved with Navier-Stokes equations; while particulate matter is here considered as discrete phase with slip velocity [33]. The interchange of mass, momentum and energy equations were examined for the 3D steady state solutions with boundary conditions as shown in Table 1.

3.2.2.3. Multi-objective design optimization. Simulations are normally based on case-by-case or scenario-by-scenario strategy; however, the slow and tedious process of computational simulation can evaluate only a few scenarios. In contrary, in case of goal-oriented design the machine extensively searches the design solution space that satisfies specified objectives. Thus, the use of coupled simulation-optimization rather than sole simulation is proposed as a rational approach to integrate computation in design process. Genetic Algorithm (GA), a technique based on Darwinian notions of survival of fittest where selection and recombination operators select higher performance ones among
population for next generation has been widely used in various fields of optimization [34]. Non-Dominated Sorting Genetic Algorithm (NSGA II), a fast and elitist GA was applied in this study for performing the goal-oriented design optimization process [35]. The major components of the models are presented in the following order: variables, constraints and objective functions.

Continuous variables of architectural parameters such as partition wall height, its orientation and its distance from air inlet, cook-stove and bed locations measured in distance (metres) from a particular side of unit were considered as major interior design variables to be optimized.

These variables were optimized subject to box constraints (constraints that give lower and upper threshold as boundary values to continuous variables). For example, if partition wall height is set as a continuous variable and the lower and upper boundary values are 1.5m and 2.9m respectively, then the corresponding box constraint is $1.5 \leq \text{partition wall height} \leq 2.9$.

Since the purpose of the study is to assist the designers in achieving ventilation effective and improved IEQ based room design, environmental attributes of air velocity, temperature and pollutant concentration amount were selected as three major objective functions as shown in Equations (3 and 4).

**Maximize**

$$\text{Indoor air velocity} = f\{(a_1x_1) + (a_2x_2) + \cdots (a_nx_n)\} + b$$

**Minimize**

$$\text{Indoor air temperature, pollutant conc} = f\{(a_1x_1) + (a_2x_2) + \cdots (a_nx_n)\} + b$$

Where $x_i$ (i=1...n) depicts the design variables, $a_i$ (i=1...n) are the derived coefficients.

These objective functions are subject to design constraints represented subsequently as follows (Table 2).

| Optimised Design parameters | BDD Chawl | Lalubhai Compound |
|-----------------------------|-----------|-------------------|
|                             | Lower threshold | Upper threshold | Lower threshold | Upper threshold |
| Distance of partition wall from window (x1) (m) | 0.9 | 2.5 | 0.9 | 1.3 |
| Height of partition wall (x2) (m) | 1.5 | 2.9 | 1.5 | 2.9 |
| Partition wall orientation (x3) (m) | 0.8 | 2 | 0.8 | 1.29 |
| Cook-stove position (x4) measured from left wall (m) | 2.825 | 3.775 | 0.3 | 2.44 |
| Bed position (x5) measured from left wall (m) | 0.5 | 1.9 | 2.5 | 4.5 |

4. Results

4.1 Household surveys.

The research initiated with housing and household surveys conducted in both BDD Chawl and Lalubhai SRA compound in order to understand the indoor environmental conditions within these low-income settlements. The three major observations were as follows:

- The unsegregated cooking and living spaces in the tenement units acted as a contributing factor towards inferior indoor environment prevailing high temperature zones and extreme pollutant concentration levels.
The socially restrained occupant behaviour in order to maintain high indoor privacy quotient, left the inhabitants with last alternative of closing the doors and windows during active hours including cooking times. Thus, lack of adequate cross-ventilation strategies reduced the ventilation threshold ultimately leading to ineffective pollutant disposal.

In order to arrest high electricity bills, the occupants used to switch off the ceiling fans and other mechanical cooling techniques.

4.2 Description of parameters.
The observations from household surveys suggested the incorporation of interior design parameters which were hypothesised to deliver better indoor environment conditions.

Design variables of height, orientation and distance of partition wall from window was introduced with the aim of segregating the cooking and living zone, thus prevailing better thermal conditions over living areas.

Other than this, the cook-stove (indoor heat source) and bed positions were considered as other major parameters.

Lastly, and most importantly, with the advent of deep plan compact high rise buildings, designers find less degree of freedom in providing adequate windows for better ventilation leading to poor cross-ventilation. Furthermore, the occupant behaviour of closing of air inlet/outlets deteriorate the indoor environmental conditions. Hence, a ventilator (0.3mx0.3m)/high air outlet area was introduced in the opposite walls of window for both unit designs to enhance natural ventilation effectiveness. Thus, major design parameters include partition wall, bed and cook-stove location and a fixed ventilator (high level air outlet).

4.3 Generation of scenarios.
The Latin Hyper cube sampling code was executed in MATLAB in order to generate scenarios (see Figure 4).

Figure 4 Generated sample scenarios by varying design parameters for BDD chawl (top) and Lalubhai compound (down)
The mean, standard deviation, lower and upper threshold values of design variables like partition wall height, orientation and its distance were computed as input boundary conditions for running the code. Ten scenarios for each design layouts were generated utilising random values of afore mentioned design variables. Ultimately, 40 design scenarios were generated for both the design layouts when two distinct bed positions and two stove positions were incorporated for all the iterated scenarios.

4.4 CFD Simulations.

4.4.1. Air velocity. In Figure 5 and 6, illustrating the indoor airflow characteristics for various examined scenarios in both the tenement layouts, the ‘blue’ colour bands represent low air velocity prevailing zones where natural ventilation coupled with mechanical means of cooling strategies only can provide indoor thermal comfort conditions, the medium air velocity zones are characterised by ‘yellow-orange’ colour bands and the ‘dark orange-red’ colour bands indicate high air velocity zones, where natural ventilation alone is sufficient to deliver comfortable indoor wind flow conditions. Literature has also established studies on comfort air velocity and temperature ranges in tropical countries. Khedari et al., had conducted a study in Thailand to identify the comfortable indoor air velocity range between 0.2m/s to 3m/s when the temperature was recorded around 26°C to 32°C [10], [36]. Another study done by Surapong et al., advocated the desirable indoor air velocity between 0.18m/sec to 1.42m/sec with temperatures between 30.9°C to 38.2°C. Therefore, the comfortable air velocity values should range between 0.2-1.5m/sec.

When wind flow characteristics of different scenarios were examined for BDD chawl as illustrated in Figure 5, partition wall orientation and its distance from window were observed to influence the indoor air velocity maximum. Cook-stove position was found to affect minimum as observed for Cases c and d of Figure 5 (Case c- left: 0.56m/sec and right: 0.59m/sec) and (Case d- left: 0.18m/sec and right: 0.19m/sec). However, significant upsurge in CFD predicted experiential wind speed values were recorded when bed position was shifted from right (0.56m/sec) to left (0.17m/sec) for Case c. It can be concluded from the vertical section views of Case b and Case d that higher partition wall height obstructed the indoor air flow entering the window thus, creating low air velocity zones over bed.

![Figure 5 CFD simulations showing indoor air velocity characteristics in BDD chawl](image)

Figure 5 CFD simulations showing indoor air velocity characteristics in BDD chawl

Figure 6 indicates that the indoor air speed for the examined scenarios of Lalubhai compound over the breathing zone (mid-bed position at 1.2m level) varied from 0.05 to 0.648m/sec, which evinces that interior design parameters like partition wall, furniture location can regulate indoor airflow characteristics.
Figure 6 CFD simulations showing indoor air velocity characteristics in Lalubhai compound

Figure 6 shows varying air speeds for Case a (0.175m/sec) and Case b (0.185m/sec), where partition wall orientation was altered keeping all other design variables like partition wall-height, its distance from air-inlet, bed and heat-source location constant. Cook-stove location, although not acting as a major hindrance to air flow path, was found to change the simulated air velocity values for left (0.175m/sec) and right (0.203m/sec) for Case a. Case d explicates a varying indoor air speed values for left (0.214m/sec) and right (0.299 m/sec), demonstrating the significance of bed position in a naturally ventilated space. This was majorly attributable to the proximity of bed position with respect to the window-inlet and ventilation.

From CFD simulated air velocity results for both the tenement unit designs, it was observed that interior architectural parameters and their design variables such as partition wall height and orientation, its distance from air-inlet or window, and furniture (cook-stove and bed) positions exhibit combined influence on the indoor natural ventilation conditions.

4.4.2. Air temperature. Subjective interpretations of Figure 7 and Figure 8 illustrating the indoor average temperature distribution owing to a burning cook-stove, found that the temperature fields for both the layouts were found relatively uniform within the occupied zone with limited considerable variations in the CFD predicted temperature values. Two distinct thermally stratified zones like the cooking zone with higher temperature values (304K) and living zone (302K) were observed due to the presence of partition wall which acted as a barrier to the indoor convective heat transfer from the heat source.
Figure 7 CFD simulations showing indoor air temperature characteristics in Lalubhai compound

The Case a (left) and Case b (left) of Figure 7, with varying partition wall orientation while maintaining all other design variables constant had experienced different temperatures over the breathing zone i.e. (301.56K for Case a-(left) and 301.83K for Case b-(left)). Contrarily, Case c (left, and right,) of Figure 7, displays fluctuating (1K difference) experiential indoor temperature with altering bed positions (Case c-left 301.3K, right 302.14K). Amongst all the design variables involved here, partition wall height and orientation was observed to influence maximum. It was found that with increase in partition wall height, the indoor temperature value recorded over the bed position decreased. This phenomenon can be contributed to the hindrance to the convective heat transfer created by the partition wall.

Figure 8 CFD simulations showing indoor air temperature characteristics in BDD chawls

CFD predicted temperature simulations for BDD chawl (see Figure 8) delivered similar observations with partition wall height, its distance from window-air inlet, and cook-stove (indoor heat source) position as the dominant contributors to the temperature records. Bed position also was also found to impact the indoor temperature values (Case c- left: 301.809K and right: 302.054K) and (Case d- left: 301.842K and right: 301.958K).

4.4.3. Pollutant concentration modelling. In this section, pollutant (PM$_{2.5}$) distribution is analysed in the natural ventilation condition considering two major sources. Ambient pollution owing to outdoor traffic and household level pollution due to combustion of unclean fuel for cooking purpose are the dominant contributors to indoor contamination. The CFD models for all the scenarios in both the layouts were examined for the wind velocity $v=0.989$ m/sec and calculated PM$_{2.5}$ mass flow rate of $m_{\text{outdoor}}=1e-$
07 kg/sec [33] and \( m_{\text{cook-stove}} = 1.46 \times 10^{-7} \) kg/sec or 5.27 gram/hour [37]. The ‘total percentage area of bed which would be found exposed to pollutant concentration’ is considered as the surrogate measure of the indoor pollutant concentration levels. Figure 9 shows the pollutant concentrations examined for different scenarios for BDD chawl and Lalubhai compound. From Figure 9 (Lalubhai compound) it can be observed that alteration in cook-stove position (as seen in ‘Case a’ and ‘Case b’), significantly modify indoor pollutant concentration distribution. For ‘Case a’, with the partition wall placement straight hindering the airflow, the pollutant levels were concentrated in the cooking zone. In contrast, for ‘Case b’ the pollutant concentration was found distributed in the living zones as well. Thus, partition wall orientation and design has an impact on indoor pollutant concentration profiles. ‘Case c’ concludes that, owing to similar trail of pollutant transfer path, with bed position alteration the PM\(_{2.5}\) concentration varied from 6.54% (left) to 11.05% (right).

**Figure 9 CFD simulations showing indoor air temperature characteristics in BDD chawls**

For BDD chawl case, in most of the generated scenarios, CFD predicted pollutant levels were mostly obstructed by the partition wall and did not reach the living zone (Case c) except for three cases where the partition wall orientation affected the flow of contaminants. In Case a, the PM\(_{2.5}\) percentage was observed to be 28.09%, while for case b and case c, it was zero.

Additionally, PM\(_{2.5}\) concentration was found maximum near the ceilings, partition wall and the walls adjacent and opposite to the window inlet (see Figure 10). This phenomenon can be attributed to the trap type boundary conditions of the walls. High kinetic energy imparted to the jet plume of particulate matter entering at the window-level can also contribute to the higher pollutant concentration on the wall opposite to inlet.
4.5 Optimised design layouts.

Figure 10 illustrates the pollutant concentrations on BDD chawl (partition wall) and Lalubhai compound (ceiling, side wall and wall opposite to window).

Figure 10 Pollutant concentrations on BDD chawl (partition wall) and Lalubhai compound (ceiling, side wall and wall opposite to window).

Figure 11 illustrates the air velocity and temperature graphs at individual level for both the design layouts of BDD chawl and Lalubhai compound to identify the ideal value of interior design parameter of partition wall that would generate optimum indoor air velocity and temperature. It can be observed that the partition wall height should range between 1.9m to 2.2m for both BDD and Lalubhai, in order to experience comfortable indoor air speed values (0.15-0.2m/sec) in natural ventilation conditions. But, for prevailing comfortable temperature range, the partition wall height should range above 2.5m for both the design cases. When the second design variable of ‘distance of partition wall from window-inlet’ was considered, the distance ranged from 1.9-2.1m for BDD chawl and 1.1-1.2m for Lalubhai compound for comfortable air velocity experience. On contrast, minimum temperature could be achieved with a partition wall distance of 2.7m for BDD chawl and 0.95-1.05m for Lalubhai compound. This challenge of varying design scenario recommendations for satisfying conflicting objectives, when individual design variables are compared against a particular environmental metric, led to the utilisation of multi-objective optimization algorithm of NSGA II. The intention was to arrive at single or near optimal design solutions for both design layouts that would deliver optimal indoor environmental quality (IEQ).
Figure 11 Nexus of built environment parameters and environmental metrics
Figure 12 explains the multi-objective optimization results of the interior layouts derived from NSGA II. In order to run the NSGA II algorithm, the required objective functions were framed through regression analysis by assuming the environmental metrics as dependent variables and architectural design parameters as exploratory variables. PM$_{2.5}$ concentration was not found to get affected by design parameters for 37 out of 40 scenarios for BDD Chawl scenarios and hence was neglected in this study.

The objective functions derived from linear regression models are as follows:

For BDD Chawl

$y (\text{Air velocity}) = 0.243 \times x_2 + (0.257 \times x_3) - 0.426$  \hfill (3)

$y (\text{Stove temp}) = (-0.174 \times x_1) + (-0.232 \times x_3) + (0.132 \times x_3) + 302.72$  \hfill (4)

For Lalubhai compound

$y (\text{Air velocity}) = (-0.180 \times x_1) + (0.094 \times x_2) + (-0.055 \times x_3) + (0.003 \times x_4) + (-0.031 \times x_5) + 0.403$  \hfill (6)

$y (\text{Stove temp}) = (0.051 \times x_1) + (-0.218 \times x_2) + (-0.089 \times x_3) + (0.005 \times x_4) + (-0.157 \times x_5) + 302.69$  \hfill (7)

$y (\frac{PM_{2.5}}{\text{conc}}) = (-15.62 \times x_1) + (2.61 \times x_2) + (3.25 \times x_3) + (1.19 \times x_4) + (-8.78 \times x_5) + 56.80$  \hfill (5)

All values significant at 95% C.I.

The NSGA II algorithm selected population size of 50 with mutation and cross-over probabilities of 0.04 and 0.95 respectively to generate the Pareto-Font based optimal solutions. Pareto-font based optimization algorithms calculate better for two to three objective functions, since many objective functions deteriorates the dominance model of one on the other [38]. Thus, if the populations turn out to be non-dominated, Pareto dominance based fitness evaluation schemes fail to generate any pressure towards the formation of a strong Pareto-Font. In order to avoid the challenges faced by many objective optimization problems, three sets of Pareto font solutions were generated for Lalubhai compound case taking a combination of two objective functions one at a time (see Figure 12).

Figure 12 Pareto font based optimal design solutions derived from NSGA II
NSGA II derived one optimal design solution for BDD chawl and three optimal design solutions for Lalubhai which are represented in Table 3. These solutions would be the most optimal interior design solutions that would deliver maximum effective IEQ.

| Optimised Design parameters                  | BDD Chawl | Lalubhai Compound |
|---------------------------------------------|-----------|-------------------|
| Distance of partition wall from window \((x_1)\) (m) | 2.52      | 0.9               |
| Height of partition wall \((x_2)\) (m)       | 2.06      | 2.89              |
| Partition wall orientation \((x_3)\) (m)     | 1.99      | 0.80              |
| Cook-stove position \((x_4)\) measured from left wall (m) | 0.5       | 2.38              |
| Bed position \((x_5)\) measured from left wall (m) | 2.83      | 3.68              |

5. 

Discussion

In this study, built environment and environmental quality linkages were investigated for two low-income housing typologies of BDD chawls and Lalubhai Slum Rehabilitated compound in Mumbai. Indoor environmental quality was selected as the built environment sustainability indicator and indoor air velocity, temperature and pollutant concentration levels was chosen as the qualitative measure of IEQ. Base case scenarios for both the layouts were examined with household and housing condition surveys coupled with in-situ sensor data records. Based on field observations, design parameters were selected followed by generation of iterated scenarios utilising Latin hypercube sampling code by introducing and varying interior design parameters like partition wall, indoor heat source and furniture location. Steady-state RANS modelling was performed, using the best practice CFD guidelines, to represent the indoor airflow, temperature and pollutant concentration in the iterated scenarios of chawls and rehabilitated tenement apartments. Computational modelling was coupled with execution of multi-objective optimization problem to arrive at a single or near optimal design solutions for both the housing types that would provide improved IEQ experience over the breathing zone.

Results have indicated that introduction of partition wall improved the indoor environment by distributing the indoor air flow and also by creating two thermally distinct stratified zones i.e. cooking zone with high temperature and living areas with relatively colder draught zones. Partition wall orientation and its distance from window were observed as the dominant indicators behind modulating indoor airflow. It was also observed that with the increase in the partition wall height, the airflow entering from the window got hindered thus creating low air velocity zones near the bed in BDD chawls. The effect of indoor thermal condition was examined through temperature simulations in the presence of a burning cook-stove (Figure 7). Partition wall height, its distance from window and cook-stove position affected the indoor temperature distribution of BDD chawls maximum. While the bed location was the most contributing factor influencing the indoor pollutant transfer, Figure 9 elucidates that due to the blockage created by partition wall, pollutant levels significantly remained concentrated in the cooking zones of BDD chawls. Owing to trap type boundary conditions of the walls, contaminant levels were found maximum near the walls and ceilings.

This study involved qualitative as well as quantitative investigation for interpreting the BE-IEQ nexus in low-income settlements to enable informed and rational decision making for environmentally sustainable renewal and rejuvenation for chawls as well as rehabilitated units. Where design interventions at site-level or building envelope level become resource and time exhaustive; the interior design alterations are the sole alternatives for the socially driven class of population. The major takeaways from this study are:

- Built-environment parameters had a close association with indoor environmental conditions.
- Interior design parameters with aerodynamic potential like partition wall, indoor heat source and furniture location are critical determinants of indoor airflow, temperature and contaminant distribution within the chawls and rehabilitated units.
Quality of life within these low-income settlements can be significantly improved by enabling better indoor airflow, reduced temperature levels and pollutant concentrations in the living spaces, such that adequate IAQ and thermal comfort levels can be achieved.

The efficacy of appropriate and optimized interior design in context to its environment can help in improving comfort and well-being thus reducing public-health vulnerabilities, especially for socially driven class of population.

This study would not just enable rehabilitation as mere resettlement but add the layers of liveability, well-being and environmental sustainability to the epistemology of the less explored concept of BE-IEQ ties.

6. Limitations and future work
The measures of indoor air velocity, temperature and pollutant concentrations as IEQ indicators in the low-income built environment portrayed strong association with interior design. However, these aforementioned parameters cannot be treated as sole causal surrogate indicators. Other environmental attributes like moisture levels (relative humidity) and indoor temperature due to external solar radiation and pollutants other than PM_{2.5} will be considered in future studies. This study focussed only on interior design parameters, hence other site-level built environment parameters like building orientation and arrangement and most importantly occupant behaviour was avoided in this study. Investigating the influence indoor built environment has on IEQ forms the basis of the ongoing work, which focuses on the objective measure of IAQ utilising sensor deployed measured data and housing surveys. This should be supported by CFD model validations for improved accuracy in results.

7. Conclusion
This study emphasised the need for conscious interior design planning for environmental sustainability in the low-income settlements, which remains a large blind-spot in the current habitat policies in India. Results indicated a strong connection between interior design parameters and indoor air quality. It was also found that introduction of optimally designed partition wall and appropriately placed furniture and indoor heat source can improve the indoor air, velocity temperature and pollutant distribution. The findings essentially emphasize the urgent need for design considerations at interior level that could enable better indoor environment conditions in the living spaces in natural ventilation settings. This would avert the occupants from shifting towards mechanical and energy exhaustive ventilation strategies thus saving energy consumption. The results of this parametric analysis on interior based airflow, temperature and pollutant transfer modelling focussed on the necessity of interior design intrusions based on aerodynamically effectual design parameters, effective cross-ventilation strategies can be utilized in the living areas.

This study is a first step approach towards solving a critical latent issue of BE-IEQ nexus vulnerability in different low-income housing typologies of Mumbai. Indoor environment can be a significant policy variable for urban renewal and rejuvenation missions. It could enable local authorities to undertake environmentally sustainable design measures while planning for hyper dense low-income communities in compact metropolitans in near future.

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