Optimizing Thermal Comfort in Low-Income Dwellings: A Pinch Analysis Approach

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Abstract

This study aims at optimizing thermal comfort through adaptive actions and building strategies in low-income group (LIG) housing. The perception of thermal comfort constrained by socio-economic and socio-cultural regimes is considered in this work. A mixed mode research methodology comprising of field survey, hybrid expert choice system, simulation approach and pinch analysis optimization technique has been adopted. The study suggests implementation of a set of five interventions based on their Degree of Effectiveness (DE) subject to pre-defined constraints for increasing thermal comfort in LIG housings. The novelty of this work is bifold. Firstly, this study focuses on thermal comfort in existing LIG dwellings which remains under researched. Secondly, pinch analysis technique that was initially developed to improve energy efficiency in industrial processes, has been extended in this study as *Energy Target Pinch Analysis (ETPA)* for application in building energy sector.

Introduction

Building and construction sector presents a major opportunity to tackle global warming and improve the quality of life and wellbeing of the occupants. According to United Nations Environment Program (UNEP), this sector offers the largest cost-effective GHG mitigation potential (Dean, Dulac, Petrichenko, and Graham, 2016) which could help in achieving the goal of limiting the global temperature rise to 2º C (IPCC 2014). However, rapid urbanization in developing countries has led to a pressure on the building sector. This would further increase as the majority of the future population growth is yet to happen in urban areas of such countries (UN-Habitat 2012). In case of India, the urban population is increasing rapidly with an addition of 121 million between 1997 to 2007 (Un-Habitat 2011) and is expected to rise by 404 million till 2050 (UNDESA 2014). The access to adequate housing has therefore become a challenge for the low-income population[1]. Due to lack of affordable and well located housing options, these low-income households are forced to live in slums and informal settlements (Un-Habitat 2011) or slum like housings called as *chawls* in Mumbai (Bardhan, Sarkar, Jana, and Velaga, 2015). *Chawl* structures resemble the tenement blocks of Victorian Glasgow, UK (Gordon Wilson, Pam Furniss 2009).

Low-income group (LIG) dwellings are often characterized as thermally uncomfortable with poor indoor environment due to lack of ventilation and daylight. The energy consumption of these dwellings is constrained by economic, social and cultural practices. However; the low income does not necessarily imply low energy consumption (Dong, Li, and McFadden, 2015). Studies have suggested that LIG dwellings may be energy intensive owing to lack of energy awareness among the occupants, use of low cost energy intensive equipments or excessive use of cooling or heating equipments due to thermally uncomfortable environment (Dong et al., 2015; Phatakare and Dalvi, 2017). Occupant behaviour plays an important role in energy consumption of such housing as they adopt adaptive actions such as opening or closing of windows and door, use of curtains, roof wetting to ensure thermal comfort. Adaptive actions can result in unintended consequences whereby choosing one action may influence the other. For example, opening of windows for better air circulation may increase the ambient temperature. This study aims at optimizing thermal comfort by taking into account the adaptive behaviour and thermal preferences of the low-income households. The study is limited to adaptive actions and retrofit techniques in LIG dwellings.

The specific objectives of this study are:

i. To understand how inhabitants of low-income group (LIG) dwellings perceive thermal comfort and identify interventions commonly adopted by them for improving thermal comfort.
ii. To explore the economic and socio-cultural constraints of these LIG households in achieving thermal comfort.
iii. To provide most suitable combination of interventions for thermal comfort using a novel optimization technique.

While most of research emphasize on thermal comfort in low-income dwellings, seldom the perception of thermal comfort constrained by socio-economic and socio-cultural regimes has been studied. The combined effect of fuel-poverty (Bradshaw and Hutton, 1983) and thermal

[1] Low-income groups (LIG) are defined as the households having an annual household income between INR three lakh to six lakhs (Ministry of Housing and Urban Poverty Alleviation Government of India, 2015).

comfort preferences especially in developing countries like India remains unexplored in literature. This study endeavours to bridge this gap by providing an optimal set of interventions to achieve occupant comfort.

Study area

The case study area is an existing low-income group (LIG) tenement housing, commonly known as *chawls* located in Mumbai, India. The Census of India defines *chawl* as a building with a number of tenements, generally single roomed, having a common corridor and common bathing and toilet facilities (Bardhan, Debnath, Jana, and Norford, 2018; Bardhan et al., 2015; Sukumar, 2001). One such *chawl* consisting of 84 single room units having an area of 19 m^2 per unit is considered as a baseline candidate for assessment. The case study building block consists of four stories having 21 units on each floor as illustrated in Figure 1.

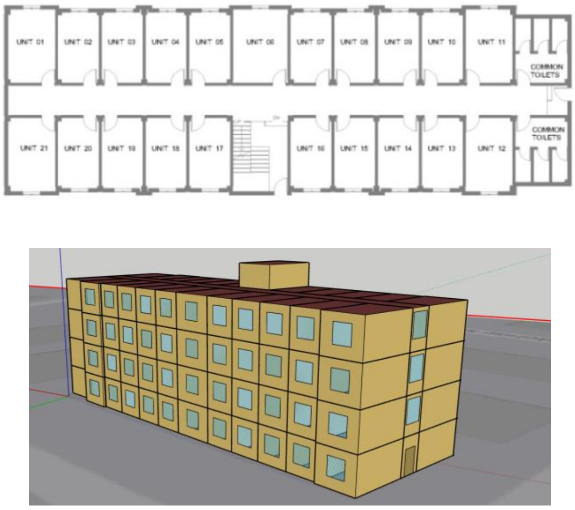

Figure 1: Typical Floor Plan and 3D Model of chawl building

Methodology

A mixed mode research methodology is adopted in this study to optimize thermal comfort in low-income group (LIG) dwellings. The first step consists of a transverse field survey in LIG dwellings to identify thermal preferences and adaptive actions of the occupants. Based on the survey findings, the most commonly adopted interventions (i.e. adaptive actions and retrofit techniques) are determined using a hybrid expert system. The determined sets of interventions are then simulated against the base case to understand their sensitivity to thermal comfort. A novel optimization approach using systematic pinch analysis technique is forwarded here subjected to economic, social and cultural constraints.

Field survey

A paper based survey and field measurements were conducted in two low-income housings in Mumbai. 65 households were surveyed in the month of February, 2018 out of which 43 survey forms were found valid. The survey consisted of questions related to the subjects' thermal preferences, adaptive actions and strategies for maintaining thermal comfort. The households chosen for survey were randomly stratified based on their floor location and orientation. Indoor and outdoor temperatures were measured using Testo 174 temperature sensor with built-in data loggers (Testo AG and Germany, 2017) to identify thermal neutral temperature of the subjects. Figure 2 depicts visual illustration of the LIG housings surveyed for the study.

Figure 2: Respondents from the field survey

Hybrid expert choice system

A hybrid expert choice system was adopted to identify suitable interventions for achieving thermal comfort in LIG households and to identify parameters contributing to the acceptability of those interventions. The first technique involved Delphi method, which is a systematic, iterative process to elicit a consensus view from a panel of experts (MacCarthy and Atthirawong 2003). The input for Delphi was based on the responses collected from the field survey. The first round of Delphi involved shortlisting of ten suitable interventions while the second round of Delphi was performed to select the parameters contributing to their acceptability. Analytic hierarchy process (AHP) was then applied to assign weightages to the identified acceptability parameters. AHP is a well-established multi-criteria decision making method created by Saaty (Saaty 1987) has been widely used for decision-making processes (Bardhan, 2013; Parekh, Yadav, Yadav, and Shah, 2015).

Modelling approach

A basecase *EnergyPlus* model of an existing chawl was created using OpenStudio2.4.1 SketchUp plug-in. OpenStudio, developed by the National Renewable Energy Laboratory (NREL) converts the 3-D model to an input file for *EnergyPlus* simulation. It also allows editing of construction materials, internal load and operation schedules on building models (OpenStudio 2015). *EnergyPlus* is a well-established simulation engine for analyzing building energy consumption (Us Department Of Energy 2010) and is often the preferred due to its accuracy and short running time (J. Cole, T. Hale, and F. Edgar, 2013). EnergyPlusv8.8 was used to carry out simulations for this study.

The simulated weather data file used for the model was imported from ISHRAE for the city of Mumbai. Mumbai has a hot and humid climate with an average precipitation of 242.2 cm and mean annual temperature of 27.2 ºC (Ministry of Earth Science 2018). Each room unit was modelled as a separate thermal zone having an average occupancy of five individuals. Separate occupancy schedules for weekdays and weekends were considered. Occupant's presence, use of artificial lighting, television, refrigerator, mobile charger, cookstove, ceiling fans and exhaust fans contributed to the internal heat gains for each zone. An LPG cook stove was considered for cooking activities operational for four hours per day (Nix, Das, Jain, and Davies, 2015). The building consisted of standard 250 mm brick wall construction with plastered walls, 100 mm reinforced cement concrete roofs and concrete floors. Building material properties were incorporated from the 'Assembly U-factor Calculator Tool' available at www.carbse.org/resource/tools for Indian cities (CARBSE 2018). The floor-to-floor height of the buildings was considered as 3000 mm. The fuel-poor occupants of *chawls* rely either on wind-driven natural ventilation through windows and doors or on mechanical ventilation in form of ceiling fans and exhaust fans. For the base case scenario, wind-driven natural ventilation was considered where the occupants for adaptive thermal comfort adopt window opening or closing behavior.

The interventions selected by the expert hybrid system were modelled as individual strategy, Si (i= 1, 2,… N) . Annual simulations were performed for the base case and the selected straegies to obtain Predicted Mean Vote (PMV) based on Fanger's Thermal Comfort Model. Since Fanger's thermal comfort model is applicable for air-conditioned buildings, an adjusted PMV, aPMV was calculated for naturally ventilated buildings with an expectancy factor, e of 0.8 (Fanger and Toftum, 2002). The aPMV values lying within the acceptable range of -0.5 to +0.5 were considered as comfortable (Standard-55 2017). The annual comfort hours for each of the strategy was calculated based on acceptable aPMV values.

Optimization approach

In this study, a new application of pinch analysis termed as *Energy Target Pinch Analysis (ETPA)* is developed to optimize thermal comfort in low-income housings constrained by their socio-economic-cultural regimes. The objective is to prioritize and select an optimal set of interventions for increasing thermal comfort in such dwellings via graphical pinch analysis diagram. Pinch technology, initially developed in 1970s for optimizing process heat integration, was based on the principles of thermodynamics (Linnhoff and Hindmarsh, 1983). This approach has been extended in literature to other domains such as supply chain management (Singhvi and Shenoy, 2002), human resource management (Foo, Hallale, and Tan, 2010), and financial management (Roychaudhuri, Kazantzi, Foo, Tan, and Bandyopadhyay, 2017). The novel approach developed in this study is based on the targeting methods of material resource pinch diagram adopted by Tan, Aziz, Ng, Foo, and Lam (2016) for industrial decision making and Parand, Yao, Tadé, and Pareek (2013) for water conservation policies.

Each intervention provides a certain level of comfort and is associated with a certain level of acceptability. There may be interventions providing high level of comfort but are not practiced by the fuel-poor residents due to their low acceptability and vice versa. Thus, for selecting the most suitable interventions it is important to maximize comfort and acceptability simultaneously. The optimization problem statement may be given as:

- A set of *N* interventions is identified for increasing thermal comfort in low-income dwellings. Each intervention may consist of an adaptive action or a retrofit technique. It is assumed that each intervention is neither mutually exclusive nor partially applicable.
- Each intervention provides a certain level of comfort translated in terms of comfort value, CV_i (i = 1, 2,… N). Comfort values are assumed to be cumulative. Comfort value, CV is the number of annual comfortable hours achieved by each of the intervention with respect to the base case intervention.

$$\text{Comfort Value, } CV_i = C_i - C_{bc} \qquad (1)$$

i= intervention index
C_i= Comfort hours provided by i[th] intervention
C_{bc}=Comfort hours provided by base case intervention

- Each intervention is associated with a certain level of acceptability translated in terms of acceptability index, AI_i (i = 1, 2,… N). The acceptability is based on the socio-cultural-economic constraints of fuel-poor residents and is affected by the factors identified by expert choice system.

$$\text{Acceptability Index, } AIi = \sum WjPi \qquad (2)$$

j= parameter index contributing to acceptability
Wj= relative weightage of each of the contributing parameter
i= intervention index
P=value of j[th] parameter for i[th] intervention

- A limiting curve is identified which represents the users' "willingness-to-accept" each intervention. This curve serves as a minimum requirement for trade-off between the comfort and acceptability for selecting the interventions.
- *Degree of Effectiveness (DE)* is considered as a quality indicator here (analogous to temperature in Heat Pinch analysis) and is represented by the comfort value per unit of acceptability.

$$\text{Degree of Effectiveness, } DE = \frac{CI}{AI} \qquad (3)$$

- The objective is to determine an optimal set of interventions via systematic pinch analysis by maximizing *Degree of Effectiveness (DE).*

The methodology for generating pinch diagram was adapted from Tan, Aziz, Ng, Foo, and Lam (2016). The first step consists of calculating comfort value and acceptability index based on simulation results and expert judgment. The next step consists of generating source composite curve by connecting all interventions in ascending order of their DE. The sink composite curve is plotted based on the users' "willingness-to-accept" each intervention. The next step involves superimposing the composite curves to identify the pinch point for selection of optimal set of interventions. The part or whole of source composite curves should lie to the right and below the sink composite curve for a feasible pinch diagram. In case of an infeasible pinch diagram, the source composite curve is shifted to the right by adding extra resources.

Results and discussion

Selection of interventions

The priority ranking and expert judgment, resulted in ten strategies, Si (i=1, 2,…10) consisting of five adaptive actions and five retrofit technique as explained in Table 1.

Table 1: Strategies identified by hybrid expert system

Strategy, Si	Intervention incorporated
S1	Opening or closing of doors
S2	Use of window curtains
S3	Use of Planters near windows
S4	Switching on/off ceiling fans
S5	Switching on/off Exhaust fans
S6	Sun control film on windows
S7	Reflective floor tiles
S8	Reflective paint on external walls
S9	EPS wall insulation
S10	Reflective roof tiles

Comfort values

Annual comfort hours for base case simulation were found to be 1008 hours. Annual comfort hours for the selected interventions were in range of 1034 hours (S6) to 1112 hours (S8). The comfort values were calculated according to equation (1), from the annual comfort hours values are shown in Table 2.

Table 2: Comfort Values for Modelled strategies

Strategy, Si	Annual Comfort hours	Comfort value (in hrs)
S0	1008	0
S1	1069	61
S2	1044	79
S3	1087	82
S4	1090	26
S5	1072	64
S6	1034	36
S7	1087	79
S8	1112	104
S9	1052	44
S10	1052	44

Acceptability index

Based on the results of the expert choice system, four important parameters affecting the acceptability of interventions were identified which are explained below:

a. Affordability (P_1): Due to economic constraints, low-income group (LIG) households often select an intervention based on its cost. Higher the cost of an intervention lesser would be its affordability and hence lesser would be its acceptability. The cost of each intervention is calculated from Detailed Schedule of Rates, Government of Maharashtra (Government of Maharashtra 2017) and is explained in Appendix A. The calculated cost is translated into affordability through an inverse function.

b. Socio-cultural consideration (P_2): Socio cultural regimes often dictate the acceptance or rejection of interventions in LIG households. For example, opening of doors may affect privacy and hence some occupants may refrain from adopting it. Higher the socio-cultural consideration for an intervention, higher would be its acceptability. Values of socio-cultural consideration are obtained from the field survey (see Appendix B).

c. Ease of transition to technology (P_3): Due to lack of awareness and understanding, LIG households often hesitate in adopting new technological interventions. Easier the transition to technology of an intervention, higher would be its acceptability. Values of Ease of transition to technology are obtained from the field survey (see Appendix B).

d. Energy load (P_4): Since energy consumption is associated with an operational cost, some of the fuel-poor households avoid using energy intensive interventions. Lower the energy consumption of an intervention, higher would be its acceptability. Energy consumption is translated into energy load through an inverse function.

Appendix B gives the values of acceptability parameter (P_i) for all the interventions. All the acceptability parameters are normalized to obtain values ranging from 0 to 1. Weightages (W_j) for relative importance of the acceptability parameters were obtained by applying Analytical Hierarchical Process (AHP) having an inconsistency ratio of 0.08 which is within the acceptable range (Saaty 1987) (see Table 3).

Table 3: Weightages assigned to acceptability parameters using AHP

Parameter Index	Acceptability Parameter	Weightages, W_j
P_1	Affordability	0.39
P_2	Socio-cultural consideration	0.13
P_3	Ease of transition to technology	0.12
P_4	Energy load	0.36

Acceptability Indices (AI_i) for all the cases were calculated according to equation (2) and normalised to obtain values ranging from 0 to 1 (See Appendix B). The values of AI_i are presented in Table 4. Base case strategy, S0 has the highest acceptability Index as opening or closing of window is most commonly adopted intervention across the LIG households.

Table 4: Acceptability Index for each strategy

Strategy, Si	Acceptability Index (AI_i)
S0	1.00
S1	0.99
S2	0.62
S3	0.99
S4	0.81
S5	0.66
S6	0.72
S7	0.52
S8	0.69
S9	0.37
S10	0.59

Selection of optimal interventions for increasing thermal comfort

Based on the data of Comfort Value and Acceptability Index, it is possible to generate a source composite curve where slope for each strategy, Si would represent its Degree of Effectiveness (DE). A sink composite curve is generated by plotting comfort values (CV_i) obtained from the simulated results and acceptability indices obtained from field survey and expert choice system. Figure 3 illustrates the graph obtained by superimposing the composite curves. The graph is an infeasible solution since there is no pinch point. Furthermore, the source composite curve is on the left of sink composite curve that indicates that there exists a gap between the acceptability of each intervention and the users' willingness-to-accept. The graph however prioritizes the interventions based on their DE, which the users can adopt by trading off intervention's acceptability for achieving comfort. For instance, strategy S8 has the highest DE but at the same time, it has the widest gap between the source and the sink composite curve.

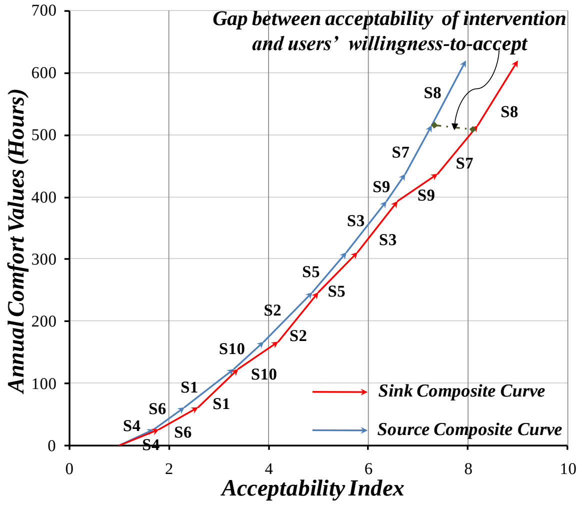

Figure 3: Infeasible pinch diagram obtained by superimposing composite curves

In order to obtain a feasible pinch diagram, it is required to shift the source composite curve to the right. This could be achieved by increasing the acceptability index of interventions through policy measures such as:

- *Creating awareness through campaigns and workshops:* At the community level, organizing awareness campaigns and workshop to educate occupants about the benefits of using such interventions can be done. This could ease their transition to adopt new technologies thereby increasing acceptability.
- *Providing subsidies for building materials:* Subsidizing the cost of building materials can lead to an increase in affordability of interventions thus increasing their acceptability.
- *Subsidizing energy cost by providing renewable energy sources:* A stringent policy measure could be the use of renewable energy sources such as Rooftop Photovoltaic (PV) systems to decrease energy cost leading to an increase in acceptability index.

Since socio-cultural considerations are governed by other exogenous factors, it would not be difficult to alter them. Based on the modified Acceptability Indices, mAI_i (see Appendix C), a modified source composite curve is generated and superimposed on the pre-defined sink composite curve as illustrated in Figure 4a. The pinch diagram thus obtained is a feasible one with a part of source composite curve lying below and to the right of sink composite curve. Since partially implementation of interventions is not possible, interventions lying completely below the sink composite curve are accepted for implementation. As illustrated in Figure 4a, S5, S3, S7 and S8 lie completely below the sink composite curve and have high degree of effectiveness (DE). Therefore, these four interventions are accepted. Moreover, S6, S10, S1, S9 and S2 lie completely or partially above the sink composite curve (Figure 4b and 4c) and hence cannot be accepted. For S4 composite curves overlap each other

(Figure 4b) indicating the acceptability of intervention-*use of ceiling fan* is the same as that of users willingness-to-accept. Thus, this intervention can also be accepted however, due to its lowest DE, S4 will have the least priority.

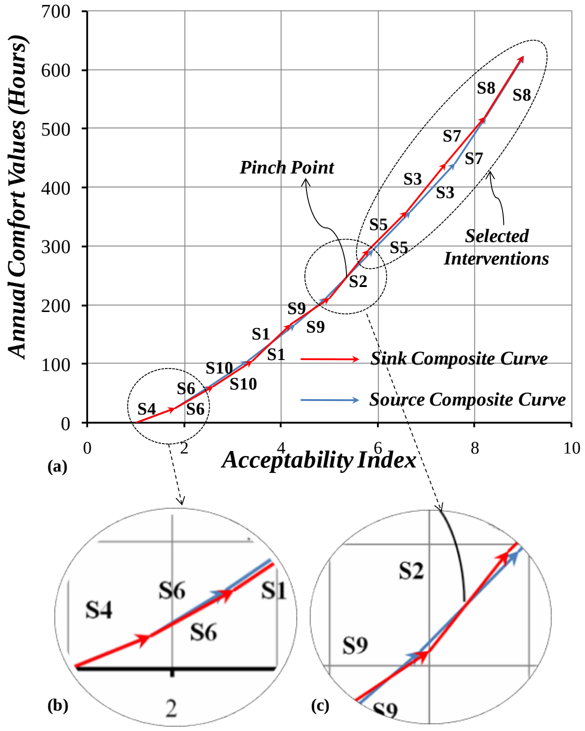

Figure 4:(a) Feasible pinch diagram with source composite curve partially below and to the right of the sink composite curve (b) overlapping of composite curves in case of S4 (c) pinch point lying partially above S2.

The selected interventions are prioritised based on their DE. Table 5 summarises the pinch analysis results by providing set of five intervention for achieving thermal comfort subject to socio-cultural and economic constraints in low-income households.

Table 5: Prioritized ranking of selected interventions from Pinch diagram

Priority Ranking	Strategy ID	Selected Intervention
1	S8	Reflective paint on external walls
2	S7	Reflective floor tiles
3	S3	Use of Planters near windows
4	S5	Switching on/off Exhaust fans
5	S4	Switching on/off ceiling fans

Conclusion

The study proposes a novel method for optimizing thermal comfort in low-income dwelling while including the socio-cultural and economic constraints of the occupants. The study involves selection of interventions for increasing thermal comfort consisting of adaptive actions and building retrofit techniques subject to pre-defined constraints. An extension of the widely used pinch analysis approach, termed as *Energy Target Pinch Analysis (ETPA)* is developed here to select and prioritize interventions. The approach is based on the principles of targeting methods adopted in material resource pinch diagram.

It is clearly demonstrated that in the current scenario, users often compromise on comfort by adopting less effective strategies mostly associated with higher affordability, socio-cultural acceptability and ease of use. To arrive at a feasible solution, policy measures in form of subsidies, awareness campaigns and renewable energy sources are applied. The optimal solution thus obtained involves the use of reflective exterior paint, reflective floor tiles and planters combined with the operation of exhaust and ceiling fans for achieving thermal comfort. *ETPA* approach developed in this study provides a graphical method for investigating trade-offs for optimisation and thus proves to be advantageous over other mathematical optimization approaches. This is helpful in decision-making processes and further applications to building energy problems of more complex nature can be explored with this approach.

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Appendix A

Table 6: Estimated Cost of each intervention

Strategy, Si	Intervention incorporated	Material/ Equipment Cost[a] per m^2 or unit (in ₹)	Labour cost[b] per m^2 or unit (in ₹)	Total Cost for each *chawl* unit (in ₹)
S0	Opening or closing of windows	0	0	0
S1	Opening or closing of doors	0	0	0
S2	Use of window curtains	0	0	0
S3	Use of Planters near windows	1200	0	1200
S4	Switching on/off ceiling fans	2370	451	2821
S5	Switching on/off Exhaust fans	1560	451	2011
S6	Sun control film on windows	1658	478	4806
S7	Reflective floor tiles	645.84	250	13133
S8	Reflective paint on external walls	66.5	54	1416
S9	EPS wall insulation	590	1900	94782
S10	Reflective roof tiles	452	250	3795

[a] *Material/Equipment cost obtained from Havells India Limited, Amazon India and E-construction Mart.*
[b] *Labour cost calculated from Detailed Schedule of Rates, Government of Maharashtra* (Government of Maharashtra 2017)

Appendix B

Table 7: Values of acceptability parameters (P_i) and corresponding Acceptability Index (AI_i) for each strategy (Si)

Strategy, Si	Cost (in ₹)	Affordability Index (P_1)	Socio Cultural consideration (P_2)	Ease of transition to technology (P_3)	Energy Consumption (KWhr)	Energy Load (P_4)	Acceptability Index ($AI_i=\sum W_jP_i$)
S0	0	1.00	1.00	1.0	3362	1.0	1.00
S1	0	1.00	0.80	1.0	3362	1.0	0.99
S2	0	1.00	0.80	1.0	3362	1.0	0.99
S3	1200	0.88	0.80	0.70	3362	1.0	0.81
S4	2821	0.80	0.50	0.60	3408	0.70	0.68
S5	2011	0.72	0.50	0.90	3691	0.10	0.70
S6	4806	0.52	0.50	0.50	3362	1.0	0.62
S7	13133	0.00	0.50	0.50	3362	1.0	0.52
S8	1416	0.86	0.50	0.50	3362	1.0	0.69
S9	94782	0.00	0.50	0.20	3362	1.0	0.37
S10	3795	0.62	0.50	0.40	3362	1.0	0.59

Appendix C

Table 8: Values of modified acceptability parameters (mP_i) and corresponding Acceptability Index (mAI_i) for each strategy (Si)

Strategy, Si	Modified Cost[a] (in ₹)	Modified Affordability Index (mP_1)	Socio Cultural Consideration (P_2)	Modified Ease of transition to technology[b] (mP_3)	Energy Consumption (KWhr)	Modified Energy Load[c] (mP_4)	Modified Acceptability Index ($mAI_{i==}=\sum W_j\ mP_i$)
S0	0	1.00	1.00	1	3362	1	1.00
S1	0	1.00	0.80	1	3362	1	0.99
S2	0	1.00	0.80	1	3362	1	0.99
S3	0	1.00	0.80	0.90	3362	1	0.94
S4	451	0.95	0.50	0.90	3408	0.90	0.80
S5	2011	0.80	0.50	0.70	3691	0.40	0.76
S6	4806	0.52	0.50	0.70	3362	1	0.72
S7	13133	0.00	0.50	0.70	3362	1	0.62
S8	708	0.93	0.50	0.70	3362	1	0.80
S9	47391	0.00	0.50	0.70	3362	1	062
S10	1898	0.81	0.50	0.70	3362	1	0.78

[a] *Modified cost obtained by providing planters and ceiling fans to users and providing 50% subsidy for building envelope strategies(S8 to S10).*
[b] *Modified ease of transition to technology obtained by providing awareness about building envelope materials and strategies.*
[c] *Modified energy load obtained by providing rooftop PV system for 25% energy consumption.*