International Journal on Emerging Technologies **9**(1): 55-66(2018)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Sensitivity Analysis of Efficiency Retrofitting in High Rise Apartment Buildings through Life Cycle Energy and Costing Analysis

***Akshay K. Bishnoi*[1], *R. Soumya*[1], *Ankur Bishnoi*[2] *and Dr. E. Rajasekhar*[3]**
[1]EDRC, B&F IC, L&T Construction Ltd., Chennai (Tamilnadu), INDIA
[2]LEAD Consultancy, Bangalore (Karnataka), INDIA
[3]Department of Architecture, Indian Institute of Technology – Roorkee (Uttarakhand), INDIA

(Corresponding author: Akshay K. Bishnoi)
(Received 12 April, 2018 accepted 16 June, 2018)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Given India's standing in global energy consumption scenario, point to ponder about is its position firm on the grounds of projected extrapolation of demand. Rapid expansion of the Schumpeterian hubs as a result of complex growth metabolism is leading to escalating energy demand in commercial and residential sector. With enough concentration on commercial sector's energy minimization, considerably less weightage is given to studies and measures towards mitigating consumption in residential sector.

This article studies the consumption, with its breakups as operational and embodied sub-head. With four years of operational consumption data, this article studies the analysis and comparison of the risks and gains associated with post-retrofit performance and energy savings and its corresponding impact on asset values through adopting Life Cycle Costing Analysis parallel to the Life Cycle Energy Analysis.

Findings indicate that building design parameters, occupancy characteristics and quality are key drivers of energy performance, but increased energy efficiency stands independent of the financial risk associated with the initial costs of efficiency retrofits thus schematized.

I. INTRODUCTION

With an estimated requirement of around 70 million *New Urban Housing Units* over the next 20 years, residential sector has seen an annual growth rate of 5%. Urban centers in developing countries have been witnessing a discernible transition from traditional independent/semi-independent abodes to high-rise residential settlements. Clusters of gated communities encompassing such dwelling units have started to increasingly dominate the urban land form. Though these residences are designed to be naturally ventilated, the use of mechanical conditioning has been synchronically increasing leading to increasing comfort conditioning operational consumption. With high initial investment of embodied energy due heavy built-up mass and increasing demand of comfort conditioning operational energy, the Life Cycle Energy demand of India is on hike.

India standing at the 2nd least power consuming country in the world faces an acute shortage of power due huge demand supply gap. With residential sector claiming 22% share in total power consumption, further already at this pace, the consumption in residential and commercial sector (22% residential and 8% commercial) is expected to hike by 8% annually.

An added plus to the present scenario is increasing GDP, enabling the consumer with an increasing affordability of consumer goods and thus escalated appliance usage. With a GDP growth of 7.8% over a period from 2005 to 2031, the electricity demand of households grows by an annual average rate of 8.2%, or by 74% of GDP growth.

II. OBJECTIVE AND METHODOLOGY

With a progressive agenda, so, end users of residential apartment buildings and community developers could achieve both in terms of energy reduction and return on initial capital investment on energy efficiency strategies together, this study looks upon following objective:

(a) Sensitivity analysis of the efficiency retrofits through Life Cycle Energy approach parallel to costing component.

For study, real time electricity data was collected from electricity regulatory authority (Tamil Nadu Electricity Board, TNEB) with subjective survey and data sorting for residential flats in multi-story apartment building with 656 flats and a population of around 2500 people located in Chennai for a stretch of 4 years was analyzed. Similarly for embodied energy analysis, Indian energy factors were referred as far as possible from across all the published energy factor data banks, discuss in detail in embodied energy section with references, beyond which, the inventory of carbon and energy was referred. With structured data a comprehensive analysis methodology was adopted to study the behavior of consumption with different factors governing a potential variation pattern both in operational and embodied energy consumption and content independently.

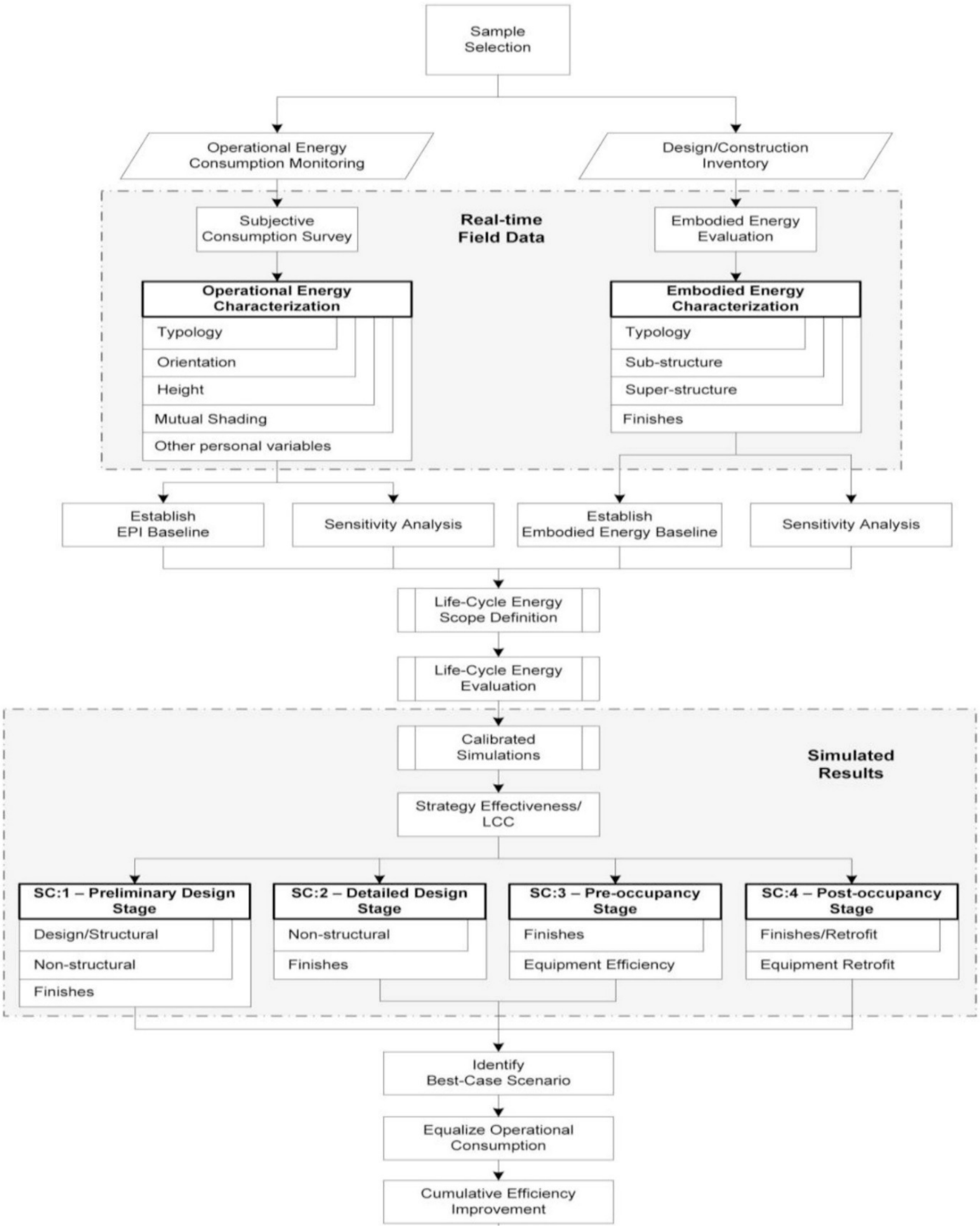


Fig. 1. Methodology chart.

Primary data analysis results in severity of critical factors governing the characteristics of energy consumption, thereby equipping with reasons corresponding to sudden and abrupt changes in consumption pattern thus observed during the life cycle energy analysis.

Exhaustive Life Cycle Energy Analysis of the energy consumption and content for the overall project and that of different types of flats is followed with a quick benchmark check.

Benchmark check includes comparing the energy consumption performance of the built mass at hand with that of the regional consumption benchmark (if available, if not, then national benchmark). If the building performs better than the set benchmark for controlled energy performance it can go on with scrutinizing the primary mitigation strategies for further enhancement (which may vary subjected to the strategies chosen in prior design consideration). Criteria and major primary scrutiny based on Life Cycle Costing analysis is discussed in detail further, followed by schematic draft for real time execution.

Ahead of scrutinizing the primary mitigation strategies study assumes a more strategic approach towards the effective deployment of the set of mitigation strategies under different scope of work. Scope thus considered majorly comprise of preliminary design stage, detailed design stage, pre-occupancy stage and post occupancy stage. Before attempting the minimization in effect with mitigation strategies, the study takes upon solving the issue relating differences occurring in consumption pattern in the same building due characterizing factors discussed in section 7. Such differences are dealt in by normalizing the percentage required to cure the differences and then equalized with minimal structural and non-structural changes possible, henceforth expanding the further scope of the study for energy efficiency retrofitting options.

III. STUDY LOCATION

Chennai (13^o N, 80.3^{o}E) represents a typical hot humid climate which is prevalent along most part of the east cost of India. The residential unit under investigation is located in a gated community encompassing 650 residential units distributed in 8 apartment blocks which are 13 floors high.

The study pertains to a gated community encompassing 656 residential units distributed in 6 apartment blocks which are 14 floors high. There are 3 apartment types; type I, type II and type III with floor areas 120 sq. m., 160 sq. m. and 186 sq. m. Buildings a, b, c and d accommodates 4 flats of type I and 4 flats of type II on each floor. Whilst buildings 1, 2, 3 and 4 accommodate 4 type-III flats on each floor. Figure 2 shows the site plan and positioning of buildings a, b, c, d, 1, 2, 3 and 4 on site, with respect to North.

Table 1: Floor area of different residential typology.

Dwelling Types	Type I	Type II	Type III
Area(s) (sqm)	96	121	144

Fig. 2. Schematic site plan.

IV. SUBJECTIVE EVALUATION OF UTILITY ENERGY CONSUMPTION

A subjective survey on utility power consumption was administered with representative condominiums (sample size of 100 units) regarding the capacity and usage pattern of air-conditioners and other major electrical equipment. Data on the lighting fixtures and their lighting power densities were also collected. The questionnaire used for this purpose is presented as appendix A. Fig. 3 and 4 provide the details and pattern of air-conditioner operation obtained through the subjective surveys. Peak operation of air-conditioner was found to be during the months of May, June and July (summer). A large non-uniformity in the pattern of air-conditioner usage and set-point temperatures were evident from the surveys. The details of it are depicted in the form of a histogram in fig. 3(a) and (b). The data obtained relating to occupancy levels per residential unit (μ=3.5), set temperature (μ=23.5^{o}C), occupancy pattern and hours of air-conditioner operation (μ=6 hours) were considered as inputs for the simulation studies discussed further.

Typically, the type III units had three of the bedrooms air-conditioned. The efficiency of the system (energy efficiency ratio, EER) was found to vary among the residences as summarized in fig. 4.

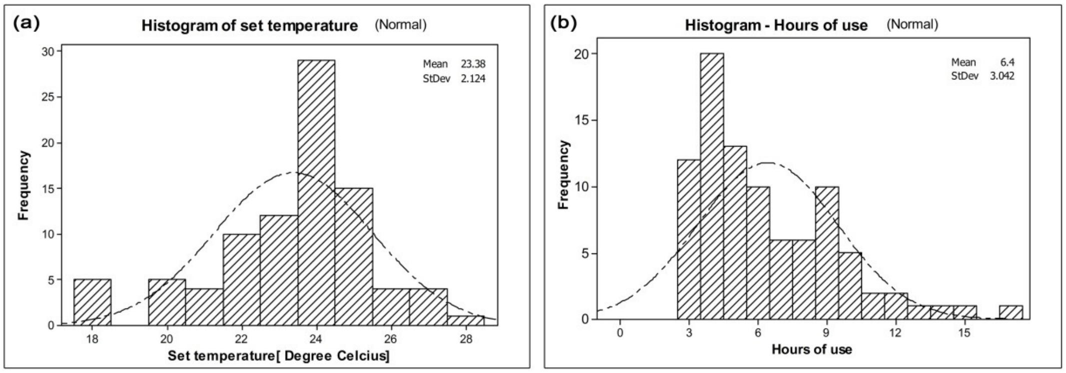


Fig. 1(a). Preferred set temperature (b) Duration of air-conditioner usage.

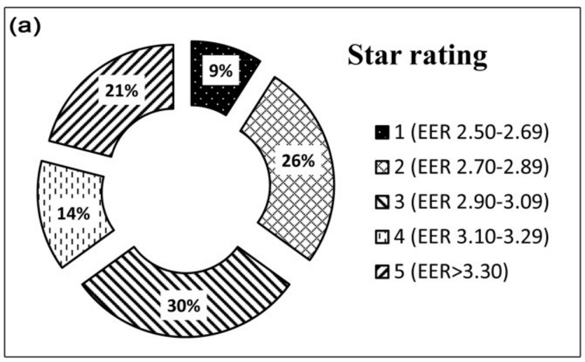


Fig. 4. Star rating of air conditioners in type III.

Normalization of the electricity consumption data was carried out to identify the outliers. Outliers in this case include a few residential units which had their living rooms air-conditioned in addition to the three bedrooms. It also includes residential units which didn't have air – conditioners. This brought the sample size of the study to 494 residential units from a total of 656 numbers of flats.

V. EMBODIED ENERGY

For calculating Initial Embodied Energy, Indian schedule of energy factors have been compiled referring the energy factors and inventories already published regarding the same. With an extensive BOQ of the project and inventory of energy factors thus compiled, embodied energy is then calculated for the project per dwelling unit by the bill of quantity obtained by detailed Revit model. The study assumes the Cradle to Gate variant for the analysis purpose excluding transportation and disposal.

Present study accounts for the Embodied Energy rates considering raw material extraction, transportation to the manufacturing site of the construction material and processing of the construction material to final product. The study opts out the embodied energy in formwork, demolition and site construction works.

For analysis a combined inventory was prepared referring embodied energy factors from published Indian energy factors (Indian energy factors were referred as far as possible to match up with all possible material provided in bill of quantity of the project). Beyond available embodied energy factors available in the stated published inventories, the study looks upon picking rates of those materials from other sources. Further, thus obtained exhaustive results from both the sub-heads of life cycle energy, i.e., operational consumption and embodied energy. Study majorly focuses upon the Life Cycle Energy analysis at first hand and having been done that, leaps a step forth towards possible mitigation strategies or pro mitigation schematics.

Overall Embodied Energy per square meter of total built-up area is 3487.14 MJ/sqm

With sub structure accounting for maximum embodied energy share, it is followed by super structure and finishes, Table 3.

In the overall consumption scenario sub-structure contributes to about 46% share in total embodied energy followed by rest 54% to be divided amongst super-structure and finishes. This high percentage share of embodied energy for sub-structure is suspected majorly due to raft foundation divided in two clusters of construction phases and two levels of basement parking.

Table 2: Embodied energy breakup by construction work type.

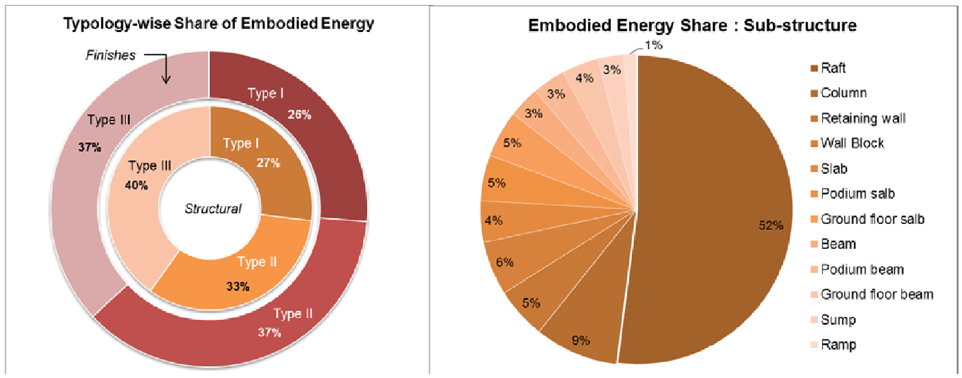
	Sub-structure	Super-structure	Finishes
Share in total embodied energy	46%	42%	12%

Table 4 shows embodied energy content of different residential typology, to consider the share of sub-structure in the embodied energy of individual flats; the sub-structure embodied energy was proportionally divided amongst different residential typology.

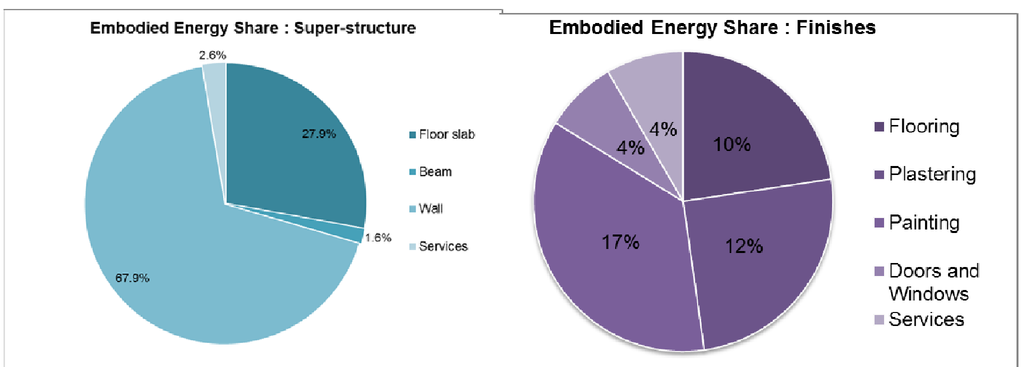
Amongst all different typology, type III accounts for approximately 39% of total embodied energy followed by 34% and 27% for type II and type I respectively. Fig. 5 shows share of different residential typology in structural and finishes break-up.

Table 3: Per square meter embodied energy for different residential typology.

	T-I	T-II	T-III
Embodied Energy (MJ/sqm)	4043.53	3790.38	3879.76



(a) (b)



(c) (d)

Fig. 5. (a) Typology-wise embodied energy share, (b) Breakup of embodied energy in sub-structure, (c) Breakup of embodied energy in super-structure and (d) breakup of embodied energy in finishes.

Also, embodied energy breakup in sub, super structure and finishes showed raft to be contributing the most in sub-structure, walls in super structure and painting in finishes followed by columns, floor slab and plastering respectively.

VI. LIFE CYCLE ENERGY

Building up upon the embodied energy and operational electricity consumption analysis, life cycle energy was calculated with its breakups. Life cycle energy presented here is confined to the energy consumption and content in operational electricity and embodied and scopes out the household fuel consumption, transportation and the energy consumption in common services.

Results show that with 8% increment in Operational Consumption per year and a total of 0.6% increment in embodied energy per year due to maintenance, the life cycle energy demand is dominated by operational (~92% by part, 50 years projection) and embodied (~8% by part, 50 years projection) requirements. Exceptionally high embodied energy here in this case is expected due two major raft foundations across the whole built mass and two levels of basement parking.Figure6 shows the overall life cycle energy of the project and life cycle energy of the project considering the embodied energy of super structure alone.

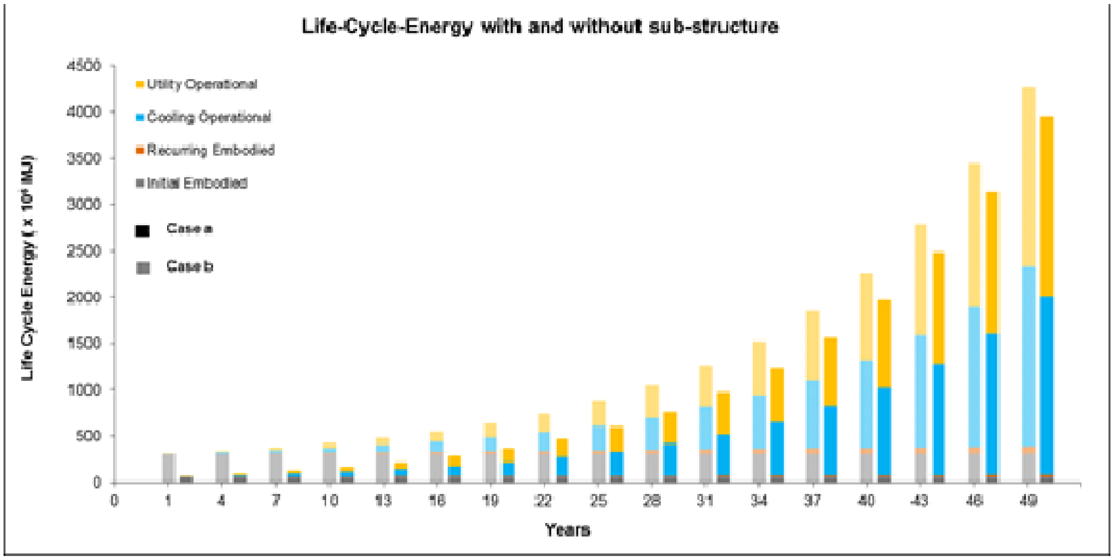


Fig. 6. Overall Life cycle energy of the residential community with and without sub-structure.

Point to ponder is that despite all possible mitigation strategies viable and applicable in context to reduce the life cycle energy of the project, sub structure majorly is inevitable and a constant additive.

A. Effect of Residential Typology

Majorly accounting for vivid operational electricity consumption pattern and also differences in embodied energy share for obvious reason, residential typology was studied for their corresponding life cycle energy contribution. Fig. 7 shows the comparative graph of Life Cycle Energy comparison for all the three residential typologies with type III accounting for a major share of 36.26% which is approximately as good as that of type II holding 35.79% of life cycle energy for the whole community, whereas type I stands consuming the lowest energy accounting for the rest of 27.9%.

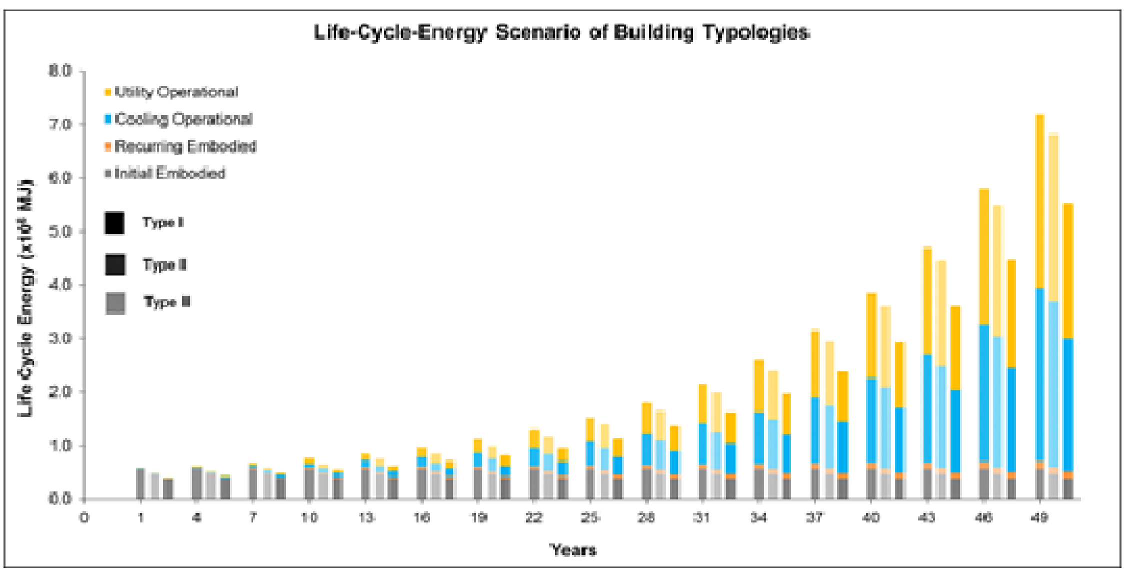


Fig. 7. Comparative life cycle energy of different residential typologies.

B. Influence of Orientation

Considering the major classifications brought in by orientation in operational electricity consumption section. The life cycle energy analysis was tried with the same typology of residential unit to understand the impact of considerably varying operational electricity consumption on life cycle energy between highest and lowest electricity consuming orientations of flats.Figure8 shows the inter-comparison of highest and lowest electricity consuming orientations of type III flats.

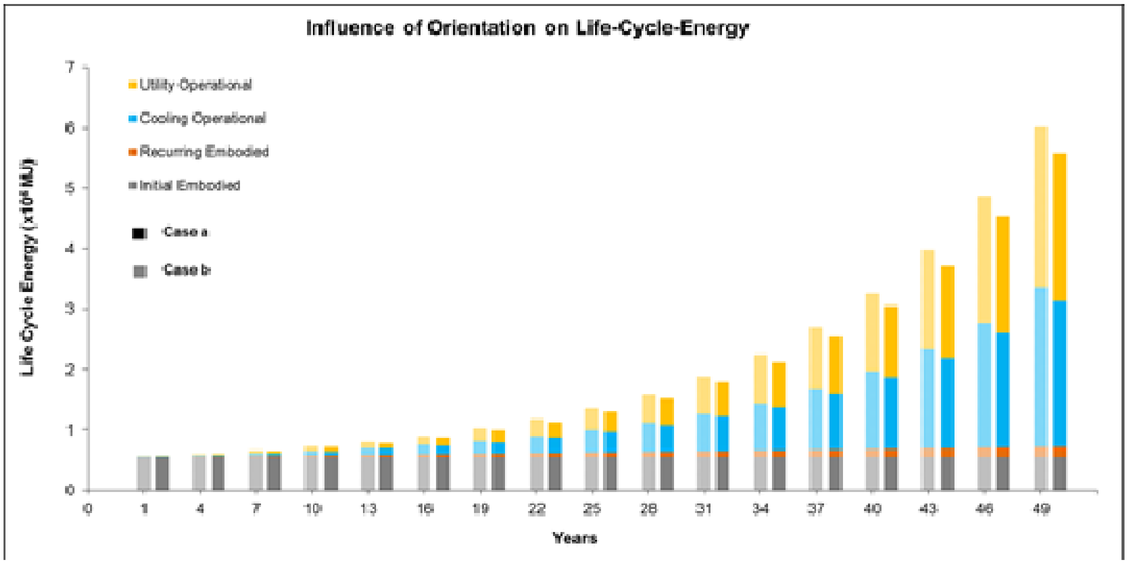


Fig. 8. Comparative life cycle energy between flats exposed to highest consuming orientations and lowest consuming orientations

A difference of 7% incremental life cycle energy was observed for high electricity consuming orientation flat over that of the low electricity consuming.

C. Mitigation Strategies

Operational consumption as analyzed on cumulative basis showed an incremental rate of 8% per annum, which is then projected forward with the same rate for a period of 50 years. Also, considering the subjective survey conducted post 3 years of occupancy of the flats, the survey subjected a prominent usage of comfort conditioning equipment for the month other than January on an average basis. Taking this into consideration, the balance consumption throughout the year is considered to be falling for comfort conditioning when January consumption figure is subtracted from the corresponding monthly value.

With this exhaustive data bank the analysis related that study concerning Life Cycle Energy to consider factors subjected to change. For instance in case of operational consumption, comfort conditioning operational consumption and lighting consumption are two major sub-heads which can be manipulated by adopting efficient measures. For Embodied Energy, superstructure majorly concerning non-structural elements and the envelope corresponds to the same.

With an aim to minimize the life cycle energy of the built mass, a comprehensive set of viable strategies based on further stated checkpoints were studied for the best possible adaptability. Diluting down to 5 core strategies which can be deployed taking in account the following heads as check:

- Scalability
- Replicability
- Cost
- Ease of installation

The purpose of this task is to identify technologies and savings incurred by them if and when deployed post several years of operation of the built mass. To provide with effective mitigation strategies for the Life Cycle Energy to the occupant, thereby letting end user to compare and decide upon the benefits of initial first cost and the benefits in return for longer run.

For this purpose, following strategies were targeted which stood clear post the preliminary scrutiny:

a. External insulation (Extruded Polystyrene 25mm)
b. Sandwiched wall insulation (Extruded Polystyrene 15mm)
c. Reduced window wall ratio to 12% from 17%
d. Low emissivity paint
e. Five star rated air conditioners
f. Low emissivity windows
g. Double glazed windows

Concerning the recommendation regarding best possible strategy as remedy for decreasing the overall Life Cycle Energy of the buildings, the following study was done in two ways. For the analysis of the usability of the product, when, other than costing, energy plays a vital role too, we need to look upon two basic structures of analysis, namely:

- Life Cycle Energy Analysis
- Life Cycle Costing Analysis

For the purpose of Life Cycle Energy Analysis the strategies were taken up to be studied assuming following procedure and variables in concern:

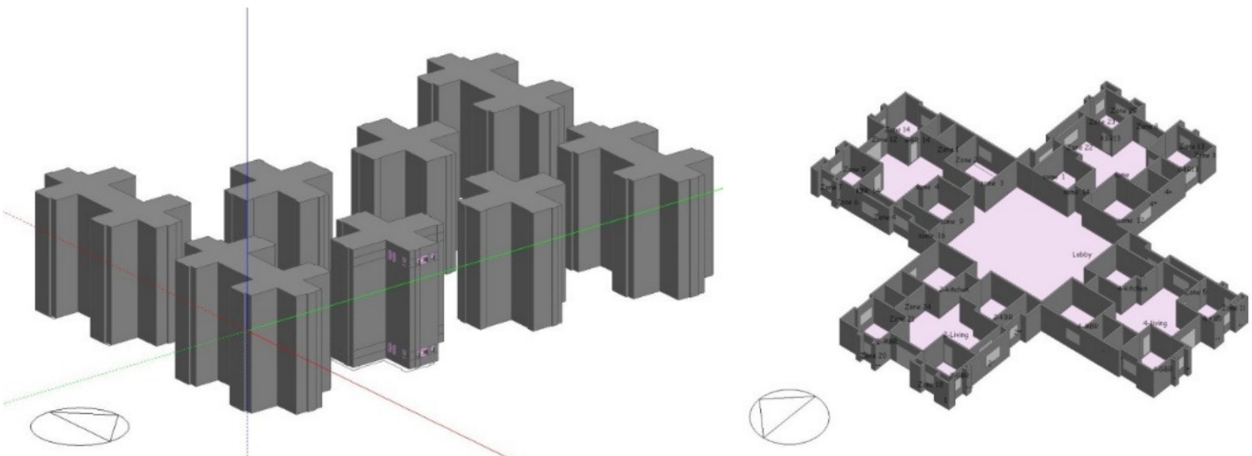
For study purpose, due availability of single typology of flat accommodated in four built towers in symmetric design fashion, the type III flat typology was considered with all the data accumulated with its operational consumption, cooling consumption and embodied energy.

D. Simulation Studies

For the purpose of simulation Design Builder version 3.4.0 Software was used to obtain the comfort conditioning operational consumption for different design options (to be used in later stages). The actual design configurations and envelope properties were adopted for the simulation model and the weather data was obtained from ISHRAE database (ISHRAE weather data 2012). Fig. 9 shows screen shots of the model developed in Design Builder software tool.

Modelling parameters thus considered for the present base case were (some depending upon the subjective survey): The flat to be evening ventilated scenario (6 PM to 8 PM) with comfort conditioning prominent at night from 8 PM till 6 PM. The air conditioners used in the base case are taken to be 3 star rated air conditioners (based on subjective survey), which in later stages is used for inter comparison by using 5 star rated air conditioners.

The basic module was studied for all the four orientations and the results were thus used to generate and compare the corresponding least consuming and highest consuming flats.



(a) (b)

Fig. 9. Simulation model (a) Simulation model of whole community on design builder and (b) Simulation model of typical floor of Type III tower on design builder.

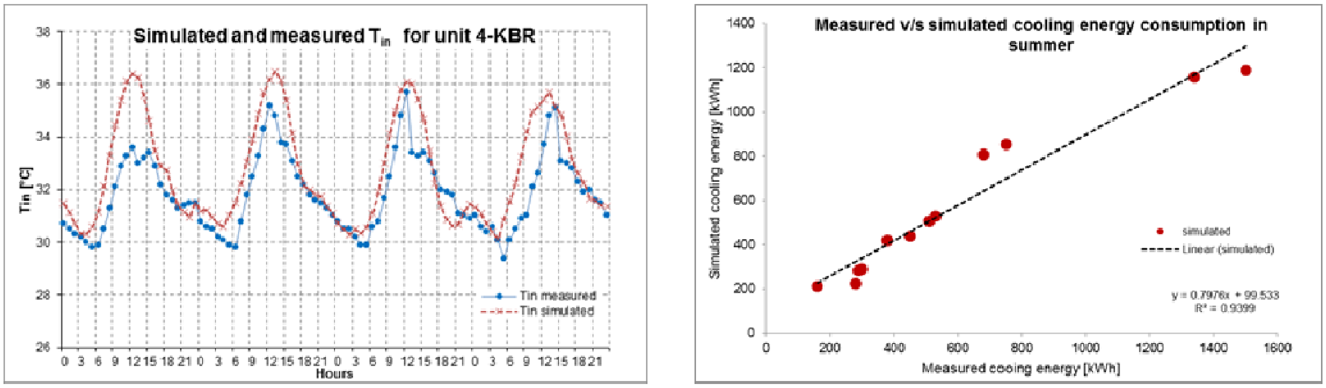
Results from simulation modeling were used to perform life cycle costing analysis and decide upon with the feasibility of options. Also, post tagging with the percentage minimization brought by individual mitigation strategy, the strategy were marked with the effectiveness on the grounds of life cycle costing also. Statistics concerning the life cycle costing analysis of the selected strategies are shown in table5.

Crucial aspect of the variability of base case lies in understanding the need for demarcating with two base cases, or a set of base case as per requirement. As will be detailed further in exhaustive manner, when the exercise adopts the shapes to club upon the best set of individual strategies to call it a mitigation strategy together, the comparison can only be carried with the exact base case without the adoption of a mitigation strategy. Whereas the case is not so when it is required to compare different strategies between themselves on cumulative basis, in that case we require a more generalized and labile base case to refer. Similarly the base case thus can always be referred according to the design requirement within a given choosing criteria.

A comparison of the simulated and actual power consumption was made in which the actual number and type of air conditioners, set temperatures and operation pattern for a few residences from the subjective survey data were simulated. The pattern of power consumption was similar in the simulated and actual scenario as indicated in figure 10.

E. Energy Efficiency Strategies (LCC)

Post simulation analysis and calculations relating the minimization brought by different mitigation strategies at hand, life cycle costing analysis was done to finalize and compare between different individual strategies. Maximum benefits were observed for altering window wall ratio, since it accounted for no initial incremental cost and net present value of returns is also highest.



(a) (b)

Fig. 10. Comparison of measured and simulated values (a) Tin (b) cooling energy consumption.

Table 4: Life cycle costing of individual LCE mitigation strategies.

	Initial Incremental cost (□)	**Annual Electricity Savings (□)**	**Net Present Value (□)**	**Internal Rate of Return (%)**	**Simple Payback Years (Years)**	**Recurring period (Years)**
Altered WWR 12%	0 (savings of □ 17037)	360 (@6.6%*)	12332	-	-	-
External Wall Insulation (25 mm XPS)	22387	702 (@13.2%*)	1660	8	32	-
Sandwiched Wall Insulation (15 mm XPS)	8093	483 (@9%*)	8555	12	16.6	-
Low e Paint	1658 (□ 1658 recurring cost per 4 years)	504 (0.2%*)	11192	26	3.3	4
5 star rated air conditioners	21120 (for 3 AC's)	1512	30674	14	14	-

F. Set of Strategies

Further, individual mitigation strategies were clubbed together according to different stages of deployment. For this purpose the major demarcation as existent was considered, preliminary design stage (or early design stage), detailed design stage (or late design stage), pre occupancy stage and post occupancy stage. Accordingly individual strategies can be classified under different stage of construction or occupancy based on the feasibility of deployment of the same. Henceforth, strategies thus considered can be clubbed as follows:

a. Preliminary design stage: External insulation, sandwiched insulation, reduced window wall ratio, low emissivity paint and five star rated air conditioners.
b. Detailed design stage: External insulation, sandwiched insulation, reduced window wall ratio low emissivity paint and five star rated air conditioners.
c. Pre-occupancy stage: Low emissivity paint and five star rated air conditioners.
d. Post-occupancy stage: Low emissivity paint and five star rated air conditioners.

For analysis, first two stages can be clubbed as test of strategies under pre-construction stage and the latter two can be analyzed as is. Pre-occupancy stage can be analyzed for their life cycle energy by considering the deployment of mitigation strategies from the first year of occupancy itself. Post-occupancy stage can be dealt in by considering different years of deployment up till the year of deployment which satisfywith the breakeven period of particular strategy.

G. Feasibility at Different Stages During Life Cycle and Construction Period of the Building

Propagating further, the study attempts to way off set of strategies (if any) which stand otherwise on the grounds of life cycle costing. For this purpose, yet another exercise of life cycle costing analysis was carried for set of strategies to understand the potential of feasibility of particular set of strategy at different stages of construction and occupancy. LCC analysis of the strategies was followed by the life cycle energy analysis rendering the minimization brought in by different set of strategies in life cycle energy of the building.

Table 5: Comparative Life Cycle Costing of different set of mitigation strategies for different scenarios.

		Design Stage	Set of strategies	Incremental Cost (₹/sqm)	Annual electricity savings (₹/sqm)	Net Present Value (₹/sqm)	Simple Payback Period (Years)	Recurring Period (Years)
	A (sub division of preliminary design stage and detailed design stage)	**Pre-construction design stage**	a. External Wall Insulation (25mm XPS) b. Altered Window Wall Ratio (12% from 17%) c. Low emissivity paint d. Five star rated AC	**301** (₹ 11/sqm recurring cost per 4 years)	13	**126**	**22.53**	4
Scenario 1								
	B (sub division of preliminary design stage and detailed design stage)	**Pre-construction design stage**	a. Sandwiched Wall Insulation (15mm XPS) b. Altered Window Wall Ratio (12% from 17%) c. Low emissivity paint d. Five star rated AC	**79** (₹ 11/sqm recurring cost per 4 years)	12	**301**	**6.63**	4
	A Refurbishment at **zeroth year**	**Post-construction design stage**	a. Low emissivity paint b. Five star rated AC	**157** (₹ 11/sqm recurring cost per 4 years)	9	**120**	**17.5**	4
Scenario 2	**B** Refurbishment at **5th year** of operation	**Post-construction design stage**	a. Low emissivity paint b. Five star rated AC	**157** (₹ 11/sqm recurring cost per 4 years)	9	**99**	**17.5**	4
	C Refurbishment at **10th year** of operation	**Post-construction design stage**	a. Low emissivity paint b. Five star rated AC	**157** (₹ 11/sqm recurring cost per 4 years)	9	**77**	**17.5**	4

Table 6 shows the statistics relating life cycle costing analysis for different set of strategies at different stage of construction and occupancy.

H. Impact on Life Cycle Energy by Set of Strategies for Different Scenarios

Post analyzing the strategies with their feasibility potential with life cycle costing analysis, next the strategies are studied for the minimization brought in by different strategies in the life cycle energy. As obvious and evident from the figure 11, scenario 1A stands most effective option in terms of life cycle energy minimization, whereas scenario 1B is most feasible option considering the cost efficiency par minimization in life cycle energy. Consequently for scenario 2 A, B, and C, the early the better, adopting energy efficiency measures from the very first year of occupancy stands potent both in terms of energy and cost. Further, figure 12 shows the pattern of net savings for different scenarios, that is for scenarios falling both under pre construction stage and when the refurbishment is done in the 10^{th} and the 20^{th} year of operation. Table 7 shows the comparative percentages of reduction in life cycle energy with gross returns on investment percentage.

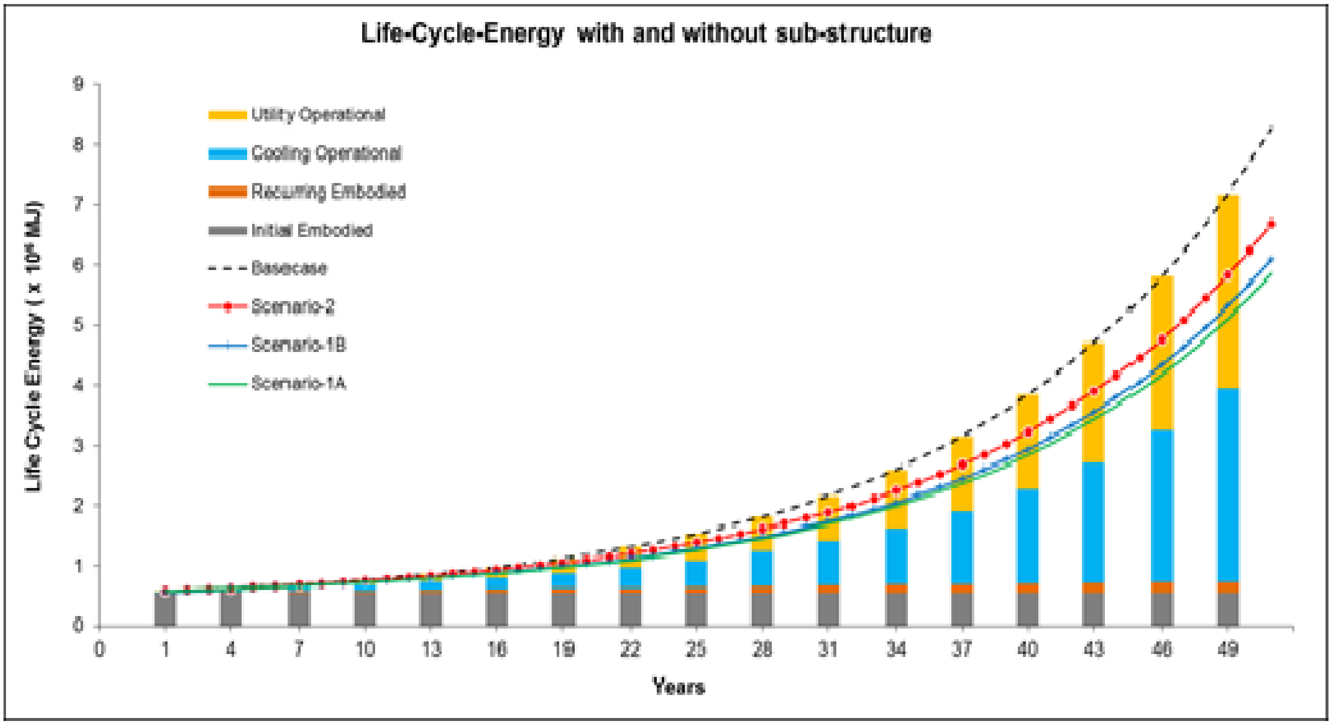


Fig. 11. Comparative Life Cycle Energy for different set of strategies deployed under different scenarios.

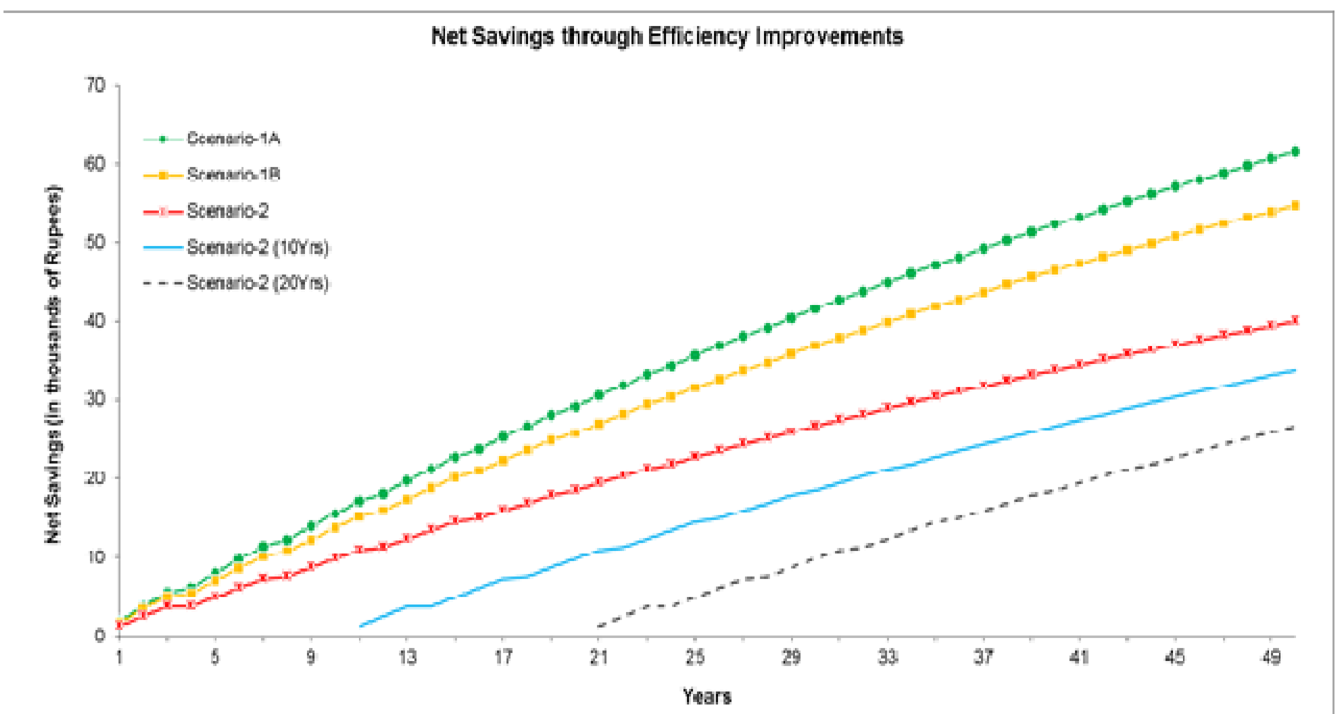


Fig. 12. Comparative graph for net savings with different set of strategies and refurbishment.

Table 6: Comparative table showing percentage decrement in LCE with gross return on investment for different years of refurbishment.

Year of refurbishment	Percentage decrement in LCE from the base case	Return on gross investment
0	19.2%	141%
5	19.1%	134%
10	19.0%	126%
15	18.7%	118%
20	18.3%	109%
25	17.5%	100.1%

VII. KEY FINDINGS

Individual residential apartment buildings and community developers could achieve both in terms of energy reduction and return on initial capital investment on energy efficiency strategy together by arriving upon cost effective, energy efficiency modifications (in design development or post occupancy stages).

(i) Time plays a crucial role in energy efficiency planning, design implementation and retrofitting. The degree impact of energy efficiency measures stands yet another check through the market forces behind, adoption of energy efficiency measure in pre or late design stage or pre or post occupancy depending upon which the availability of scope of minimization varies.

(ii) Minimal structural and non-structural interventions in design taken by pre design stage can bring up to 34% reduction in comfort conditioning operational consumption alone. Likewise, the percentage gradually decreases with narrowing of scope of minimization with time slipping to the post construction scope from pre design scope.

REFERENCES

[1]. Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, **42**(8), 1238-1247.

[2]. Ioannou, A., &Itard, L. C. M. (2015). Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy and Buildings*, **92**, 216-233.

[3]. Hemsath, T. L., & Bandhosseini, K. A. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy*, **76**, 526-538.

[4]. Wang, L., & Greenberg, S. (2015). Window operation and impacts on building energy consumption. *Energy and Buildings*, **92**, 313-321.

[5]. Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, **29**, 394-416.

[6]. Erlandsson, M., & Borg, M. (2003). Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. *Building and environment*, **38**(7), 919-938.

[7]. Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, **42**(10), 1592-1600.

[8]. Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and environment*, **37**(4), 429-435.

[9]. Yohanis, Y. G., & Norton, B. (2002). Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy*, **27**(1), 77-92.

[10]. Devi, P., & Palaniappan, S. (2014). A case study on life cycle energy use of residential building in Southern India. *Energy and Buildings*, **80**, 247-259.

[11]. Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, **66**, 232-245.

[12]. Praseeda, K. I., Mani, M., & Reddy, B. V. (2014). Assessing impact of material transition and thermal comfort models on embodied and operational energy in vernacular dwellings (India). *Energy Procedia*, **54**, 342-351.

[13]. Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications–a review. *Applied Energy*, **115**, 164-173.

[14]. Chappells, H., & Shove, E. (2005). Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. *Building Research & Information*, **33**(1), 32-40.

[15]. Rajasekar, E., & Ramachandraiah, A. (2010). Adaptive comfort and thermal expectations–a subjective evaluation in hot humid climate. *Proceedings of the adapting to change: new thinking on comfort. Windsor, London, UK*, 9-11.

[16]. Annual report on the working of state power utilities and electricity departments. (2014). *Power and Energy division, Planning Commission, Government of India*.

[17]. Bureau of Energy Efficiency. (2014). Design guidelines for energy-efficient multi-storey residential buildings (Composite and Hot-Dry climates). New Delhi.

[18]. TV, Rijil Das., & Rajasekar, E. (2014). Effect of location specific climatic diversities on comfort and energy consumption: A study on India's composite climate zone. *Proceedings of counting the cost of comfort in a changing world. Windsor, London, UK*, 9-11.