

# Optimizing Interior Layout for Effective Experiential Indoor Environmental Quality in Low-income Tenement Unit: A Case of Mumbai, India

## Abstract

This study intends to optimise the interior layout of tenement unit in a low-income urban habitat to obtain the maximum experiential indoor environmental quality within the breathing zone. A variety of interior layouts using partition wall and furniture position was generated for optimising the design layout that could maximise indoor environment quality. This study followed "Sampling-based Parametric Modelling- CFD Simulation- Multi-objective Optimization" based framework. The optimized interior design delivered indoor air velocity of 0.58m/sec when outdoor wind velocity was as low as 0.9m/sec in nat-vent condition. The experiential indoor air temperature was recorded 301.05K (27.9°C) over the breathing zone during cooking condition (heat source temperature: 308K i.e. 35°C). This study intends to develop a methodology for optimising interior layout design in a bid to offer ideas to address the current incongruity and poor synergy between architectural design and technological analysis.

## Introduction

Literature has established an inherent correlation between human health and built environment. There exists a strong relationship between the United Nations Sustainable Development Goals (SDG) 11, which targets to cultivate sustainable urban habitats by reducing pollution and SDG 3, which inculcates good health and well-being (Debnath, Bardhan, & Banerjee, 2017). This implies that a well-designed built environment can produce healthy living among occupants (Bardhan, Kurisu, & Hanaki, 2015). Household Air Pollution (HAP) is the primary factor behind the degradation of Indoor Air Quality (IAQ) in urban habitats. The recent but fast evolving phenomenon of low-income rehabilitated high-rise apartments in metropolitan cities can increase HAP, under improper design conditions. Currently the single tenement units of the low-income habitats lack proper design and natural ventilation considerations.

Natural ventilation, a low-cost passive solution not only improves thermal comfort but also decreases energy consumption and provides healthier indoor environment by boosting Indoor Air Quality (IAQ) within a particular space. However, the airflows generated in naturally ventilated space are more complicated than that of mechanical systems and are difficult to predict. Hence,

careful designing of natural ventilation strategy is necessary especially in case of highly compact low-income high-rise apartments where natural ventilation is the only cost-effective solution.

Several studies have shown a strong correlation between indoor airflow characteristics and building parameters like size and type of openings/windows, balconies (Mohammadi et al., 2009), courtyards, overhangs (Hien & Istiadji, 2003) blinds and, boundary wall (Hawendi & Gao, 2017) at envelope level and building arrangements at site level. However, there are limited studies on the effect of interior design configurations on wind motion, airflow rate and indoor air quality. Interior design plays a vital role in controlling natural ventilation and indoor air quality within the breathing zone of low-income housing where space is a constraint. A study by Sanaieian et al. (Sanaieian, Tenpierik, Linden, Mehdizadeh Seraj, & Mofidi Shemrani, 2014) showed that furniture layout is an essential contributor to ventilation effectiveness, and helps in modifying air quality in breathing zone. This study aims to visualise the indoor environment characteristics under a wide range of interior layout alternatives. The objective of this study is to optimise the interior architectural elements in a low-income tenement unit that would provide effective indoor environmental quality in the breathing zone under nat-vent condition.

## Background

The present affordable housing programs like 'Housing for All 2022' etc. provide affordable rehabilitation units to low-income groups. However, their efficiency in terms of sustainable living is yet to be explored. This becomes exigent given that the current rehabilitation housing provides a limited habitable space of 24.6sq.m. This provides the inhabitants less degree of freedom in interior layout, advertently leading to ineffective experiential indoor environment quality. Here an exploration of the options of the interior layout was performed such that an effective indoor environment quality could be achieved.

The existing low-income settlements in Mumbai experience inadequate airflow in living spaces, leading to a higher temperature and poor indoor air quality. The slum improvement strategies provided by Mumbai City Development Plan 2005-2025 suggest a translation of horizontal slums into formal multi-storey housing. However, these do not take into consideration liveability

parameters like indoor environment quality (Debnath, Bardhan, & Jain, 2017). The lack of sustainable slum redevelopment guidelines in India is a significant blind-spot in policy planning that needs immediate attention for better and inclusive growth of country. A rational approach towards low-income habitat designing is required to ensure sustainability of the forthcoming low-income housing stocks.

### Methodology: sampling-based parametric simulation for optimization

A two-step methodological framework was adopted in this study. First, site surveys were conducted to obtain physical dimensions and interior layout of a typical low-income tenement unit, along with deployment of in situ sensors to obtain indoor air velocity and air temperature of the unit. Second, CFD code was executed to predict indoor air velocity, temperature and pollutant profiles within various design layouts generated from the adopted sampling technique. Lastly, multi-objective optimization was performed to predict the best design layout with maximum indoor environment quality over the breathing zone. The step-wise methodology is illustrated below in Fig 1.

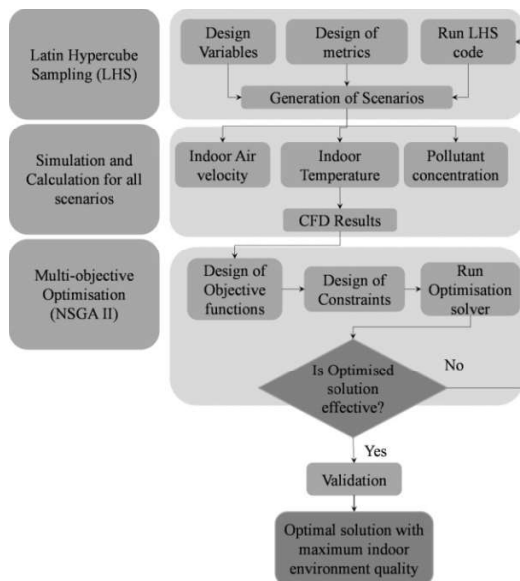


Figure 1: Methodology adopted for the study

To acquire data on the air quality metrics of the unit, in-situ environmental sensors Testo 480® vanemeter and temperature sensors were installed in the tenement units for three consecutive days in January 2018.

### Study area

The field survey was conducted in the low-income tenement units of British era Bombay Development Department (BDD) Chawl (similar to social tenement housing) in Mumbai. The tenement units are one-room unit (13.23sq.m), attached to a common corridor with shared toilets on each floor. Typically the interior space has two undivided zones: cooking and living zone. This study introduced a partition wall for dividing the room

into cooking zone and living zone. To understand the effectiveness of the indoor environment quality under varying interior layouts, a monitoring point in the living area was selected. The monitoring point was 0.7m above ground level at mid-bed position. It can be considered as the approximate height of a human both in sleeping condition over bed and sitting condition on floor. Hence in this study, the plane of 0.7m above ground floor was considered to be the point at which it is most important to have comfortable conditions. The ventilation and thermal performance in the typical low-income tenement unit (4.725m x 2.8m x 2.9m) was used as a surrogate for measuring the effectiveness of the indoor environment quality (as shown in Fig 2). A commercially available Computational Fluid Dynamics (CFD) tool was used to simulate the ventilation and thermal performance of the unit. The unit contained one casement window (1mx1.2m) and door (0.9mx2.1m) on the opposite wall.

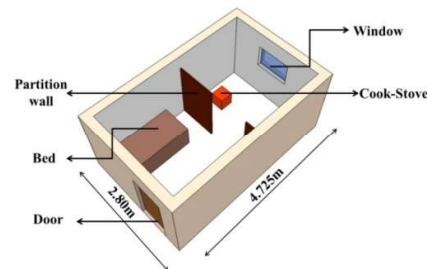


Figure 2: Model of Tenement Unit

An item of furniture (bed: 1.9mx1.0mx0.635m) was placed in the room to understand its most preferred location to avail the maximum indoor environment quality. A cook-stove (0.4m x 0.4m x 0.4m) was set directly below the window and 0.9m away from the wall, which acted as the major source of heat and pollutant. The locations of bed and cook-stove were placed as observed from the field survey. All the simulations have been performed taking the furniture and stove location constant. However, change in the relative locations of bed and stove would have different impact on indoor experiential environment quality which is out of the scope of the study.

To determine the effect of interior architectural parameter on indoor environmental quality in nat-vent condition, a specific interactive study was performed taking into account combination of two rarely ventured but important design parameters: i) partition wall and ii) bed location.

### Step 1: sampling scheme

In order to generate the design alternatives, the random Latin Hypercube sampling (LHS) technique was used (Nix, Das, Taylor, & Davies, 2015). The design variables included height of partition wall, its distance from the window, partition wall gap and varying outdoor wind velocity. The mean, standard deviation, lower and upper threshold values of the above-mentioned design variables were computed as input boundaries to execute LHS code in MATLAB. Fifteen random samples along with the base case scenario (without partition wall)

which involved a combination of the above mentioned four design parameters were generated. The LHS code ultimately generated thirty different scenarios when two different bed positions were included as seen in Fig. 3. The partition wall opening was assumed to be constant (i.e. 1.2m), which was moved horizontally to generate various scenarios.

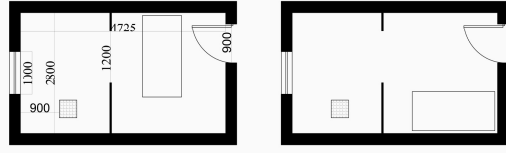


Figure 3: Layout with two different types of furniture locations (bed positions)(All dimensions in millimetre)

## Step 2: simulating the indoor airflow, temperature and pollutant concentration

It is difficult to measure and estimate natural ventilation numerically due to the unreliability linked with it like stochastic nature of the local wind conditions, hindrances in the airflow path and human behaviour regarding opening and closing of windows etc. The thirty scenarios generated from sampling scheme were modelled and simulated in Ansys Fluent v16.2 CFD code. The RANS standard k- $\epsilon$  turbulence model along with energy model was solved until the 3D steady-state simulations reached convergence. The simulations employed double precision, three dimensional, parallel, and finite volume solver. The applied Navier Stokes governing equations are as follows:

1) Continuity equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

2) Momentum Conservation:

$$\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_i} \left( v \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right)$$

3) Turbulent kinetic energy (TKE, k):

$$\frac{\partial k \bar{u}_i}{\partial x_i} = \frac{\partial}{\partial x} \left( \frac{v_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + v \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_j}{\partial x_i} - \epsilon$$

4) Energy dissipation rate:

$$\frac{\partial \epsilon \bar{u}_i}{\partial x_i} = \frac{\partial}{\partial x} \left( \frac{v_t}{\sigma_k} \frac{\partial \epsilon}{\partial x_i} \right) + C_{1\epsilon} \frac{\epsilon}{k} v \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_j}{\partial x_i} - C_{2\epsilon} \frac{\epsilon^2}{k}$$

The turbulent viscosity ( $v_t$ ) is calculated in terms of  $k$  and  $\epsilon$  by

$$v_t = C_\mu \frac{k^2}{\epsilon}$$

The air in this study was assumed as incompressible ideal gas with variable density. The CFD simulations employed finite volume method for spatial discretisation of the domain by applying fine 3D tetrahedral meshing option. Three times refinement was imposed on the window (inlet), door (outlet) and cook-stove surface to

resolve the high gradient regions of the flow field with higher accuracy and precision level. The details of boundary conditions are shown in Table 1. The monitoring point was taken at the mid-bed position at the height of 0.7 m from the ground level.

Table 1 : Boundary Conditions used in CFD simulations

Computational Domain	Boundary Conditions
Door (Pressure outlet)	Gauge pressure = 0; T = 300 K, Hydraulic diameter= 1.26 (authors' computation) ; Turbulence intensity = 10%
Window (Velocity inlet)	Gauge pressure = 0 ; T = 300 K, Hydraulic diameter= 1.09(authors' computation) ; Turbulence intensity = 10%, Velocity (authors' computation)
LPG Cook-stove Surface (heat source)	Gauge pressure = 0 ; T = 308K, Hydraulic diameter= 0.15 (authors' computation) ; Turbulence intensity = 10%
Wall (wall surface)	Stationary wall; No slip

The code used SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm along with second order UPWIND scheme for solving the algebraic equations for velocity and pressure components. Though the hybrid-initialized simulations achieved convergence within 2200 iterations, a minimum of 5000 iterations were computed for each model to arrive at a reliable steady value of the solution variables. Apart from justification of the grid independence test, the solution was considered to have converged until  $10^{-6}$  (RMS) of the residuals in each of the simulated models.

## Step 3: Multi-objective Optimisation using Non dominated Sorting Genetic Algorithm (NSGA-II) for the interior layout

Genetic algorithm (GA) is a well-known stochastic method for solving optimization problems and has been successfully applied to different real-world applications. Salazar et al.(Salazar et al., 2006)reported that 90% of Multi-Objective Optimization Problems (MOOPs) focus on finding an approximate Pareto solution. The fast Non-dominated Sorting Genetic Algorithm (NSGA-II) is the most powerful and well-known version of multi-objective GA. Here, the proposed MOOP was solved using NSGA-II algorithm. Traditionally, the indoor environment quality is formulated with the objective of maximizing indoor ventilation rate or air velocity. However, to obtain a higher level of environmental quality, this study included additional objectives of minimizing indoor air temperature and pollutant concentration. Air velocity, temperature and contaminant levels were assumed as function of built parameters considered in this study. The simulated metrics of air velocity, temperature and pollutant levels for thirty scenarios were then used to formulate the objective functions. Based on the above assumptions, the proposed mathematical model for the MOOP is as follows:

Maximize (1)

$$\text{Air velocity} = f\{(a_1x_1) + (a_2x_2) + (a_3x_3) + (a_4x_4) + (a_5x_5)\} + b$$

Minimize (2)

$$\begin{aligned} \text{Air temperature, Pollutant concentration} \\ = f\{(a_1x_1) + (a_2x_2) + (a_3x_3) \\ + (a_4x_4) + (a_5x_5)\} + b \end{aligned}$$

Where

$x_i(i=1\dots n)$  depicts the design variables

$a_i(i=1\dots n)$  are the derived coefficients

These objective functions were optimized subjected to the constraints as shown in Table 2.

Table 2: Constraints for multi-objective optimization

Description of variables	Constraints of the variables	
	Lower range	Upper range
Height of partition wall ( $x_1$ )	1.5m	2.9m
Outdoor wind velocity ( $x_2$ )	0.6m/sec	1.01m/sec
Distance of partition wall from window ( $x_3$ )	0.914m	1.5m
Partition wall gap ( $x_4$ )	0.6m	2.2m
Distance of bed from window ( $x_5$ )	2.75m	3.475m

The design variable ranges were used to bound the optimization problem and generate inputs for the meta-model. This step evaluated the best possible interior design solution for obtaining highest experiential indoor environment quality in the breathing zone.

## Results and analysis

### Indoor air temperature analysis

The average LPG stove surface temperature was recorded 308.15k i.e. 35°C (from field measurement as shown in Fig 4) in cooking condition while the ambient temperature of the room was considered 300k(27°C). The temperature distribution inside the room in the presence of a burning cook-stove is illustrated in Fig 5. The temperature fields were relatively uniform within the occupied zone with no considerable variations in the CFD predicted air temperature values.

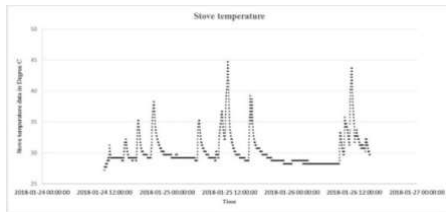


Figure 4: Stove temperature data recorded from sensors installed in field

The analysis shows that for the base case scenario (case (a) in Fig.5) i.e. the layout without partition wall, the zone of relatively higher temperature was distributed uniformly within the interior. On the other hand, higher temperature zone existed mostly near the heat source for

other cases (b, c, d and e). Subjective interpretations of these interior layouts reveal that the presence of partition wall inherently obstructed the convective heat transfer within the room thus, maintaining a relatively lower temperature zone near the bed.

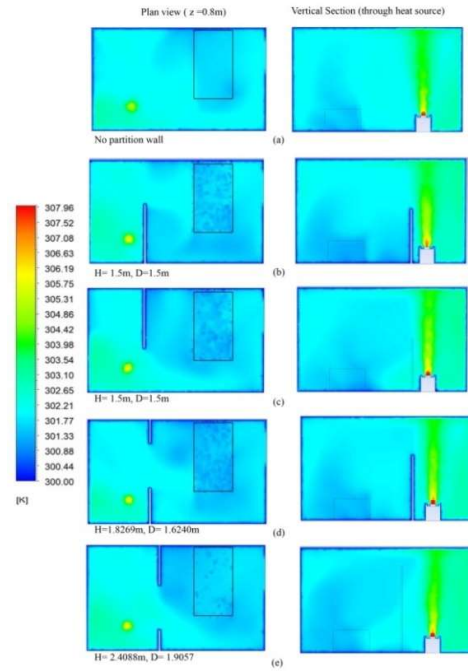


Figure 5: Plan view (left) and vertical sections (right) of air temperature fields for varying partition wall height, gap and its distance from the heat source.

However, parameters such as partition wall gap and distance of furniture location from the window had minute effect on indoor temperature distribution. Generally, for all the cases determined, the CFD results show that the temperature field divided the room into two gradient zones at horizontal level.

The zone with the highest temperature (30-35°C) was close to the cook-stove (heat source), and the rest of the room on the other side of partition wall had lower temperature values (27-28°C). The CFD predicted average temperature values in the cooking zone and living area were found to be 34°C and 28°C respectively for all the cases determined. Fig. 6 illustrates the temperature distribution inside the room with two different furniture locations.

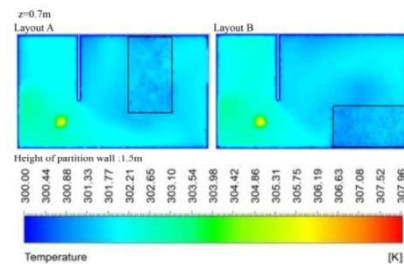


Figure 6: Temperature distribution in two layouts with different furniture locations

All other boundary conditions like the position of heat source, partition wall height, gap and width were kept same for both the cases. Although the differences in air temperature in the breathing zone for both the scenarios were not found much significant (layout A: 301.69K and layout B: 301.16K in Fig 6), the results conclude that the placement of furniture although minutely but helps in reducing the risk of experiential heat droughts marginally within the occupied zone. In results not shown, the omission of the partition wall resulted in the formation of higher temperature plumes (302.1K or 28.95 °C) in the occupied zone.

### Indoor airflow analysis

The CFD predicted air velocity results show that for all examined scenarios, the air velocity was within the range of 0.056m/s -1.56m/s. This suggests that by controlling design variables like partition wall and bed position, it is feasible to maintain effective levels of indoor air velocity in naturally ventilated spaces.

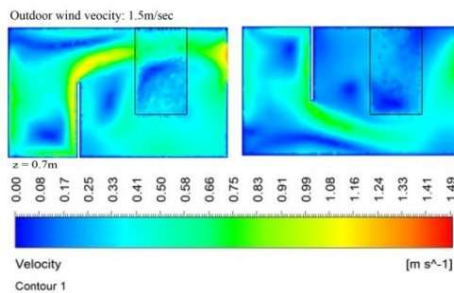


Figure 7: Floor plan view above 0.7m with different partition wall locations

From Fig 7 authors observed that CFD predicted air velocity values in breathing zone were found different with varying partition wall orientation keeping all other design variables constant.

It shows that the air velocity at the monitoring point of layout on left and right were 0.577m/sec and 0.173m/sec respectively. This implies that the change in partition wall direction with respect to furniture location has significant impact on airflow characteristics at breathing zone. The reason behind this phenomenon is the change in airflow vortex and air turbulence formation due to the presence of partition wall, which is acting as a barrier in the airflow path. In contrast, it can be observed from Fig. 8 that for base case scenario (a) i.e. without partition wall, the CFD predicted air velocity over breathing zone was higher than other cases (case b, c, d). A possible explanation is that the air entered through the window (velocity inlet) and rushed out through the door (pressure outlet) on the opposite wall without creating any zone of turbulence. Thus, the air was not distributed within the room for the base case scenario. The right-most column of Fig. 8 highlights the airflow velocities and the draught plume for scenarios. The results predict that a zone of low air velocity was formed beside the partition wall.

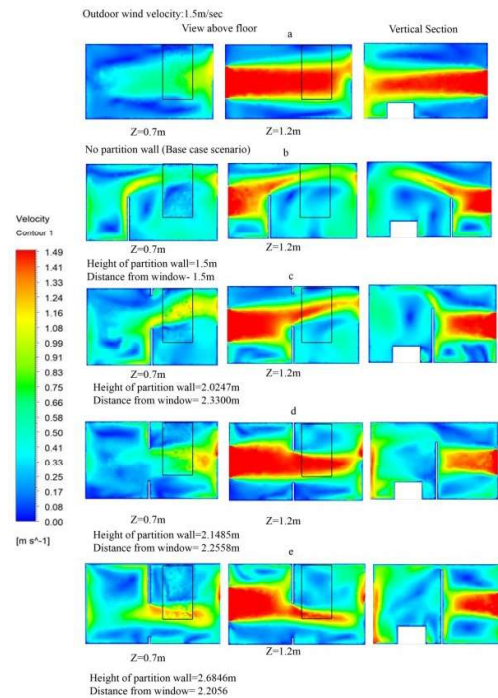


Figure 8: Plan view (left two) and vertical sections (right) of velocity fields for varying partition wall height and wind speeds.

With the increase in the height of the partition wall, the size of the low air velocity zone increased. This is mainly due to the obstruction in the air flow path caused by the high partition wall. In case b, with lower partition wall height (1.5m), the air passed over the partition wall and moved towards the door creating a hollow zone below it. However, for the case c ( $H=2.02\text{m}$ ) d ( $H=2.14\text{m}$ ) and e ( $H=2.68\text{m}$ ), the movement of the air got blocked entirely due to the increasing height of the partition wall (see vertical section views of Fig 8). This explains a negative relation of indoor air velocity with partition wall height. But from plan views, scenarios a and d experienced similar air velocities over breathing zone. However, indoor air velocity was found to have a high correlation with the distance of partition wall from the window. The plan views in Fig. 8 show that the placement of partition wall forced the air to travel a longer period, get diverted at the corners, increased the speed by creating air vortices and hence improved the indoor air speed over the breathing zone. The CFD results also show that for same conditions of outdoor wind velocity, height, the width of the partition wall, and its distance from the window, CFD predicted significantly higher wind velocity for the scenario with different bed location from the window as shown in Fig 9.



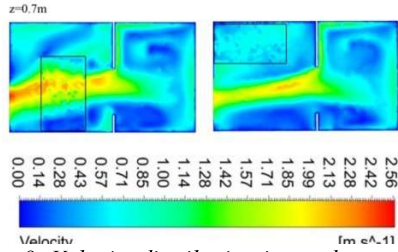


Figure 9: Velocity distribution in two layouts with different furniture locations

### Indoor pollutant concentration analysis

The pollutant concentration model in this study used Euler –Lagrange approach in ANSYS for simulating indoor PM2.5 concentration. In this method, the fluid (air in this case) is considered as continuum in which Navier-Stokes equations are formed, while the discrete phase is solved by steady tracking of particles (PM2.5 in this study). There is an exchange of mass, momentum, and energy between the continuum and discrete phases. Since the diameter of PM2.5 is small, the collision between particles was ignored in this study, which reduced the computational time. Since wall can trap PM2.5, trap type boundary was adopted for the wall. Meanwhile, the escape type boundary was adopted for the discrete phase in the cook-stove top surface (inlet) and door (outlet). Since we carried steady-state simulations, the released particle was tracked until it reached the final destination. Fig. 10 shows the PM2.5 concentration and velocity distribution within the room in natural ventilation condition for the particle inlet velocity  $v=5\text{m/sec}$ , air inlet velocity =  $1\text{m/sec}$  and the mass flow rate =  $5.27\text{gram/hour}$ (Jetter et al., 2012).

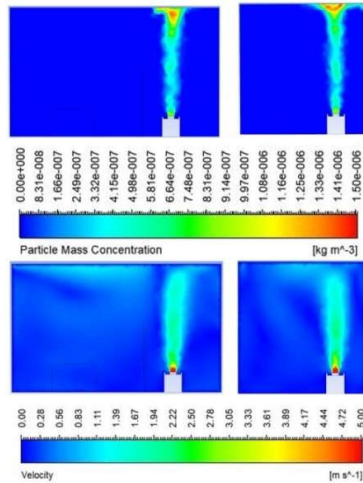


Figure 10: PM2.5 concentration and velocity distribution within the room

The CFD predicted PM2.5 concentration was found to be consistent with the velocity profile. In addition, the concentration of PM2.5 was found higher near the ceiling because the wall can trap PM2.5 particles(Ma, Jiang, & Li, 2015). High kinetic energy imparted to the jet plume is also responsible for the high PM2.5 concentration near the ceiling. However, it can be

concluded that the distribution of PM2.5 is maximum concentrated in the cooking zone because the window (air inlet) was assumed closed during cooking activity. This was observed during field surveys. The results did not observe any diversion in the path of pollutant concentration. Hence, no correlation was found between pollutant levels and interior layout parameters in this study in nat-vent conditions.

### The optimized solution

This section describes the results observed from optimization of the interior layout that could provide maximum experiential indoor environment quality. NSGA II based multi-objective optimization requires a set of continuous objective functions along with constraints of independent variables. The CFD predicted results of indoor air velocity and air temperature at the monitoring point was recorded for all the thirty scenarios. Linear regression model was performed to generate the two objective functions (see equation 3 &4). The CFD simulated air velocity and temperature values were considered as dependent variables (y) while the partition wall design parameters, furniture location and outdoor velocity acted as the major dependent variables (x). Since PM2.5 concentration levels had no variation with partition wall and bed position, indoor air velocity and temperature were considered as the two major objective functions.

$$y(\text{Air velocity}) = (-0.431x_1) + (0.217x_2) + (0.478x_3) - (0.327x_5) + 1.0639 \quad (3)$$

$$y(\text{Air temperature}) = (-0.151x_1) + (0.167x_4) - (0.709x_5) + 303.713 \quad (4)$$

All values significant at 95% C.I

From equations 3 and 4, it can be observed in line with the CFD predicted results; the regression coefficients suggest that the indoor air velocity increases with decrease in partition wall height( $x_1$ ) and distance of bed from window ( $x_5$ ) (see Fig 8). However, it maintains a strong correlation with outdoor wind velocity ( $x_2$ ) and distance of partition wall from window ( $x_3$ ). The ultimate goal was to provide an interior design solution with maximum air velocity and minimum temperature. In the algorithm runs, the authors used a population size of 50 in the optimization process. The crossover and mutation probability were 0.95 and 0.4 respectively. Crossover being a convergence operation is intended to pull the population towards a local maximum/minimum. On the other hand mutation is a divergence operation which breaks one or more members of population out of a local maximum/minimum space. Since the end goal is to bring the population to convergence, selection or crossover occurs more frequently than that of mutation. Hence higher value of crossover probability (0.95) and lower value of mutation probability (0.4) would help in faster selection of individuals that will go through genetic operations. In Fig 11, the optimal solutions have

been illustrated by the generating Pareto front of two objective functions (Air velocity and Temperature).

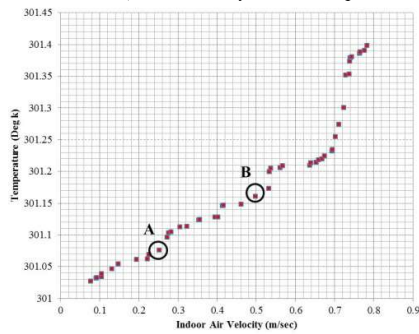


Figure 11: Pareto front of two objectives Air velocity and temperature

In the Pareto optimal solution, by moving over the points from A to B in Fig 11, air velocity increases from 0.25m/sec to 0.5m/sec, while temperature becomes worse (increases by 8%). The best design solution derived from NSGA II was found at air velocity to be 0.54m/ sec and air temperature to be 301.1K(27.95degC) over the breathing zone. Table 3shows the best possible interior design parameters generated by the GA for maximising the indoor air velocity and minimising air temperature.

Table 3: Design parameters of the optimized solution

Variables	Parametric values
Height of partition wall ( $x_1$ )	1.5m
Outdoor wind velocity ( $x_2$ )	0.98m/sec
Distance of partition wall from window ( $x_3$ )	1.49m
Partition wall gap ( $x_4$ )	0.60m
Distance of bed from window ( $x_5$ )	2.79m

### CFD analysis of optimized solution

In this section, an iterative approach was adopted to evaluate the suitability of optimized interior layout for maximising experiential indoor environment quality in the breathing zone. To understand the efficiency of the interior layout with respect to indoor environmental characteristics, the optimized design parameters were modelled to generate two iterated hypothetical scenarios. These two layouts were developed such that they had different bed placement directions keeping the five above mentioned parameters (see table 3) same for both. The CFD predicted indoor airflow and temperature pattern inside the layouts are illustrated in Fig. 12.

The CFD predicted wind velocity over the monitoring point was found to be 0.58m/sec and 0.27m/sec for Layout Type A and Layout Type B respectively. The higher occurrence of green-yellow bands over the bed was observed distinctly in Layout A, which infers the possibility of better indoor air exchange through cross ventilation. The temperature contours of the layouts showed 301.05k in case of Layout A(left) and that of 301.20k for Layout B(right).

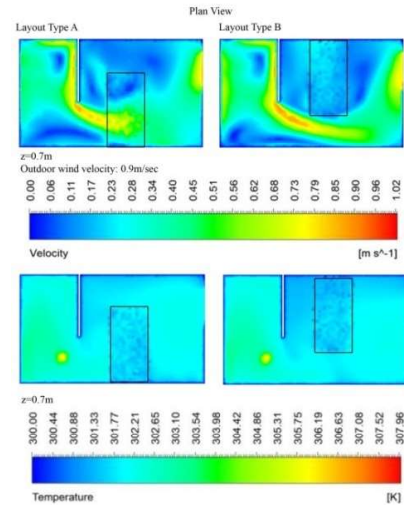


Figure 12: Airflow and temperature characteristics of two different optimized interior layouts

This explains that location of furniture and its direction also contribute in modifying indoor environment quality in the occupied zones. The simulated results were found in sync with the results generated from NSGA II as seen in Table 4.

Table 4: Results from NSGA and CFD simulation

Optimized Solution	NSGA	CFD simulation
Indoor Air Velocity (m/sec)	0.54	0.58
Indoor Air Temperature (K)	301.1	301.05

Thus, Layout A can be considered as most suitable interior design alternative for promoting maximum experiential indoor environment quality in the breathing zone.

### Discussion and conclusion

This paper has reported on the impact of interior design on indoor environment quality in a low-income tenement unit. A gap was identified in knowledge regarding the modification of natural ventilation and thermal performance based on controlling of indoor architectural design parameters. The novelty of this study lies in the transverse approach of low-income multi-rise apartment policy intervention under fixed envelope design and area constraints. To address this, the authors studied an existing unit layout proposed by the government and generated scenarios by varying interior architectural elements like partition wall parameters and bed locations. Finally, airflow, temperature characteristics coupled with pollutant transport mechanisms were investigated to propose the most suitable interior layout under spatial and socio-technical complexities. This study revealed that the partition wall plays an important role in maintaining indoor temperature distribution. Fig. 5 elucidates that partition wall separated the room into two zones: the cooking zone with higher temperature and living area with a relatively lower temperature

gradient. However, change in placement of bed with respect to partition wall had little effect on temperature distribution over the breathing zone. Fig. 7 shows that efficient placement of partition wall with respect to bed location can modify the indoor airflow characteristics. This can be attributed to the diversion of airflow path and formation of turbulent airflow zone due to the partition wall. Fig. 8 concludes that the low partition wall height significantly increased the indoor airflow. A possible explanation is that with the increase in the partition wall height, the obstruction in airflow increased. A unit with low partition wall height, higher partition wall distance and lesser bed location distance from the window can provide maximum airflow within the breathing zone. This study employed Latin Hypercube sampling to generate scenarios for predicting indoor environment quality. After execution of the CFD simulations, the predicted values of all the samples along with design constraints were utilised to perform multi-objective optimization. Finally, the GA derived optimized design solution was evolved which was found to deliver maximum air velocity of 0.58m/sec within the room when outdoor wind velocity was as low as 0.9m/sec. However, the pollutant distribution was concentrated mostly in the cooking zone, and hence was not affected by interior layout parameters in this study. Building indoor environment plays a powerful role in maintaining the health of occupants. However, a dearth of process-driven slum redevelopment guidelines is a less ventured area in urban housing policies of India, and around the world. The existing low-income housing stocks have degraded into slum-like living conditions affecting heavily on occupants' health condition. This study tried to bridge this gap through simulation of airflow, heat and pollutant levels within a low-income single tenement unit, a most probable future of mass housing in India. The findings advised that by optimising interior architectural parameters like partition wall and bed position, experiential indoor environmental quality over the breathing zone can be significantly improved.

### Limitations and Future Work

This study was limited to steady-state simulations for all the models and considered uniform occupant behaviour of opening and closing of windows. This can be improved using transient simulations that consider the effect of time-dependent phenomenon, transient weather conditions and variable wind directions. Future work includes experimentation, validation of current study and working on probabilistic models, which consider the unsteady nature of natural ventilation. The results from this study can pave a path towards the development of rational design solutions for sustainable low-income urban habitats in developing countries through decoupling of health and built environment.

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