Efficient Indoor Design in Slum Rehabilitation: A Systematic Simulation for Optimized Energy and experiential Indoor Environmental Quality (e-IEQ)

Ahana Sarkar¹, Ronita Bardhan¹

¹Centre for Urban Science and Engineering, Indian Institute of Technology Bombay,
Mumbai, India 400076

Abstract

This study intends to optimise the indoor design layout of a multi-rise low-income tenement unit that would not only improve perceived indoor environmental quality (IEQ) but would also harness maximum cooling energy saving potential. The research framework initiated with household surveys, in-situ environmental sensor deployment and sequential computational modelling involving 'Sampling based parametric modelling' followed by CFD simulations, multi-objective optimisation and numerical analyses. Air velocity, temperature, humidity and pollutant concentrations were modelled for iterated scenarios that were generated by introducing and altering design variables of partition-wall, indoor heat-source and furniture locations. The final design saved cooling energy of 788.4KWhr annually, experienced indoor air velocity of 0.39 m/sec when outdoor velocity at window-inlet was recorded 0.98 m/sec and observed temperature drop of 2°C. Dearth of sustainable design guidelines is a major blind spot in current habitat policies of India. This design framework if implemented through building design guidelines would shape a way forward towards environmentally sustainable habitat design for forthcoming housing stock.

Introduction

In dense tropical cities like Mumbai, extreme temperature and humidity cause thermal stress, which can affect human health with built-environment aggravating the situation. Extreme outdoor climate with urban heat island, pollutant dispersion and thermal discomfort push people indoors. With people spending 90% time indoors, the indoor environment becomes crucial for better health and well-being. However, poor indoor environment not only affect health but also compel the inhabitants to utilise electro-mechanical ventilation for achieving acceptable thermal comfort. Environment-insensitive interior design blocks the airflow trajectory and creates stagnant zones locally. Thus, interior design, albeit a function of individual choice and socio-cultural context, have knock-off effects on indoor environment and energy consumption pattern. Therefore, the phenomenon of investigating into environmentally-efficient interior design parameters becomes exigent particularly for low-income population, who are constrained with social and economic restrains. Well-designed naturally ventilated (nat-vent) space can reduce the electro-mechanical ventilation usage along with improving indoor air quality,

occupant comfort through fresh air renewal within the occupied space (Bardhan, et al., 2018). Passive cooling systems not only reduce world energy requirements by 2.35%, but also incurs 18% savings in health cost (Brager & Baker, 2009). Studies which have elucidated interlinkages between built-environment and nat-vent efficiency have focussed on community level architectural parameters such as housing morphology and building patterns, and envelope level architectural parameters such as window, balcony etc. However, there are inadequate comprehensive work on interior level parameters with aerodynamic potential. At post-construction stage, when environmental quality is experienced by the inhabitants, the criteria becomes difficult to solve. So, in order to deliver thermal comfort to the current low-income population staying in existing housing stock, cost and nat-vent effective retrofitted interior design remains the only degree of freedom. The concept of nat-vent effective and energy efficient interior design holds pivotal position in Indian context particularly Mumbai. Quantitative methods for determining habitat design quality and measuring their efficacy remains a major blind-spot in current habitat policies. The 'pigeon-hole' like tenement units in recently mushrooming hyper dense slum rehabilitated high-rise colonies of Mumbai suffer from inefficient indoor airflow, high temperature trapped zones and pollutant concentration. Mumbai records an average outdoor temperature between 23.7°C-29.7°C with maximum 33.5°C during summer months (Debnath, et al., 2017). In 2017, Mumbai recorded PM_{2.5} levels of 60µg/m³, 10 times higher than World Health organisation (WHO) prescribed levels (Times, 2019). Despite adverse outdoor climate conditions, the low-income population of Mumbai are compelled to utilize natural ventilation due to economic constraints which refrain them from utilizing electromechanical ventilation strategies. This coupled with household air pollution (HAP) degrade IEQ within these low-income tenement units (Sarkar & Bardhan, 2018). In this instance, the aggravated situation can be alleviated by improving interior design which would promote faster heat and pollutant removal through cross ventilation strategies, thus eradicating the problem at receiver end.

The novelty of this study lies in exploring the interior design layout that would ensure improved indoor environment in terms of airflow, temperature, humidity and pollutant concentration levels. This paper also

explores the potential to reduce energy consumed by electro-mechanical ventilation modes by utilising natural ventilation. This study would help the building engineers to promote environmental sustainability measures while designing or rejuvenating low-income habitats.

Methods

The two-step methodology commenced with household survey, in-situ environmental sensors (Testo 480® vanemeter and ibutton temperature sensors) deployment within one typical low-income tenement unit in August 2018 for three days (Fig 1). Similar experiment based studies have been conducted in different low-income settlements of Mumbai, where authors had performed indoor sensor based measurements for consecutive days in order to reduce uncertainties and observe temperature fluctuation (Debnath, et al., 2017). However, this study limited to three days due to constraints regarding permission to install sensors for longer duration in the selected unit. This was because of the unwillingness of the occupants to install sensors (Bardhan et al, 2018). The occupants were unwilling to approve sensor installation in their unit for more than three days.

Figure 1: Methodology adopted in this study

CFD simulations were performed for iterated design layouts to predict indoor air velocity, temperature, humidity and indoor pollutant concentrations in nat-vent conditions. Lastly, with multi-objective optimization, a set of optimal design solutions was generated with maximum IEQ over breathing zone. Then, the indoor air velocity performance of these optimal solutions were further tested with hourly CFD simulations for nat-vent as well as mech-vent (ceiling fan) situations. This was performed to recognise the final optimal design that would deliver maximum hours of comfortable indoor air velocity values over the breathing zone solely through

wind-driven natural ventilation. This particular optimal design solution would thus harness maximum cooling energy saving potential by minimising ceiling fan operation in those hours.

Study area

Lallubhai Compound, a slum rehabilitated colony containing 65 buildings in Mumbai was chosen as study area. The existing tenement units (21.42sq.m) placed serially along common corridor consisted of an attached toilet (2.47sq.m) and undivided cooking-living zone with a window and a door on the opposite side (Fig 2).

Figure 2: Floor plan of Base-case scenario

This study introduced a cook-stove (0.4mx0.4m) placed near the window (observed from survey) as key indoor heat-source and a single-bed (item of furniture) to interpret its most favourable location for feeling improved indoor environment. To identify the effectiveness of the unit's perceived IEQ, a monitoring point at 1.2 m level from ground level (human-height during sitting) at mid-bed position was designated. The aim would be to offer maximum perceived IEQ over this monitoring point, connoted further as 'breathing zone'.

In order to improve indoor liveable conditions, a specific interactive study was performed taking into account combination of three rarely ventured but significant interior design parameters: i) partition wall, ii) furniture (bed) position and iii) cook-stove (indoor heat-source) location. Additionally, a standard size high-level air-outlet (0.3mx0.3m) was introduced on the opposite side of the windows in the hypothetical scenarios, which would ensure effective cross-ventilation even when the door remains closed, thus maintaining similar privacy quotient. The tenement units within 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, limiting cross-ventilation in absence of any pressure outlet. The justification behind adopting the conventional ventilator approach was to enable stack ventilation strategy, which is often established to increase indoor air velocity up to thermal comfort thresholds in nat-vent condition (Essah, et al., 2017; Ismail, et al., 2012). Owing to the economic constraints of the low-income population that refrain them from adopting mechanical ventilation mode, a small size ventilator was found to be a cost-effective solution as well. 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) had demonstrated through wind-tunnel test that the indoor air velocity in a test room rapidly increased when active stack/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. Hence, this study concluded smaller active stack of size 0.3x0.3m to be feasible for volume of space.

Step 1: Random sampling code

Latin Hypercube Sampling (Lhs) code was executed in MATLAB to generate the design scenarios(Das et al., 2014). The mean, standard deviation, lower and upper threshold of the design variables including height of partition wall, its distance from window (inlet), its orientation and gap, along with bed and cook-stove positions were used as input boundaries to generate 40 sample scenarios (Fig 3).

Figure 3: Scenarios with varying design parameters

Step 2: CFD simulations

Indoor airflow analysis

Irregularities in aerodynamic behaviour of wind, obstacles in wind flow path, fluctuations in wind directions are the major challenges that makes it difficult to investigate the natural ventilation conditions numerically. Hence, this study employed a deterministic approach with Finite Volume Method (FVM) including 3D steady-state RANS k-ε turbulence model for simulating airflow of 40 scenarios (Table 1).

Table 1: Boundary conditions (airflow and temperature (due to cook-stove) simulation)

Computational Domain	Boundary Conditions
Door (Pressure outlet)	Gauge pressure = 0; T = 300 K, Hydraulic diameter= 1.26 (authors' computation) ; Turbulence intensity = 5%
Window (Velocity inlet)	Gauge pressure = 0 ; T = 300 K, Hydraulic diameter= 1.09(authors' computation) ; Turbulence intensity = 5%, Velocity (authors' computation)=0.98m/sec
Cook-stove surface	T=308.15K
Wall(wall surface)	Stationary wall; No slip

Fine tetrahedral meshing option with three times mesh-refinement in window (inlet), air-outlet and cook-stove inlet zones were applied for all models. Second order discretisation scheme along with SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was employed for solving velocity and pressure coupling equations. Other than grid-independence tests, the iterations continued until the solutions reached pre-assigned convergence criteria of 10^{-6} RMS.

Indoor temperature analysis (external solar radiation)

Solar Load model coupled with solar calculator was utilised for determining the effect of external solar radiation on indoor temperature profile(Abed, et al., 2018) (Table 2). Under-relaxation factors: 0.3 for pressure, 0.7 for momentum and 0.8 for energy and density; were applied to regulate the deviations of variable values between sequential iterations and evade deviation of the solution results.

Table 2: Boundary conditions (temperature simulation)

Computational Domain	Boundary Conditions
Global position of test room	72.8777 °Long, 19.0790 °Lat, 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 = 5%, 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 W/m²K;

Pollutant Concentration analysis

Euler Lagrange model approach with Discrete Phase Model (DPM) in ANSYS Fluent was employed for simulating the indoor pollution concentration models for the scenarios. In this model, air is considered as the continuum phase which executes the solution for Navier-Stokes equations; while discrete phase is solved by the pollutant particles (Ma, Jiang, & Li, 2015). The 3D steady state solutions were iterated until the pollutants reached the final destination. The interchange between mass, momentum and energy conservation were examined here. Walls used trap type boundary conditions because of their pollutant trapping capability, while escape type boundary condition was provided to the cook-stove and window inlet.

Humidity analysis

ANSYS was utilised to compute the RANS-Navier Stokes equation over each discrete flow field using FVM. Species Transport coupled with Discrete Phase model in

FLUENT solver was utilised. The models used droplet-type spray particles with diameter of 10^{-6} m, inlet velocity of 0.0254m/sec and case-specific computed mass flow rate of 1.26kg/sec as boundary condition variables.

Step 3: Multi-objective optimisation

It becomes challenging to derive a single design layout, which would deliver perceived IEQ in terms of all the environmental attributes. Hence, indoor environmental condition was derived utilising multi-objective optimisation algorithm of NSGA II, a fast and elitist method for handling multi-objective situations (Deb et al., 2002). The process formulated a set of conflicting objective functions like maximising indoor air velocity, and minimising indoor temperature (due to cook-stove and external solar radiation), pollutant concentration, and humidity (H_2O mass fraction) levels (Eq 1).

Maximize/Minimize

$$\begin{aligned} & \text{Indoor air velocity, temperature,} \\ & \text{pollutant level, relative humidity} = \\ & f\{(a_1x_1) + (a_2x_2) + \dots + (a_nx_n)\} + b \end{aligned} \quad (1)$$

Where

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

The objective functions used design constraints as seen in Table 3.

Table 3: Constraints for multi-objective optimisation

Description of variables	Constraints of the variables	
	Lower range	Upper range
Distance of partition wall from window (x_1)	0.9m	1.3m
Height of partition wall (x_2)	1.5m	2.9m
Partition-wall orientation (x_3)	0.8m	1.29m
Cook-stove position (x_4) measured from right wall (Fig 3)	0.3m	2.44m
Bed position (x_5) measured from right wall (Fig 3)	2.5m	4.5m

This step evaluated the optimal design solutions for obtaining maximum perceived IEQ over the breathing zone.

Step 4: Cooling energy saving potential calculation of optimised solution

The notion of ‘natural ventilation hours’ was employed here to compute the cooling energy saving potential of the optimal solutions derived from NSGA II. Taking sensor based recorded hourly wind flow data, air velocity was simulated for the NSGA II generated optimal design solutions using CFD both for nat-vent and mech-vent (ceiling fan) situations. The aim was to identify the optimal design with maximum natural ventilation hours i.e. the number of hours a unit would not require the aid of a ceiling fan for achieving comfort conditions. The

design solution with highest number of potential ‘natural ventilation hours’ would advertently minimise the consumption of mechanical ventilation, thus maximising cooling energy potential.

Results

Indoor airflow analysis

The CFD predicted indoor air velocity over the breathing zone for all scenarios was found within 0.05m/sec to 0.648m/sec when outdoor air velocity at window-inlet was recorded 0.98m/sec. This explains that by monitoring interior design parameters like partition wall, cook-stove and furniture position, it is possible to maintain comfortable indoor air velocity levels in nat-vent spaces. A-(i) and (iii) of Fig 4 experienced a variable indoor air velocity of 0.19 m/sec and 0.07 m/sec respectively over the breathing zone. This explains that change in partition wall orientation, while keeping other design variables like partition wall height, gap, its distance from window, and cook-stove and furniture location constant, can significantly modify indoor air velocity. Partition wall, as a direct barrier obstructed the airflow in A-(i). However, change in cook-stove position was found to be a lesser dominant design variable for modifying indoor airflow. On other hand, Fig 4 (B) shows variable velocity values of 0.05 m/sec, 0.21m/sec, 0.10m/sec and 0.24 m/sec for scenarios (i), (ii), (iii) and (iv) respectively indicating the significance of bed location.

Figure 4: Indoor air velocity profile of different iterated interior design scenarios

From all tested scenarios, partition wall height, its orientation and bed location were found to be dominant design variables with aerodynamic potential.

Indoor temperature analysis

The average LPG stove surface temperature was recorded 35°C (from field measurement) in cooking condition while the ambient temperature of the room was considered (27°C). The indoor temperature distribution fields were found relatively uniform over the breathing area with no considerable fluctuations in the CFD predicted temperature values. Fig 5 showcases that the partition wall segregated the room into two distinct thermally stratified zones i.e. cooking area with higher temperature (30.85°C) and living area with relatively lower temperature (28.85°C). Fig 5 (A-i and ii; A-iii and iv) explains that the CFD predicted temperature values

over the breathing zone changed with varying cook-stove position keeping all other design variables constant. The scenarios A-(i) and (iii), with two different partition wall designs while keeping all other design variables constant experienced minute but different temperatures over the breathing zone i.e. (28.41°C) for A-(i) and (28.68°C) for A-(iii)). On contrary, Fig 5 (B), shows varying experienced indoor temperature values with change in bed position. The temperature recorded for case B-(i): 28.15°C, (ii): 29.25°C, (iii): 28.4°C and (iv): 28.45°C. Partition wall height and orientation affected indoor temperature maximum. The indoor temperature over breathing zone decreased with increase in partition wall height, as partition wall acted as a barrier formation to the convective heat transfer.

Figure 5: Indoor air temperature profile of different iterated interior design scenarios

This study observed similar results for indoor temperature distribution due to external solar radiation. The temperature ranged from 29.44°C to 29.79°C for constant furniture location indicating the importance of partition-wall.

Indoor pollutant concentration analysis

This study examined the pollution owing to combined effect of ambient traffic exposure and indoor cooking. The ‘total percentage of area of bed which was found exposed to pollutant concentration’ was used as surrogate variable for measuring pollutant concentration. For ‘Scenario 10’, in Fig 6A, with a partition wall directly obstructing the window-inlet, high pollutant was observed concentrated in the cooking zone. While in ‘Scenario 9’, the pollutant concentration was distributed in the living area. Thus, partition wall orientation and design was dominant on indoor pollutant concentration profiles. It can be observed from ‘Scenario 6’ that, since the pollutant flow followed a similar profile, with alteration in bed position the $PM_{2.5}$ concentration varied from 6.54% to 11.05%. The $PM_{2.5}$ amount varied from 34.9% for ‘Scenario 1’ to 58.68% for ‘Scenario 3’, 45.46% for ‘Scenario 7’, and 28.68% for ‘Scenario 8’, which concludes that different partition wall designs affect indoor pollutant concentration levels keeping bed and cook-stove position constant. Furthermore, $PM_{2.5}$ concentration was higher near the ceiling and the right and south walls (Fig 3) due to the trap type boundary conditions of the walls. High kinetic energy imparted to

the jet plume of $PM_{2.5}$ entering at the window-level can contribute to the higher pollutant concentration on the wall opposite to inlet (Fig 6B).

Figure 6: Indoor pollutant concentration profile of different iterated interior design scenarios

Indoor humidity analysis

Fig 7 explains that H_2O mass fraction which has been considered as a proxy variable for measuring indoor humidity levels vary significantly with change in partition wall design, cook-stove and bed position.

Figure 7: Indoor H_2O mass fraction profile of different iterated interior design scenarios

H_2O mass fraction was concentrated in the cooking zone for ‘Scenario 10’ in Fig 7 due to the partition wall which acted as a direct barrier to the moisture flow from window-inlet. On contrary, higher concentration of H_2O mass fraction was observed in the living zone in ‘Scenario 9’ owing to the partition wall orientation which did not create diversion in the water droplet flow. As the bed shifted towards the wall in ‘Scenario 6’, the H_2O mass

fraction was observed to increase from 0.00800267 (weight/weight) in (b) to 0.00805516 (w/w) in (a). This was majorly due to the proximity of air-outlet (ventilator) with respect to bed location. However, design variables such as partition wall height and its distance from the window-inlet were found to be less dominant.

Most optimal design solution

The CFD predicted outcomes of indoor air velocity, temperature, pollutant levels and relative humidity for 40 scenarios were assumed as function of design variables to formulate the objective functions using linear regression analysis (Eq. 2-6). These objective functions with design constraints were applied in NSGA II algorithm to generate Pareto font solutions (see Fig 8).

$$y (\text{Air velocity}) = (-0.18 * x_1) + (0.09 * x_2) + (-0.05 * x_3) + (0.03 * x_4) + (-0.03 * x_5) + 0.40 \quad (2)$$

$$y (\text{Stove temp}) = (0.05 * x_1) - (0.22 * x_2) + (-0.09 * x_3) + (0.01 * x_4) + (-0.16 * x_5) + 302.69 \quad (3)$$

$$y (PM_{2.5} \text{ conc}) = (-15.62 * x_1) + (2.61 * x_2) + (3.25 * x_3) + (1.19 * x_4) - (8.78 * x_5) + 56.80 \quad (4)$$

$$y (\text{Solar temp}) = (-0.18 * x_1) - (0.12 * x_2) + (0.07 * x_3) + (0.01 * x_4) + (0.005 * x_5) + 303.18 \quad (5)$$

$$y (H_2O \text{ mass}) = (-8.2e - 05 * x_1) + (2.77e - 05 * x_2) - (9.7e - 05 * x_3) + (2.23e - 05 * x_4) + (1.46e - 05 * x_5) + 0.008 \quad (6)$$

Bold values significant at 95% C.I.

Figure 8: Pareto Font solutions derived from NSGA II

However, Pareto-dominance based optimization algorithms perform well on only two objective functions. The many objective optimisation problem weakens the dominance of one on another. Thus, if the populations turn out to be non-dominated, Pareto dominance based fitness evaluation schemes fail to generate any pressure towards the formation of a strong Pareto-Front (Ishibuchi, Tsukamoto, & Nojima, 2008). In this context, 10 sets of Pareto Font solutions were generated by taking a combination of two objective functions at a time. These 10 optimal design solutions derived from NSGA II could be considered as most optimal design solutions with maximum perceived IEQ (see Fig 8).

Cooling energy saving potential calculation

Stochastic nature of the wind with fluctuating wind velocity and direction increases the uncertainty of natural ventilation potential. In this context, hourly averaged wind velocity data was retrieved for consecutive eight hours of a day by installing a vane meter, which delivered an impression of the uncertainty of natural ventilation. The average hourly outdoor wind velocities at the window inlet was recorded 0.47 m/sec, 0.52 m/sec, 0.52 m/sec, 0.31 m/sec, 0.23 m/sec, 0.61m/sec, 0.21 m/sec and 0.98 m/sec respectively from 11:52pm to 7:53pm. The NSGA II derived 10 optimised scenarios were simulated for the eight hours to retrieve the indoor wind velocity values over the breathing zone in nat-vent condition (Fig 9A).

Figure 9: Indoor air velocity of optimal solutions at (A) nat-vent condition (eighth hour) and (B) ceiling fan

In order to determine the optimised solution with highest cooling energy saving potential and natural ventilation efficiency, the indoor air velocity profile of optimised 10 scenarios were simulated in presence of mechanical ventilation (active cooling) source i.e. ceiling fan (Fig 9B). Here, the hypothesis was - 'the design solution which would deliver maximum hours of comfortable indoor air velocity i.e. within the range of 0.2-1.5m/sec, would be the solution with highest cooling energy saving potential

(Khedari, et al, 2000).’ This explains that the total number of hours a design solution would deliver comfortable indoor air velocity values in nat-vent condition, ceiling fan would not be operated which would indirectly trim down additional electricity cost.

Fig 10 elucidates that Optimised solution 4, 5 and 6 failed to deliver comfortable indoor air velocity over the breathing zone with sole natural ventilation strategies and hence would require the assistance of a ceiling fan throughout.

Figure 10: Comparison between nat-vent and mech-vent simulated results (top) of optimal solutions and their cooling energy saving potential (down)

Out of eight hours, optimised solutions 3, 7 and 9 delivered comfortable indoor air speed over breathing zone for five hours, which increased their cooling energy saving potential to 600watt/8hour. ‘Optimised solution 1’ was found to be the most desirable solution with maximum natural ventilation efficiency since the breathing zone in this design solution experienced comfortable nat-vent efficient indoor air velocity for six out of eight hours. Thus, the cooling energy saving potential for ‘Optimised solution 1’ was 720 Watt/8 hours or 2.16 KW/day or 788.4 KW annually. The design variables of the ‘Optimised solution 1’ were $x_1=0.96\text{m}$, $x_2=2.8\text{m}$, $x_3=0.8\text{m}$, $x_4=1.84\text{m}$ and $x_5=2.5\text{m}$ (refer Table 3).

Model validation

Figure 11: Model validation (simulated vs measured)

The simulated base-case scenario was validated using sensor recorded measured data (Fig 11). The percentage error, MBE and CV(RMSE) (formulas adopted from

(Bardhan, et al., 2018)) values of 3.3%, 4.5% and 11.99%, were found within well-accepted range (Shailza, 2018).

Discussion

This study adopted a stepwise ‘sampling- computational simulation- optimisation-numerical analyses’ based framework. IEQ was represented as the environmental sustainability indicator with indoor air velocity, temperature (due to indoor heat-source and outdoor radiation), indoor pollutant concentration (due to indoor fuel combustion and outdoor traffic) and humidity levels as key proxy variables. The transverse methodological approach initiated with generation of hypothetical iterated interior layouts with varying design parameters like partition wall, cook-stove and bed position. K- ϵ turbulence model for air velocity, energy model for air temperature (due to cook-stove), solar load model for air temperature (due to external solar radiation), Lagrangian DPM for pollutant concentration and species transport model for indoor H_2O mass fraction were applied for executing the steady-state CFD simulations for all iterated scenarios.

The unliveable conditions of existing tenement units with undivided cooking-living zone had degraded the IEQ. The results of the study suggested that introduction of partition wall with proper design variables like its height, orientation and distance from window-inlet provided relatively cooler zone in the living area. Pollutant levels were concentrated near the cooking zone and on the walls, and that proper furniture location could reduce the high $\text{PM}_{2.5}$ levels exposure over the breathing zone. Afterwards, multi-objective optimisation method of NSGA II was applied to derive ten Pareto-front based optimal solutions, which would deliver better IEQ over breathing zone. Lastly, a comparison analysis was performed for the ten optimal solutions in relation to their indoor airflow performance for nat-vent and mech-vent (adding a ceiling fan) situations. Lastly, ‘Optimised solution 1’ not only harnessed improved perceived IEQ over breathing zone but also had highest cooling energy saving potential by offering maximum number of potential nat-vent hours.

Conclusion

The data-driven methodology followed here formulated a computational modelling based ‘design flow’ along with a ‘proof of concept’ for establishing the influence interior design parameters have on environmental attributes and energy-efficiency in low-income tenement units. Suitable partition wall placement with respect to appropriate cook-stove and furniture position can improve perceived IEQ as well as energy consumption pattern. Thus, this research targets in presenting an unconventional means to improve the perceived IEQ and energy-efficiency through a better interior design solution (which can be applied even at post-design stage) evading excessive expenditures. This ‘sampling-simulation-optimisation-numerical analysis’ based design-flow is applicable as a generalized tool to all tropically located building design cases (both new and retrofitting cases), provided it depends solely on natural ventilation or ceiling fan. The selection of interior design

parameters, design variable constraints, boundary conditions for simulations will be context-specific and will also depend on ambient climate and country-specific building design code. Higher number of scenarios can also be generated for improved accuracy and precision.

Limitations and Future Work

Indoor air velocity, temperature, pollutant concentration, and relative humidity were selected as major surrogate measures of IEQ. Building orientation, occupant details, material of construction and other pollutants will be considered in future work. Further research would also consider monthly and annual outdoor wind velocity variation while calculating energy saving potential. The study limited to steady-state CFD simulations which do not consider transient weather conditions. The validation for optimised case will be performed in future study. The results from this study can pave a pathway to the formulation of environment-sensitive and energy-efficient habitat design solutions for low-income settlements in developing countries through decoupling of energy, health and built environment.

Acknowledgement

The material presented in this study is based in part on the work supported by the Ministry of Human Resource Development (MHRD), the Government of India (GoI) project titled CoE-FAST, Grant No. 14MHRD005.

References

- Abed, F. M., Ahmed, O. K., & Ahmed, A. E. (2018). Effect of climate and design parameters on the temperature distribution of a room. *Journal of Building Engineering*, 17(February), 115–124. <https://doi.org/10.1016/j.jobbe.2018.02.007>
- Bardhan, R., Debnath, R., Jana, A., & Norford, L. K. (2018). Investigating the association of healthcare-seeking behavior with the freshness of indoor spaces in low-income tenement housing in Mumbai. *Habitat International*, 71(September 2017), 156–168. <https://doi.org/10.1016/j.habitatint.2017.12.007>
- Bardhan, R., Debnath, R., Malik, J., & Sarkar, A. (2018). Low-income housing layouts under socio-architectural complexities: A parametric study for sustainable slum rehabilitation. *Sustainable Cities and Society*, 41(April), 126–138. <https://doi.org/10.1016/j.scs.2018.04.038>
- Brager, G., & Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. *Building Research and Information*, 37(4), 369–380. <https://doi.org/10.1080/09613210902899785>
- Das, P., Shrubsole, C., Jones, B., Hamilton, I., Chalabi, Z., Davies, M., ... Taylor, J. (2014). Using probabilistic sampling-based sensitivity analyses for indoor air quality modelling. *Building and Environment*, 78, 171–182. <https://doi.org/10.1016/j.buildenv.2014.04.017>
- Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2), 182–197. <https://doi.org/10.1109/4235.996017>
- Debnath, R., Bardhan, R., & Jain, R. K. (2017). A data-driven and simulation approach for understanding thermal performance of slum redevelopment in Mumbai, India. *Proceeding of the 15th IBPSA Conference*, 2745–2752.
- Essah, E. A., Yao, R., & Short, A. (2017). Assessing stack ventilation strategies in the continental climate of Beijing using CFD simulations. *International Journal of Ventilation*, 16(1), 61–80. <https://doi.org/10.1080/14733315.2016.1203609>
- IS 4021. (1995). Indian Standard, Timber Door, Window and Ventilator Frames-Specification.
- Ishibuchi, H., Tsukamoto, N., & Nojima, Y. (2008). Evolutionary many-objective optimization: A short review. *2008 IEEE Congress on Evolutionary Computation, CEC 2008*, 2419–2426. <https://doi.org/10.1109/CEC.2008.4631121>
- Ismail, M., Malek, A., & Rahman, A. (2012). Stack Ventilation Strategies in Architectural Context: a Brief Review of Historical Development, current trends and future possibilities. *International Journal of Research and Reviews in Applied Sciences*, 11(May), 291–301. Retrieved from http://www.arpapress.com/Volumes/Vol11Issue2/IJR_RAS_11_2_14.pdf
- Khedari, J., Yamtraipat, N., Pratintong, N., & Hirunlabh, J. (2000). Thailand ventilation comfort chart. *Energy and Buildings*, 32(3), 245–249. [https://doi.org/10.1016/S0378-7788\(00\)00050-5](https://doi.org/10.1016/S0378-7788(00)00050-5)
- Ma, Y., Jiang, Y., & Li, L. (2015). Numerical Simulation of PM2.5 Distribution in Indoor Air. *Procedia Engineering*, 121, 1939–1947. <https://doi.org/10.1016/j.proeng.2015.09.183>
- Priyadarsini, R., Cheong, K. W., & Wong, N. H. (2004). Enhancement of natural ventilation in high-rise residential buildings using stack system. *Energy and Buildings*, 36(1), 61–71. [https://doi.org/10.1016/S0378-7788\(03\)00076-8](https://doi.org/10.1016/S0378-7788(03)00076-8)
- Sarkar, A., & Bardhan, R. (2018). Optimizing Interior Layout for Effective Experiential Indoor Environmental Quality in Low-income Tenement Unit: A Case of Mumbai, India. *Building Simulation & Optimization Conference*, (September), 11–12.
- Shailza. (2018). Energy Modeling of multi-storied residential buildings- a manual calibration approach (pp. 550–557).
- Times, H. (2019). PM2.5 in Mumbai in 2017 was six times the safe limit: SAFAR study, pp. 2–8.