**Investigating optimised ventilator and furniture position for increasing indoor environmental efficiency in slum rehabilitated tenements:**

**Evidence from Mumbai, India**

**Abstract**

*This study optimises the ventilator and furniture location of a tenement unit in a low-income urban habitat to obtain maximum experiential indoor environmental quality over the breathing zone. Hypothetical interior layouts using a combination of the two design parameters of ventilator location and bed position were generated for optimising the design layout that could promote maximum indoor airflow and minimum indoor air temperature and contaminant concentration. Here, we hypothesise that improved indoor environment is attainable through better natural ventilation and thermal performance in the occupied zones. A sequential methodology involving "parametric design modelling- computational simulations- multi-objective optimisation- multi-criteria decision making" based framework was selected. Results exhibit that the currently designed tenement unit had poor indoor environment, while hypothesised iterated layout ‘Optimised Design Layout, Scenario 3', derived from optimisation and decision making algorithm performed better in providing experiential indoor environmental quality. An increase in experiential indoor air velocity by 0.2m/sec and decrease in temperature by 2 degree Celsius was observed over the monitoring point in the optimised design layout, scenario 3 with respect to the existing scenario. This study, therefore, can find a way towards the development of sustainable habitat design guidelines under upcoming slum redevelopment policies across the nation.*

**Keywords**

Ventilator; Furniture layout; Low-income tenement; Indoor Environmental Quality (IEQ); Computational Fluid Dynamics (CFD); Multi-objective Multi-Criteria Decision Making (MCDM) optimization.

# Introduction

It is well-established through the connection of UN-Habitat Sustainable Development Goals (SDG) 3 and 11 that healthy and sustainable living can be achieved through the rational and well-designed built-environment. This interconnection becomes exigent since, with unprecedented urbanization, people are shifting indoors. Thus, the indoor environment turns integrally crucial to human health and well-being. Yet, the effect that the indoor built-environment has on its occupants remains under-explored. The poor indoor environment is not only attributed to climate-insensitive outdoor design but also to inappropriate interior design. Inefficient indoor design apart from deteriorating indoor thermal comfort threshold, affect human health as well as coerce the residents to utilise more mechanical ventilation strategies. Inappropriate interior design also reduces the wind-channelizing effects and hinders the airflow route. This phenomenon by generating localised stagnant zones amplifies conditions that create unpleasant situation and discomfort for indoor habitation. Hence, indoor design, despite being a factor of personal comfort, specific choice and social environment, has a rippling effect on indoor environmental conditions. Therefore identifying the environment-sensitive interior design parameters can commit to forthcoming sustainable habitat design policies.

The major factor behind the degradation of low-income (LIG) habitats is poor Indoor Air Quality (IAQ) owing to Household Air Pollution (HAP) (Sarkar & Bardhan, 2019a, 2019b). This coupled with the majority of urbanites spending 90% time indoors, result in high risk from sick building syndrome (SBS) and upper respiratory diseases like tuberculosis (Ruiz et al., 2018). Researchers denoted Liquefied Petroleum Gas (LPG) as cleaner fuel due to its lower pollution levels in comparison to solid fuels and hence LPG is currently used widely in India (Jetter et al., 2012). The national scheme of Pradhan Mantri Ujjwala Yojana (PMUY) was launched by Prime Minister of India on 1 May 2016 to distribute 50 million LPG connections to women of Below Poverty Line (BPL) or LIG families in India. However Lueker, Bardhan, Sarkar, & Norford, (2020) through experimental observations in the low-income apartments established that even with cleaner fuel (LPG) use, the HAP levels were found high, probably due to other external sources and ill-designed ventilation-insensitive built-environment.

The literature on the effect of indoor ventilation on occupants’ health reveals that the compact indoor spaces with reduced ventilation frequently fail to attain effective thresholds, which is required for faster removal of indoor pollution. The existing single multi-purpose low-income urban tenements in metro-cities of developing nations are devoid of proper indoor design and ventilation considerations. Ventilation, being a function of architectural design, the optimal design solution is required to reduce the risk of health.

However, design-based ventilation strategies can be effortlessly applied at early design stages using community-level architectural parameters like building orientation, boundary wall, atriums, and envelope-level architectural parameters like balcony, window, shading devices etc. Nevertheless, interior design modification like retrofit remains the only alternative to amend IAQ and thermal discomfort at the post-construction stage. This becomes more critical for LIG tenements, where space constraint couples with socio-cultural and economic constraints.

Natural ventilation, a passive building cooling strategy apart from improving IAQ and thermal comfort through fresh air exchange, also enables in energy saving (Stavrakakis, et al., 2012). In tropical climates, where extreme weather can cause thermal stress, natural ventilation can be used as an effectual strategy because it preserves the equilibrium of indoor and outdoor relative humidity. ASHRAE standard 55 documented that an indoor air velocity of 0.8m/s can reduce the temperature by 2.6oC, provided the air temperature equals to radiant temperature (Nguyen & Reiter, 2011).

Perception-based studies on adaptive thermal comfort in the summer months of Indian tropical context has established that decreased indoor temperature and high indoor air movement through application of adaptive controls aid in attaining thermal comfort levels (Indraganti, Ooka, & Rijal, 2012). Indraganti, (2010a, 2010b) through repeated experimental observations in naturally ventilated Indian apartments in summer had identified comfort band in the range of 26-32.45oC, with the neutral temperature of 29.23oC, way above the Indian standards (23-26oC). Similar studies in the tropical climate of Thailand identified air velocity of 0.2-1m/sec and 24-27oC to be thermally comfortable (Khedari, Yamtraipat, Pratintong, & Hirunlabh, 2000).

Among the different aerodynamically efficient architectural design parameters, air-inlet or window has been regarded as the most constructive solution for effective natural ventilation. Design variables of openings like window type, size, its position and shape affect air movement inside spaces, thus improving the indoor ventilation rates (Elshafei, Negm, Bady, Suzuki, & Ibrahim, 2017; J. Wang, Wang, Zhang, & Battaglia, 2017; J. Wang, Zhang, Wang, & Battaglia, 2018). However, effective cross-ventilation is a subject of both indoor air inflow and outflow as well. This calls for a design agenda for a detailed design intervention into the air-outlet location to improve indoor airflow rate and contaminant removal efficiency. An appropriately located air outlet would not only increase the indoor airspeed through pressure creation but also would aid in effective disposal of indoor pollutants and heat, thus enhancing the IAQ and thermal comfort levels. This becomes exigent in the current trends of denser built-environment with increased need for deep plan compact buildings, where space constraints compromise with adequate number of openings. Another less intervened interior design parameter is the furniture location and its effectiveness in improving experiential Indoor Environmental Quality (e-IEQ). Furniture layout, a significant interior design element influences micro-level wind channelization, by acting as guide to indoor airflow. Furniture height differentials enable the taller items to trap the passing wind and downwash the flow to the lower zones (Edward Ng, 2010). This downwash and recirculation phenomenon apart from affecting the windward facades also occurs at the leeward facades through eddy vortexes. Furthermore, furniture disposition induces micro-level positive and negative pressure. Yet, the system-driven technique to decide the environmentally feasible locations of an air-outlet and furniture within a specified volume of space remains an elusive concept in architecture-concerning literature.

The novelty of this paper lies in testing the efficacy of applying architectural design-based passive cooling parameters to improve e-IEQ taking a low-income multipurpose tenement as a case study. The specific objective of this research is to examine the interior-level design parameters, set their optimal values and explore their influence on indoor environmental performance under socio-cultural complexities. To determine the effect of interior design on IEQ, a specific interactive study was performed considering a combination of the two rarely ventured architectural design parameters: i) ventilator (small high-level air outlet) and ii) furniture (here, bed) location. Here, hypothetical interior layouts were generated with variable locations of the ventilator and furniture layout. Airflow, pollutant and temperature simulations were executed to understand the IEQ levels with respect to various interior layout scenarios. This study followed a ‘parametric based modelling-computational simulation–multi-objective optimisation-multi criteria decision making’ based approach for determining the final optimal interior design layout.

# Background

The notion of indoor built-environment design and natural ventilation potential interaction is integrally crucial in the Indian context, predominantly for the socially driven class of population. The slum improvement strategies provided by Mumbai City Development Plan 2005-2025 propose translation of horizontal slums into formal multi-storey housing (Bardhan, et al., 2015). However, these newly built rehabilitation towers lack the liveability parameters like IEQ and thermal comfort. The current low-income tenements in Mumbai, built devoid of specific design guidelines, suffer from over-crowding leading to ineffective airflow in the living zones and implicating poor IAQ with higher indoor temperature and pollutant concentration (see Figure 1). According to the Slum Rehabilitation Authority (SRA) guidelines, a hutment dweller in a slum is given free of cost, a residential tenement unit with a carpet area of 25 sq.m. (269 sq.ft.) which shall include a multipurpose living room, bedroom, kitchen/alcove, bath, water closet and balcony excluding common areas (SRA - Govt. of Maharashtra, 1995). These SRA housings have ‘pigeon-hole’ like tenement units with undivided cooking and living spaces, which are compacted alongside a double-loaded corridor with gallery access. This limited habitable space coupled with socially constrained occupant behaviour warrants the inhabitants lesser degree of freedom in interior layout which consequently affects IEQ.

Studies conducted in the social housing of Mumbai have concluded that architectural parameters like compact building disposition without open spaces, indoor space constraints, and unsegregated cooking-living zones degrade the indoor environment which in turn affects the health-seeking behaviour of the inhabitants on one hand and energy decisions on the other hand (Bardhan, et al., 2018; Bardhan, et al., 2018; Sarkar & Bardhan, 2018; Sunikka-blank, et al., 2019). These contextual researches have further promoted the crucial need of additional comprehensive investigation into the epistemology of interior level architectural design parameter optimization and their impact on the indoor environment, both at pre and post-construction stage.

Figure 1 Typical slum rehabilitated colonies of Mumbai

In this aggravated situation, the single multipurpose tenement units should receive increased attention from the building designers, architects and research communities. Fresh air supply through natural ventilation and extraction of air through an outlet is equally necessary for the release of stale air and increase of indoor air exchange rate. In these low-income compact tenements, where the window/door operating schedule depends on socially-constrained occupant behaviour and privacy concerns, the concept of stack ventilation becomes inevitable for maintaining continuous indoor airflow.

Stack ventilation, defined as the upward movement of air through openings or voids in a building owing to thermal buoyancy can be an efficient alternative in these resettlement colonies. In dense built environment with vertical structures, where natural cross ventilation has limited scope, the application for stack ventilation has gained importance by ensuring a comfortable indoor environment. The need for compartmentalization of spaces to maximize the number of tenement units within a given land footprint leaves less opportunity for employing enough openings that can facilitate cross ventilation. Additionally, the occupants tend to close the openings for most of the time in lieu of safety and privacy concerns. In this constrained situation, high-level air-outlets can be provided to enable stack ventilation, while maintaining the same privacy quotient.

# Research Methodology

Building design performance can be assessed through analytical and empirical calculations, physical scale models, field measurements, small scale modelling with experimentation and computational modelling. Based on the comparative parameters of accuracy, cost, suitability, precision level of results and time requirement, a hybrid method of computation simulation and field measurements was selected as the most suitable investigatory methodology for the current study. Among many computational models such as network flow model, multi-zone models, computational fluid dynamics (CFD) was selected here based on its accuracy and precision levels. CFD has been used widely for assessing the ventilation performance of different architectural parameters like window (Wang, et al., 2017), external shading devices, windcatcher (Montazeri & Montazeri, 2018), balcony (Prianto & Depecker, 2002), atrium (Vethanayagam & Abu-hijleh, 2019), ceiling (Nguyen & Reiter, 2011), boundary wall (Hawendi & Gao, 2017). Validation processes were attempted to calibrate the results.

A system-driven sequential non-integrated framework was adopted to evaluate the suitability of the interior design of a low-income multi-purpose apartment for providing enhanced IEQ. The research plan revolves around five major non-integrated sequential steps:

1. Step 1: Experimental set-up, data collection, base-case examination, modelling and simulation was performed to recognise the current environmental status of existing low-income tenements. This step also helped in understanding the socio-architectural complexities of the setting, as well as identifying the design variables that need to be tested and incorporated for better indoor environmental performance.
2. Step 2: Iterated hypothetical scenarios were formulated by varying design variables to explore the importance of interior design in modifying the indoor environment.
3. Step 3: Computational modelling and simulation of the iterated scenarios were performed to investigate the changes in environmental performance among the designs.
4. Step 4: Multi-objective optimisation algorithm was executed to find set of optimised design scenarios that would promote a better indoor environment.
5. Step 5: Stakeholder’s participation was lastly involved in finalising the single optimal design layout with improved IEQ.

The research plan-driven methodology adopted in this study is illustrated in Figure 2.

Figure 2 Research methodology adopted

First, site reconnaissance surveys were conducted to obtain physical dimensions of the interior of a typical LIG apartment, along with the deployment of in-situ environmental sensors to obtain outdoor and indoor air temperature, velocity, and contaminant concentration and distribution profiles. The data from the experiments were utilised as boundary conditions for the forthcoming stages. CFD code then was executed within various iterated interior layouts generated from an adopted sampling technique to predict indoor air velocity, temperature, and pollutant concentration profiles. Multi-objective optimisation tool coupled with the quasi-quantitative method of Multi-Criteria Decision Making (MCDM) approach was lastly employed to generate the best design layout with maximum IEQ over the breathing zone. To acquire data on the IEQ metrics of the unit, the experimental process initiated with the installation of in-situ environment sensors in one typical tenement unit for three consecutive days of a typical summer month in 2018.

## Selected case study

Lallubhai rehabilitation colony in Munkhurd, Mumbai was chosen as the study area. The residential colony is a cluster of 65 buildings with 9300 dwellings and was constructed in 2003 under the Slum Rehabilitation (SR) Act. The tenements are one-room unit with attached bath (2.47sq.m) connected to a common corridor. Typically, the interior space consists of two undivided zones: cooking and multi-purpose living zone (see Figure 3).

Figure 3 Layout plan and 3D model of tenement unit showing 5 survey points apart from inlet points

To understand the effectiveness of IEQ under varying interior layouts, a point of measurement at z=1.2m at the mid-bed point in the living zone was selected. The optimised design would be the one with maximum IEQ over this monitoring point. The ventilation and thermal performance along with pollutant profile in the tenement (21.42sq.m/230.5sq.ft) were adopted as a proxy measure for efficacy of e-IEQ. The unit contained one window (1.5m x 1.2m) in the multipurpose room 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 favourable position for availing the maximum e-IEQ. A cook-stove (0.4m x 0.4m x 0.4m) placed below the window (as observed from field survey), was considered as the chief indoor source of heat and pollutant. The floor-to-ceiling height was measured as 2.9m.

Another notable observation among the resettlement units was the hindrance of natural ventilation paths. While privacy was the chief concern behind the closing of doors for the residents of lower floors, the requirement of additional storage space forced others to install permanent window coverings. These coverings were observed to have significant impact on the indoor natural airflow. Figure 4 includes examples of window and door obstructions observed in occupied resettlement colonies of Lallubhai compound.

Figure 4 Permanent window obstructions observed in resettlement dwellings inhibiting ventilation paths

## Climate of Mumbai

The dense tropical city of Mumbai records an average outdoor temperature between 23.70C-29.70C with maximum 33.50C during summer months (see Figure 5). From 2011-2015, Mumbai recorded average PM2.5 levels of 60µg/m3 and PM10 levels of 120µg/m3 , much higher than the World Health Organization (WHO) recommended levels (10µg/m3) (World Health Organization (WHO), 2016). However, owing to extreme economic burden, natural ventilation remains the only alternative for the low-income population of Mumbai.

Figure 5 Annual temperature and wind speed profile of Mumbai (IMD Mumbai)

## Formulation of iterated scenarios with altered design variables enabling passive cooling

Two principal interior design parameters were applied to the case study tenement to generate hypothetical iterated interior design layouts. Following is the brief description of both the strategies and justification behind their use.

### Ventilator

A standard size air-outlet (0.3mx0.3m) was introduced on the wall adjacent to the double-loaded corridor in the hypothetical scenarios, which would guarantee better cross-ventilation even when the other natural ventilation paths like the door remains shut, thus preserving same privacy measure (see Figure 6). The tenements in the compactly arranged deep planned slum rehabilitated towers share external walls, thus limiting the designers to provide adequate openings. Moreover, the field survey revealed that the occupants tend to close their doors to maintain safety, security and privacy, thus limiting cross-ventilation in the absence of any pressure outlet. Owing to the economic constraints of the low-income population that refrain them from adopting mechanical ventilation mode, a small size air-outlet or ventilator was found to be a cost-effective solution as well.

Figure 6 Cross-ventilation strategies showing maximum efficiency of the ventilator

The Indian Standard (IS 4021, 1995) recommends ventilator sizes from 0.59mx0.59m-0.59mx1.19m with timber framing. However, a study by Priyadarsini, et al., (2004) demonstrated through the wind-tunnel test that the indoor air velocity in a test room rapidly increased when active ventilator size was increased from 0.2mx0.2m to 0.3mx0.3m. However, the air velocity decreased when the stack size increased further to 0.4mx0.4m. Furthermore, a market-ready available ventilator size is 0.3mx0.3m. From the above discussions, this study concluded smaller active stack of size 0.3x0.3m to be feasible for the particular volume of space.

### Furniture location

It was reckoned from the field reconnaissance survey that the residents spend most of the time near their bed other than cooking activities due to high space limitations. Therefore, this research introduced bed location as a design variable, estimating that bed position or the active zone of the tenement should experience better IEQ. The monitoring point in this study was considered over the bed (refer to Section 3.1). Four possible bed locations (as observed from the survey) were considered here to generate the interior design layouts (see Figure 7).

After the initial stage of experiment and physical measurements related data collection and identification of aerodynamically-efficient design variables, alternative hypothetical interior design layouts were generated by adding a ventilator (high-level air outlet) through a random sampling technique (Iman, 2008). The design variables that were sampled included varying ventilator location both at horizontal and vertical planes (See Figure 7). The algorithm bounded by the average value, standard deviation, upper and lower limits of the design parameters were executed in MATLAB to generate the samples. The sampling scheme by incorporating a combination of above two locational variables, generated eight random samples. Finally, 32 different scenarios were formed when four different bed positions as demonstrated in Figure 7 were included for all eight cases. These 32 scenarios with varying ventilator and bed locations were generated in order to check their environmental suitability in terms of airflow, temperature and indoor pollution exposure levels. A comparative analysis of these scenarios would aid in selecting the environment-sensitive design layouts.

Figure 7 Sample Layouts with four different ventilator and furniture locations (bed positions)

## Computational simulations

### CFD settings

The well-established tool of CFD was utilised to predict the indoor environmental conditions of the 32 iterated scenarios. Predictability of environmental metrics at each grid point of the room and especially the distribution of airflow, indoor heat and pollutant transfer path for each layout could be attained using CFD. Hence, the commercial CFD simulation software used for this study was Ansys Fluent. The objective of this step was to explore the performance of the iterated scenarios in terms of airflow, temperature and pollution levels distribution, and to examine the detailed differences in each of the scenarios. A comparative analysis of the environmental performance of the iterated scenarios would aid in understanding the significance of environment-sensitive interior design, and how locational change in design variables would affect the e-IEQ.

Numerical estimation of natural ventilation is difficult due to uncertainties associated with it which include stochastic nature of local wind conditions, obstacles in the airflow path and random user behaviour regarding operation of windows/doors. This study adopted a deterministic simulation approach while considering the unreliability linked with natural ventilation. The models were well-mixed using double precision, three dimensional, parallel, and finite volume pressure-based solver.

The recently developed varying approaches for estimating turbulent flows include Reynolds-Averaged Navier–Stokes (RANS), Detached Eddy Simulation (DES), Large Eddy Simulation (VLES), (B. Wang & Malkawi, 2019). The CFD simulations employed the finite volume method for spatial discretisation of the domain by applying 3D tetrahedral meshing option. A fine mesh for the whole domain with three times refinement on the window (inlet), ventilator (outlet) and the cook-stove air inlet was employed to resolve the high gradient regions of the flow field with higher accuracy and precision level. The finalised mesh model consisted of 58538 nodes and 310166 elements. The RANS standard k-ϵ turbulence model along with energy model was solved until the 3D steady-state simulations were converged. The simulations used second-order UPWIND scheme to discretise the convection term in the governing equation. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used for coupling pressure and velocity components. The simulations used hybrid initialization with minimum 10,000 iterations to achieve convergence. Along with justification of the grid independence test, the solution was considered to converge till *10*–*6* (RMS) of the residuals of the air velocity profile in all the simulated models.

The CFD simulations were supported by in-situ environmental sensor measurements including one-time HAP point measurements and data logging sensors deployment. Environmental sensors including “*Testo 480 large vane air velocity probe*” measured the air velocity at air-inlet or window and five other locations within the room (see Figure 3). While Kestrel 5400 multi-sensor gathered point measurements of ambient temperature, the temperature of the heat source (cook-stove) was recorded using ibutton stove surface temperature sensors. Hand-held portable particulate matter (PM) sensor named DUSTRAK 8532 was employed to gather PM2.5 point measurements near the kitchen area and the living zones.

The air was assumed to enter the tenement unit through the window (velocity-inlet) and escape through the introduced opening on the opposite wall i.e. ventilator (pressure-outlet). The middle of the window was maintained at a constant atmospheric temperature of 300K (26.85oC). The pressure was constant across inside and outside boundaries of the tenement. The LPG cook-stove was considered as the major indoor heat source.

Solar load model that employs a solar calculator in FLUENT was used to investigate temperature owing to incoming external solar radiation. The models were simulated using three-dimensional solver under steady conditions. This study employed the SIMPLE algorithm for pressure-velocity coupling of steady-state solutions (Abed, et al., 2018). The turbulent flow due to natural convection inside the room was simulated using the energy and standard *k-ɛ* turbulence model. The general boundary conditions are shown in Table 1.

Table 1 Boundary Conditions for Air Velocity, Temperature Profile, and Solar load model

The pollutant concentration model in this study used the Discrete Phase Model (DPM) coupled with the Euler-Lagrange approach in ANSYS FLUENT for predicting the indoor PM2.5 concentration (Ma, et al., 2015). Since the diameter of PM2.5 is small, the collision between different particles was ignored in this analysis thus reducing the computational time. In this method, fluid (air in this case) is considered as continuum in which Navier-Strokes equations are formed, while the discrete phase is solved by steady tracking of PM2.5 particles. There is an exchange of mass, momentum and energy between continuum and discrete phases. Since wall can trap PM2.5, trap type boundary condition was adopted for the wall. Meanwhile, escape type boundary condition was assumed for the discrete phase in the window (inlet) and ventilator (outlet). Since steady-state simulations were carried out in this case, the released particle was tracked until it reached the ultimate destination.

### CFD validation

A validation study with the above-mentioned CFD simulation settings was conducted, by comparing the CFD predictions and field measurements of the base-case.

* + - 1. ***Computational domain and grid***

A grid independence test of the indoor air temperature due to external solar radiation was performed for the optimised scenario to validate the CFD model. Three typical tetrahedral meshes were created for demonstrating the coarse, medium and fine resolutions (see Figure 8).

The temperature results were verified for the CFD monitoring point of the room over the breathing zone. The refinement ratio (r) was stated, which is explained as the ratio between the number of elements in the fine and coarse meshes (see Equation 1).

|  |  |
| --- | --- |
| $$r= \frac{∆\_{fine}}{∆\_{coarse}}^{\frac{1}{3}}$$ | (1) |

Figure 8 Grid typology with parameters and results from CFD simulations

The grid convergence index (GCI) method was utilised to execute the quantitative grid verification. The method is broadly used as a CFD best practice guideline for grid convergence error recording in which error band is set for given simulation results such that the exact solution is within that band at 95% confidence interval (CI) (Bardhan, et al., 2018).

* + - 1. ***Boundary conditions***

Environmental sensors like “*Testo 480 large vane air velocity probe*” and calibrated ibutton stove surface temperature sensors were utilized to perform full-scale experiments in the existing tenement unit (see Figure 9).

Figure 9 Stove temperature data derived from the calibrated sensor (Sarkar & Bardhan, 2019c)

The data derived from the sensors were used for validating CFD predicted simulations. Uniform wind speed profile was imposed at the window-inlet as recorded from the sensor (U∞ = 0.989m/sec), and a turbulent intensity, I, of 5% is expected for the inlet flow according to the measured data. The turbulent kinetic energy k is calculated from U∞ using Equation 2. The turbulent dissipation rate is given by Equation 3 where Cµ is a constant. The turbulence length scale is considered as I= 0.07DH where DH is the calculated hydraulic diameter of the domain (here window and cook-stove inlet).

|  |  |
| --- | --- |
| $$k= U\_{\infty }I^{2}$$ | (2) |
| $$ε= C\_{μ}^{3/4}\frac{k^{3/2}}{l}$$ | (3) |

The computational domain walls were modelled as no-slip walls with zero roughness heights (ks=0). The standard wall functions with zero gauge static pressure were applied at the outlet openings (ventilator in this case).

## Optimisation using Non-dominated Sorting Genetic Algorithm

The stage of CFD simulations of iterated scenarios was followed by multi-objective optimisation. Traditionally, IEQ is formulated with the objective of maximising indoor ventilation rate or air velocity. However, since promoting better environment in tropical climate currently involves an integrated application of conflicting multi-objective like higher indoor air movement, lowered thermal sensation and decreased pollution concentration; multi-objective optimisation becomes a suitable approach. Therefore, to get an improved e-IEQ, this study additionally included objectives of minimizing indoor air temperature due to external radiation and the indoor heat source and pollutant concentration. The objective of this step was to identify the set of environmentally-sustainable optimal interior design layouts that would promote better indoor environmental experience, among all the 32 iterated scenarios.

Genetic algorithm (GA), a well-established random search method for resolving multi-objective optimization problems has been efficaciously applied to varying real-world applications (Konak, et al., 2006). Non-dominated Sorting Genetic Algorithm (NSGA II), a special class GA, is a population-based algorithm that produces a number of Pareto-optimal solutions for solving multi-objective optimization problems (MOOPs) (Salazar, et al., 2006). NSGA II utilises the features of the law of adaptation which considers both rank and distance from each solution (Ardakan & Rezvan, 2018). Here, the proposed MOOP was solved using NSGA II.

The CFD simulated indoor air velocity, temperature and contaminant concentration values over the monitoring point of all 32 scenarios were reckoned. Next, these environmental metrics were assumed as function of interior design parameters. Based on the above assumption, the multiple objective functions for MOOP were formulated using Equations 4 and 5:

|  |  |
| --- | --- |
| $$Maximize Indoor air velocity=f\left\{\left(a\_{1}x\_{1}\right)+\left(a\_{2}x\_{2}\right)+\left(a\_{3}x\_{3}\right)+\left(a\_{4}x\_{4}\right)\right\}+b$$ | (4)) |
| $$Minimize indoor Indoor air temperature, pollutant con.= f\left\{\left(a\_{1}x\_{1}\right)+\left(a\_{2}x\_{2}\right)+\left(a\_{3}x\_{3}\right)+\left(a\_{4}x\_{4}\right)\right\}+b$$ | (5) |
| *xi*(i=1...n) are the architectural design parameters , ai(i=1...n) are the regression coefficients |

The major design thresholds utilised for multi-objective optimisation are shown in Table 2.

Table 2 Multi-objective optimization constraints

The design variable ranges were used to bound the optimization problem and generate inputs for the meta-model. After the initial random population was ranked in relation to the objective functions, the population were modified to achieve a better ranking. This step evaluated the most feasible sets of interior design solution for obtaining highest e-IEQ over the breathing zone.

## Use of Multi-Criteria Decision Making (MCDM) methods (coupled AHP-TOPSIS) for prioritization

The stakeholder’s participation along with architects’ and habitat policy-makers’ perspective is an integrally crucial factor while proposing building bye-laws and habitat planning policies and regulations. While taking practicality of the design regulations into consideration, the feedbacks from the policymakers and planners are absolutely essential. Hence, this study applied an integrated approach to capture the responses of the planning and design experts from reputed authorities and involve them in finalising the single optimised design layout.

Owing to the multi-dimensional nature of IEQ, the quasi-quantitative method of MCDM was employed to select the optimised layout from a finite number of optimal alternatives generated from NSGA II code. This approach was performed in order to select the most feasible and acceptable interior design layout that can deliver improved e-IEQ over the breathing zone.

Analytical Hierarchy Process (AHP) was initially used to quantify the experts’ opinion on alternative preference to the qualitative indicators and for indicator weight elicitation (Mu & Pereyra-Rojas, 2017). Then the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to rank design alternatives depending on the different indicators scores and weights. The combined method of AHP-TOPSIS is well-established and has been used widely by researchers in various fields as a major tool for decision making (Sindhu, Nehra, & Luthra, 2017). These methods are comprehensively described in the following subsections.

### 3.6.1 Quantitating the qualitative indicators using experts’ opinion method of AHP

The criteria used in the selection exercise included indoor air velocity, pollutant concentration, and air temperature due to an internal heat source (i.e. active cook-stove) and external solar radiation. There are several researches on railway station site selection (Mohajeri & Amin, 2010) and assessment of urban renewal process (Lee & Chan, 2008) using AHP where 19 to 40 experts were considered for evaluation. Here, a team of 28 experts from the academic, research and industrial fields who work on indoor air quality and building science were consulted to transform qualitative criteria into ratings. In this study, the top executives holding positions of director, senior architects and deputy planners of planning, development planning, roads, building, and IT departments of city administrative authorities such as Mumbai Metropolitan Region Development Authority (MMRDA), Brihan Mumbai Municipal Corporation (BMC) and other academic professionals from institutes of national importance, were involved as experts. The scores from these experts were combined by utilising a pair-wise comparison for obtaining the priorities for each criterion. Consistency was checked for every Pair Comparison Matrices (PCM) proposed by the experts and group decisions were aggregated. In case of any inconsistency in AHP, the experts were re-consulted to remove the irregularities.

### 3.6.2 Prioritising alternatives using TOPSIS

TOPSIS, a countervailing weight-based MCDM method is proved to be most efficient in solving complex and qualitative decision-making problems (Triantaphyllou & Shu, 1998). TOPSIS follows Euclidean distance approach to quantitatively compare the alternatives over the set of attributes by benchmarking the positive and negative ideal solutions simultaneously (Gogate, et al., 2017). This approach is employed to evaluate the relative closeness of alternatives to the ideal solution. Thus, the preferred order of alternatives is produced by relating these relative distances. Another advantage of utilising TOPSIS is the prevention of loss of information, since the actual detail regarding the scenarios are considered here. Hence in this study, TOPSIS was used to determine the most optimised design layout among the set of optimal interior layout options generated from NSGA II.

#  Results and Discussion

## CFD validation

## 4.1.1 Computational domain and grid

The results of grid independency tests demonstrate that the grid refinement ratios (recommended value =>1.3) were maintained to be 1.47 for medium and 2.11 for fine mesh, indicating acceptable grid fine-tuning as per the CFD best practice guidelines (Tominaga et al., 2008). The computational time for the simulations for 10,000 iterations was approximately 9hr (fine mesh), 4hr (medium mesh) and 1.5hr (coarse mesh) respectively on an intel i7 CPU with single solver. The fine mesh size was selected for all the models to avoid compromise on results’ accuracy.

### 4.1.2 Experiment and simulated results

Figure 10 (a, b and c) compares the CFD outcomes and the sensor-recorded results for the existing case. The outcomes exhibited that the simulated indoor air velocity values synchronise with the sensor data at the same points. Figure 10a illustrates that the mere addition of ventilator increased the indoor airspeed by 22.2% keeping bed location and other conditions same. With the increase in distance from window, the optimised solution was found to perform better than other cases. Figure 10b shows the change in indoor air velocity with an increase of height for three CFD predicted scenarios along with the base case. The average error between experimental and CFD predicted results were found to be 7.72% for 10a and 5.26% for 10b respectively.

Figure 10 Comparison of wind velocity magnitude along (a) horizontal and (b) vertical planes by CFD simulation and sensor deployment for wind direction normal to the window-inlet

## CFD simulations

The CFD simulated indoor airspeed over the breathing zone was found within the range of 0.03m/sec to 0.406m/sec (inlet velocity=0.989m/sec) for 32 scenarios. This explains that by modifying interior design variables like ventilator location and bed position, it is feasible to maintain effective indoor airflow levels in naturally ventilated spaces.

Figure 11(i) explains that the CFD simulated experiential indoor airflow over the breathing zone was different with varying ventilator location when bed location was fixed. The air velocity at the monitoring point of case (a) was 0.126m/sec. With the shifting of ventilator location, the experiential indoor air velocity values changed from 0.106m/sec in case (b) to 0.069m/sec and 0.029m/sec for cases (c) and (d) respectively. This implies that change in ventilator location with respect to bed location has a significant impact on airflow characteristics over the breathing zone. This is primarily owing to the change in the location of pressure outlet which diverts the indoor airflow path direction. For case (d), where the ventilator is located right opposite to the window, the airflow barely gets distributed, thus delivering low air velocity zones over the bed.

Figure 11 Air velocity distribution in four layouts with (i) different ventilator location and (ii) different bed location

Similarly, it can be observed from Figure 11(ii) that experiential indoor air velocity changed significantly with varying bed location when inlet and ventilator locations were kept same for all cases. A possible explanation is the proximity between the ventilator and bed location. For case (a) and (c), the bed was placed away from the ventilator location and hence had experienced indoor air velocity of 0.126m/sec and 0.139m/sec respectively over the monitoring point. While case (d) had the highest experiential indoor air velocity of 0.374m/sec due to the closest proximity between ventilator and bed. On comparing cases (b) and (d) from Figure 11 (ii), it can also be concluded that experiential indoor air velocity over the breathing zone is not only affected by bed location but also by the bed alignment or orientation. Case (b) experienced air velocity of 0.159m/sec which was found significantly lower than the case (d).

Next, the average LPG stove surface temperature was recorded to be 308.15K (35oC) in cooking condition whereas the ambient room temperature was considered 300K (26.85oC), as verified from the environmental sensors (Sarkar & Bardhan, 2018). The CFD predicted indoor temperature distribution in the presence of an active cook-stove was found relatively uniform. Figure 12(i) elucidates that CFD predicted experiential indoor air temperature over breathing zone altered with varying ventilator location keeping the bed and cook-stove location constant. However, subjective interpretations of these interior layouts reveal that the presence, as well as location of the ventilator, affected the indoor convective heat transfer direction, thus maintaining a relatively lower temperature zone near the bed. The air temperature at monitoring point of case (a) in Figure 12(i) was highest among the other cases (b, c, d) i.e. 302.032K (28.88oC). A possible explanation behind this could be the ventilator that was located immediately above the bed. Since the convective heat was transferred from cook-stove (heat source) towards the ventilator (pressure-outlet in this case), the higher temperature zone was uniformly distributed in case (a).

The experiential indoor air temperature over the breathing zone changed to 301.873K (28.72oC) for case (b) and 301.882K (28.73oC) for case (c) with the shift of ventilator location. However, case (d) recorded the least air temperature of 301.325K (28.17oC) which was observed due to higher proximity between bed and ventilator. For case (d), the lower temperature zone was observed to be distributed more evenly than other cases (a, b, c).

Figure 12 Temperature distribution in four layouts with (top) different ventilator locations and (bottom) different bed locations

In contrast, Figure 12(ii) depicts change in experiential indoor air temperature with varying bed positions and constant ventilator locations. The lowest temperature recorded for case (a) was 301.325K (28.17oC) while the highest temperature was found for case (d) i.e. 302.101K (29oC). This can be attributed to the proximity between bed and ventilator locations and the bed orientation as well.

A similar trend was observed in temperature fields for the scenarios when external radiation was modelled in CFD using solar load model in FLUENT solver. When the bed location was constant, the temperature field varied from 302.825K (29.67oC) (closest proximity between ventilator and bed location) to 302.66K (29.51oC) for the case with the farthest distance of ventilator from the bed.

Figure 13 shows the indoor PM2.5 concentration in natural ventilation condition for particle inlet velocity=0.5m/sec, air inlet velocity= 0.98m/sec and the mass flow rate= 0.1mg/sec (Ma et al., 2015).

Figure 13 PM2.5 concentration within the occupied zone PM2.5 concentration on ceiling (z=2.85m) (left); sidewall adjacent to the window (middle) and wall opposite of window (right)

The ‘percentage of the area of bed with high PM2.5 concentration’ was considered as a proxy measure of indoor pollutant concentration over the monitoring point. Figure 13 explains that PM2.5 concentration followed a similar profile for cases (a), (b), (c), and (d) when inlet and ventilator (outlet) locations were kept constant. However, with the change in bed location, the PM2.5 concentration varied significantly for all the cases. Case (d) had the highest indoor PM2.5 concentration (50%) while case (c) had the least (0%).

Additionally, PM2.5 concentration was found higher near the walls (see Figure 13) because the walls can trap PM2.5 particles. The kinetic energy of the incoming wind can also be a factor behind the higher PM2.5 concentration near the northern wall.

## Optimised design layouts

The CFD simulated results of indoor air velocity, temperature and PM2.5 levels were recorded for all the 32 scenarios. Next, linear regression was employed to generate the four objective functions (see equations 6, 7, 8 and 9), where xn is the ventilator and bed location.

|  |  |
| --- | --- |
| $$y \left(Air velocity\right)=\left(-0.038\*x\_{1}\right)+\left(-0.015\*x\_{2}\right)+\left(-0.078\*x\_{3}\right)+\left(0.084\*x\_{4}\right)+ 0.356$$Adjusted R2 value: 0.611 | (6) |
| $$y \left(Stove temp\right)=\left(-0.094\*x\_{1}\right)+\left(0.057\*x\_{2}\right)+\left(-0.113\*x\_{3}\right)+\left(0.081\*x\_{4}\right)+ 302.29$$Adjusted R2 value: 0.554 | (7) |
| $$y \left(\begin{array}{c}PM\_{2.5}\\ conc\end{array}\right)=\left(-0.059\*x\_{1}\right)+\left(-0.111\*x\_{2}\right)+\left(-0.023\*x\_{3}\right)+\left(0.282\*x\_{4}\right)- 0.138$$Adjusted R2 value: 0.716 | (8) |
| $$y \left(Solar temp\right)=\left(-0.050\*x\_{1}\right)+\left(-0.096\*x\_{2}\right)+\left(0.024\*x\_{3}\right)+\left(0.204\*x\_{4}\right)+ 302.373$$Adjusted R2 value: 0.698 | (9) |

All values significant at 95% C.I.

The goal was to provide a single optimal interior design solution with maximum indoor air velocity and minimum indoor air temperature and pollutant concentration.

However, Pareto dominance based algorithms like NSGA II perform better on two objectives and their searchability for optimal solutions severely degrade with increase in the number of objectives (Cheng, et al., 2017). The difficulty for many-objective problems in case of Pareto optimal algorithms lies in the fact that many objectives are not likely to be dominated by others (Ishibuchi, et al., 2008). Hence, if all individuals of the population become non-dominated, Pareto dominance based fitness evaluation schemes fail to generate a strong Pareto font (Ishibuchi, et al., 2009). Taking this challenge into consideration, six optimal Pareto-font based solutions from the above-mentioned four objective functions taking two at a time were generated (see Figure 14). In the Pareto optimal solutions, by moving from one point to other, one objective function gets better worsening the other one.

Figure 14 Pareto font for six optimal solution sets

Figure 15 demonstrates the plan and section of the six NSGA II derived optimised design layouts (ODLs). The ODLs vary in terms of bed and ventilator locations.

Figure 15 Plan and sections of the NSGA II derived six Optimised Design Layouts (ODLs)

The six sets derived from NSGA II optimization method (shown in Table 3) were accounted to be the most optimal design solutions that would provide effective IEQ over the breathing zone. Table 3 also demonstrates that Optimised Design Layout, Scenario 3 (ODL 3) performed better in CFD predicted air velocity field for all the survey points considered in Figure 3.

Table 3 NSGA II algorithm derived optimal design solution sets with CFD predicted air velocity profiles at different survey points

The most optimal interior design layout among the six optimal sets was finally obtained using coupled MCDM approach of AHP-TOPSIS (Figure 16).

Figure 16 AHP TOPSIS framework adopted in this study

The six optimal design layouts generated from NSGA II optimization algorithm were geometrically modelled and CFD simulations were performed to record the experiential indoor temperature (both solar and stove), velocity and contaminant concentration values for the six ODLs. Once the consistency ratio was checked, the weights of 28 experts were aggregated to formulate the weight matrix. The consistency ratio of the AHP of the 28 experts varied between 0.009 and 0.11, well within the accepted range. The final aggregated AHP derived weights were 0.377 (Air velocity), 0.155 (Stove temperature), 0.262 (PM2.5 concentration) and 0.204 (Solar temperature). The six ODLs were then ranked using TOPSIS with the help of the indicator weights. The results of ranking (Table 4) show that ODL 3 (with a score of 0.682) is the most preferred design layout.

Table 4 Results of CFD simulations of six solution sets (left); Results from TOPSIS ranking (right)

Figure 17 compares the CFD simulated air velocity, temperature (stove and solar) distribution profiles and contaminant concentration levels of base-case scenario (without a ventilator) and ODL 3. The existing unit does not have an outlet other than the door located on the opposite side of the inlet. Keeping in mind the culturally restrained occupant behaviour of shutting down of doors, only inlet boundary conditions were considered while performing CFD simulations for the base-case scenario.

Figure 17 Comparing the simulation profiles of base case and final optimized design layout (ODL 3)

The air entering the occupied space through inlet/ window did not find any pressure outlet for cross ventilation and hence got redirected towards the inlet after being obstructed from the opposite wall. The air did not get distributed in the room and hence lower indoor air velocity zone (0.125m/sec) prevailed over the breathing zone (see Figure 17 and Table 5). Similarly, absence of any outlet inhibited the convective heat transfer in the occupied zone for the base-case scenario. Hence, the heat remained trapped inside the room thus, increasing the temperature over breathing zone. However, the bed location proved to be advantageous while considering area of higher pollutant concentration over the bed.

Table 5 Results of CFD predicted values of base case scenario and final optimized solution

The air velocity over the CFD monitoring point of ODL 3 was reckoned as 0.30m/sec, while the cooking-induced and external radiation sourced temperature were 29.19oC and 29.6oC respectively, a value within the adaptive Indian thermal comfort range as established by Indraganti, (2010a, 2010b). This explains that addition and appropriate location of ventilator along with suitable bed location and its orientation significantly contribute to modifying e-IEQ in the occupied zone. Thus, ODL 3 can be considered as the most suitable interior design alternative for promoting maximum IEQ in the breathing zone under the socio-technical constraints.

#  Conclusions

Indoor Environmental Quality plays a significant role in maintaining health and quality of life of citizens. Slum proliferation is currently an epidemic in developing nations which diminishes the quality of life. The lack of process-driven sustainable slum redevelopment and habitat design guidelines has been observed as a rarely ventured area in urban housing policies of India. The space constraints and socially restrained behaviour of the low-income population within the deep plan compact buildings offer fewer choices in interior design layouts. While re-design of a building envelope is a resource-intensive process, modification in interior design with retrofit alternatives gives abundant agency to individuals at no or low cost. The solution warrants faster intervention without requiring any adjustment in personal behavioural practices.

Here, a cross-sectional study of a low-income tenement of Mumbai was investigated to derive at an optimal air-outlet and furniture location that would orchestrate with the special needs of sustainable development of low-income habitats. This mixed-mode study comprised of computational simulation of indoor airflow, temperature and pollutant levels of 32 iterated hypothetical indoor design layouts. This method facilitated in recognizing the aerodynamically-efficient indoor architectural parameters, fix their feasible locations and finally deriving at an optimal interior design solution that can promote better experiential indoor environmental quality. Our findings suggest that the current design is unable to provide adequate quality of life to the rehabilitants and merely an addition of ventilator at an optimum location and rearrangement of bed/furniture layout as shown in Optimised Design Layout: Scenario 3 can deliver more liveable conditions.

The results of this study might be useful for different interest groups. This study is absolutely essential for low-income housing design; where financial constraints restrain the population from using active means of cooling to achieve thermal comfort. Moreover, experiment-based researches in slum rehabilitation colonies in Mumbai have established that despite the provision of improved infrastructure and cleaner cooking fuel, the household air pollution remains high, majorly due to ill-designed tenement units (Lueker et al., 2020). The design variables, explored here, if implemented in future slum rehabilitation habitat design bye-laws, would aid in delivering better indoor environment to the inhabitants, which would advertently improve their health, liveability and well-being. Thus, not only the current status of low-income apartments’ design was investigated, but this study also came up with feasible scientifically-evolved design recommendations, which remain under-researched. Furthermore, 80% of housing stock is yet to be built, of which one-third belongs to low-income sector (MHUPA, 2015). Hence, significant modification of existing building bye-laws and design regulations using these studies becomes vital for delivering environmentally-sustainable low-income habitats in future.

Nevertheless, the non-integrated sequential methodology involved here can be emulated for designing naturally ventilated residential buildings in tropical climates by applying optimised passive architectural design elements. This system-driven heuristic applied here would also aid in promoting the energy-saving cooling potential of the tenements by reducing the use of energy-driven mechanical cooling systems.

**Limitations**

Firstly, the results demonstrated here, are specific for single-multipurpose low-income tenements; and can change depending on the number of rooms, unit size, opening area etc. The results of this study would also be impacted by the change in size of the ventilator, inclusion of other interior design variables suchlike higher furniture items, which would act as barrier to air path. The impact of the furniture-sourced indoor pollutants including volatile organic compounds, formaldehyde on the experiential indoor environmental quality was a limitation in this study. This study also focussed on the summer months’ ventilation status, since the environmental heat stress turns critical during summer in tropical climates. However, seasonal variations in natural ventilation, being an integrally crucial factor would need further experimental and observation-based temporal analysis.

This study was limited to steady-state simulations and considered uniform occupant behaviour. However, this can be improved using transient simulations that consider the effect of a time-dependent phenomenon, transient weather conditions and variable wind directions. From the methodological viewpoint, future work includes detail 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 architectural design solutions for sustainable low-income urban habitats in developing countries through the decoupling of health and built environment.

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Table 1 Boundary Conditions for Air Velocity, Temperature Profile, and Solar load model

|  |
| --- |
| **Air Velocity and Temperature Profile** |
| **Computational Domain** | **Boundary Conditions** |
| Door (Pressure outlet) | Gauge pressure = 0; T = 300K; Turbulence intensity = 5% |
| Window (Velocity inlet) | Gauge pressure = 0; T = 300K; Turbulence intensity = 5%, Velocity = 0.989 m/sec |
| Cook-stove Surface (Velocity inlet) | Gauge pressure = 0 ; T = 308.15K (from sensor data); Hydraulic diameter= 0.15 (authors’ computation) ; Turbulence intensity = 5% |
| Wall-room(Wall surface) | Stationary wall; No slip |
| **Solar Load Model** |
| **Computational Domain** | **Boundary Conditions** |
| Global position of test room | 72.8777 0Longitude, 19.0790 oLatitude, GMT= +5.5 |
| Solar properties | Direct solar irradiation =1423 W/sq.m; Diffuse solar irradiation= 200 w/sq.m; Spectral Fraction=0.5 |
| Door (Pressure outlet) | Gauge pressure = 0; T = 300K; Turbulence intensity = 5% |
| Window (Velocity inlet) | Gauge pressure = 0; Outdoor T = 303.15K; Turbulence intensity = 10%, Velocity = 0.989 m/sec |
| Glass window (Semi-transparent wall) | Absorptivity=0.1; Transmissivity= 0.8; Participates in solar ray tracing; Heat transfer coefficient=1.01 |
| Wall-room(Opaque Wall surface) | Stationary wall; No slip; Free stream temperature=300K; External radiative temperature=301.15K; Heat transfer coefficient=0.65;  |
| Under-relaxation factors | 0.3 (pressure)0.7 (momentum)0.8 (energy and density) |

Table 2 Multi-objective optimization constraints

|  |  |
| --- | --- |
| **Design variables** | **Constraints** |
| **Lower limit**  | **Upper limit**  |
| Horizontal location of ventilator (*x1*)(distance measured from left wall) | 0.65m | 4.1m |
| Vertical location of ventilator (*x2*)(distance measured from ceiling) | 0.2m | 0.8m |
| Bed location x-coordinate (*x3*)(distance measured from left wall) | 2.1m | 4.5m |
| Bed location y- coordinate (*x4*) (distance measured from door-wall) | 1m | 2.56m |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **ODL 1** | **ODL 2** | **ODL 3** | **ODL 4** | **ODL 5** | **ODL 6** |
| Design variable (in m) | Air velocity | Air velocity | Air velocity | Stove temp | Stove temp | Solar temp  |
| Stove temp | PM2.5 level | Solar temp | PM2.5 | Solar temp | PM2.5 |
| *x1* | 4.09 | 0.65 | 1.95 | 4.09 | 4.1 | 4.1 |
| *x2* | 0.20 | 0.70 | 0.79 | 0.62 | 0.798 | 0.8 |
| *x3* | 3.93 | 2.10 | 2.1 | 4 | 2.20 | 3.20 |
| *x4* | 2.55 | 1.39 | 1.04 | 1 | 1 | 1 |
|  |

Table 4 Results of CFD simulations of six solution sets (left); Results from TOPSIS ranking (right)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Air Velocity (m/sec)** | **Stove temperature (K)** | **PM2.5% (Kg/cu.m)** | **Solar Temperature (K)** | **TOPSIS Rank** |
| ODL 1 | 0.153 | 301.711 | 9.62 | 302.671 | 0.307 |
| ODL 2 | 0.162 | 302.262 | 5.29 | 302.933 | 0.436 |
| ODL 3 | 0.301 | 302.178 | 0 | 302.754 | 0.682 |
| ODL 4 | 0.057 | 301.891 | 0 | 302.641 | 0.391 |
| ODL 5 | 0.105 | 301.95 | 0 | 302.68 | 0.455 |
| ODL 6 | 0.091 | 301.729 | 0 | 302.514 | 0.433 |

Table 5 Results of CFD predicted values of base case scenario and final optimized solution

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Environmental metrics** | **Base case scenario** | **ODL 3** | **Remark** | Better Indoor Environmental Quality(IEQ) for ODL 3 |
| Air velocity (m/sec) | 0.13 | 0.301 | Positive |
| Stove temperature (K) | 304.50 | 302.17 | Positive |
| Solar temperature (K) | 303.04 | 302.75 | Positive |
| Pollutant concentration % over breathing zone (Kg/cu.m.) | 10.95 | 0 | Positive |