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ENERGY MODELING OF MULTI-STORIED RESIDENTIAL BUILDINGS – A MANUAL CALIBRATION APPROACH

Shailza
Indian Institute of Technology Roorkee (India)-247667

ABSTRACT

In this paper evidence based manual calibration approach is adopted to calibrate five mixed-mode multi-storied apartment blocks in composite climate of India. The baseline models are calibrated using monthly energy-use curve and validated using statistical indices. It is inferred that the evidence based manual calibration technique has fairly validated the energy-use profile of the chosen case studies and are found to be within acceptable tolerances (i.e. ±25% for percentage error , ±15% (CV (RMSE) and ±5% for MBE%).

INTRODUCTION

Building energy modeling is widely used to evaluate the thermal environment and energy usage of buildings; however, studies have often reported performance gaps between the predicted and measured values (Branco et al., 2004; Staepels et al., 2013). The most common practice to reduce this gap is calibration by systematically adjusting the input parameters to the simulation model. Calibration in building energy modeling is a process of reducing the uncertainty of a simulation model by comparing the predicted output to the actual measured data for a specific set of conditions (ASHRAE 14-2014). The calibration techniques range in complexity from manual (based on iterative and pragmatic intervention) to automated (based on special tests ; i.e. blink tests, STEM tests, and analytical procedures) (NREL 2013, Reddy 2006, Coakley et al., 2014) approach. The measure of accuracy of these calibrated models is checked for the acceptable tolerances as defined by ASHRAE 14 Guidelines, the International Performance Measurement and Verification Protocol (IPMVP) and the Federal Energy Management Program (FEMP) (Ruiz G.R. and Bandera C.F. 2017). There are several studies in the literature on calibration methods for commercial buildings in India, however, no systematic calibration guideline is available for mixed-mode buildings, where space conditioning is a combination of natural ventilation and mechanical systems (using stand-alone air conditioners). The aim of this paper is to present a simplified methodology, using manual calibration approach, to calibrate the simulated energy models of multi storied residential buildings with the monthly metered utility values.

CASE STUDY

Hill View (HV), Canal View (CV), BhaimatiDas (BMD), Trishla (TR) and Growmore (GMR) are the five mixed mode multi-storied apartment blocks chosen for the analysis. HV & CV are located in Roorkee (at 29° 51'N, 77° 53' E with outdoor temperatures ranging from 40°C in summer to 5°C in winter). BMD,TR & GMR are located in Chandigarh (at about 30.44°N & 76.47°E with a maximum temperature of 39°C in summer and minimum temperature of 7°C in winters). The floor area of the dwelling units varied between 119 to 173 m^2, refer Table1. The basic layout, orientation of each building has varied considerably: with BMD, GMR & TR orientated along NE-SW axis while HV along E-W axis and CV planned with longer axis along N-S. Figure 1a-e illustrates the geometric configuration and orientation of each building.

Table 1 Detailed summary of the surveyed buildings

Building	Floors	DU/ floor	A (m^2)	Orientation	S/V	WWR
GMR	G+9	6	132.1	NE-SW	0.4	1.9
TR	G+6	12	119.2	NE-SW	0.2	0.9
BMD	G+8	4	155.5	NE-SW	0.4	0.5
HV	G+7	4	173.7	E-W	0.4	0.4
CV	G+6	3	162.5	N-S	0.3	0.8

** A : Area of each dwelling unit (DU); S/V: Surface to Volume Ratio; WWR: Window to Wall Ratio*

METHODOLOGY

Design Builder's (DB) v.3.0.0.105 is used to create the baseline models. Methodology as adopted by Pedrini et.al. 2002 (three steps) and Yoon et.al. 2003 (seven steps) and Valentina et.al. 2015 (four steps) is referred in this study. Evidence based manual calibration approach is employed to calibrate the baseline models using monthly utility bills.

A representative simulated environment for the case studies is created using a wide range of information collected during the interviews and walkthrough visits; including architectural drawings, monthly utility bills, operational schedule of appliances, occupancy details, tenancy details etc. The simulation input values for the building fabric (i.e. walls, roof, windows etc.) and operation schedules (i.e. lighting, heating &cooling system, occupancy etc.) are defined on the basis of responses received during the questionnaire survey of fifty five dwelling units for one complete year. For evaluating the accuracy of baseline models, percentage error, normalized Mean Bias Error (MBE%) and the Coefficient of Variation of the RMSE (CV (RMSE)) are calculated and compared with Reeves 2012 and ASHRAE guideline 14 for tolerance limits, respectively.

Baseline Model

The construction system of a typical mixed-mode multi storied residential building is analogous in north India. The buildings under study are reinforced cement concrete (RCC) structures with the infill of brick masonry (230mm) and cement plastering (15mm) on both the sides of the wall. Roof is composed of reinforced concrete slabs with a layer of bitumen felt/ glass wool having a thermal resistance of R=0.4-.48 (m^2 $^{\circ}C/W$). Floors are concrete slabs with either tile finish or stone chipping/marble /Kota stone finish. Windows are all clear, single pane glazing with an aluminum/wooden frame. Natural ventilation is predominant in all the buildings with the use of stand-alone cooling/heating appliances during extreme summer and winter period. The baseline models of all five buildings are created in compliance with as-built technical data collected during the survey. Table 2 presents the design parameters that are used in the baseline model for each building.

Table 2 Summary of thermal properties of building

Parameters	GMR	TR	BMD	HV	CV
Glazing	U.F=7.1 SHGC=0.8 VLT=0.76	U.F=7.1 SHGC=08 VLT=0.76	U.F=7.1 SHGC=08 VLT=0.76	U.F=7.1 SHGC=08 VLT=0.76	UF=7.1 SHGC=0.8 VLT=0.76
Wall (External)	U.F= 1.9	U.F= 1.9	U.F= 1.9	U.F= 1.9	UF= 1.9
Internal Partition	U.F = 2.3	U.F = 2.3	U.F = 2.3	U.F = 2.3	U.F = 2.3
Roof	U.F= 2.4	U.F= 2.4	U.F= 2.4	U.F = 2.1	U.F = 2.1

** U.F(U-factor)=Thermal conductance,[W/$m^{2\circ}C$] ; SHGC=Solar Heat Gain Coefficient Through Glass*

Model Calibration

The 'errors' or 'uncertainties' in any simulated model are either attributed to the behavior of the occupants (Reeves 2012), personal bias of the modeler or the input variables representing the operational schedules of a building. The international performance measurement and verification protocol (IPMVP, 2010) and ASHRAE guideline 14, 2002, endorse the *whole-building calibrated simulation* approach for measuring and verifying the energy savings achieved in the existing buildings. It is recommended to collect utility bills, spanning at least a year or 12 continuous months, for calibrating the simulation outputs with the actual data. In this study, following steps are employed to calibrate the simulation output with the metered data of monthly electricity consumption:

- Baseline modelling: using building data, construction details, as-built drawings, occupancy schedule, operation schedules of appliances, weather data etc.
- Analyze the preliminary results for debugging.
- Calibrate the simulated values against the monthly utility bills (two consecutive years).
- Model validation using Percentage (%) Error and CV (RMSE) and MBE%.

Once the simulation input values are defined and readily entered to the baseline model, the results are compared. In the beginning stages, the desired tolerances are not achieved and the anomalies between the simulated and metered data (energy use in kWh of each building) are analyzed to identify and eliminate the input errors, the process is called debugging. The changes made during debugging are based on the earlier simulation input /output checks with the collated data, as also suggested by Kaplan et.al. (Kaplan 1990). It is obserevd during debugging that most of the errors are associated with the assigning of input variables to each zone i.e. operational schedules for appliances (i.e. fans, lighting, A/Cs, heaters/hot blowers etc.), ventilation selection and acitivity schedules of occupants. In case of residential buildings, the indoor thermal environment, occupancy and the operational schedules of the equipments are erratic, making it quite difficult to define these uncertainties. There are large number of zones in a typical multi-storied dwelling unit (each having 4-5 zones) and, therefore, great deal of effort, expertise and time is demanded for carrying out such calibration.

The main constraint faced during the calibration is to create a simulated environment of multiple dwelling units with multiple operation and activity schedules within each building. Therefore, decision is to be made prior to baseline models as to what level the details are used as model inputs. It is decided to construct a baseline model with high accuracy in building fabric details and thermal zoning, and to simplify the operation schedules of appliances and occupancy (details given in the following section) using average value based on responses of the occupants of HV, CV, BMD, GMR and TR.

The following section gives the summary of input data used in the baseline model for calibration:

Building Plans

The as-built building plans are obtained from the architect's office or concerned authorities of the apartment developers. Refer Figure 1a-e for the key plan and the floor plans of all the surveyed buildings. Site visits are conducted to cross check the data for any missing detail and to make any additions. Properties of windows, glazing type, shading from the nearby buildings, contextual details of the site are few of the other details that are also collected. The zones are decided as per the functional use of each room in a typical design layout of each dwelling unit (eg. Bed Rooms, Toilets, Kitchen and Living cum Dining room).

Figure 1 Typical Zones in a Dwelling Unit (Floor Plan of BMD)

Utility Bills

Monthly utility bills of all the buildings are collected for two consecutive years from the regional electricity board. The billing data includes the monthly kWh consumptions of all the dwelling units (DU). Budget and time are the main constraints to use data loggers with minimum intrusion (considering the dynamic environment of a normal household without supervision). And, considering the skepticism of the occupants, with the frequent visits, it is decided to conduct the survey on a monthly basis.

Spot Measurements

The spot measurements are made during the visits to record the indoor environmental variables (air temperature, T_a; globe temperature, T_g; relative humidity, RH & air velocity, A_v) of the surveyed dwelling units. This data is used to evaluate the accuracy of comfort output of the simulation software with the measured data. 'SIKA' MH 3350-Thermo Hygrometer was used to measure indoor air temperature and relative humidity (using sensor probe 'TFS0100 E') and indoor globe temperature was measured using sensor 'TP101' whose probe was inserted in a black-painted table tennis ball (40 mm diameter)

Operation Schedules

Structural and construction details provide the information about the thermal mass of the building envelope. However, heat flow process (gains/loss) through the building is a very complex system and depends upon the internal gains through lighting system, occupancy, heating and cooling systems etc. Therefore, one-to-one interviews were conducted with the residents (82) of each building on a monthly basis and data related to the number occupants/DU, tenure of tenancy, type of lighting system, operation hours of various appliances (fans, A/c etc.) is collected to assign the following schedules:

- Activity/occupancy
- Operation schedule of appliances (which directly or indirectly affects the heating and cooling load)
- Type of ventilation and heating/cooling systems for each zone.
- Window operation schedule

Zones are, usually, aggregated (merged) in simulation models; such that the multiple zones with similar operation schedules are represented as a single large zone in the model. This approach (i.e.'5 zone' per occupied floor having one core zone and four perimeter zones) has been the benchmark for the simulation results in the previous studies (Raftery et.al. 2011, Pan 2007). Such simplifications and approximations in the model can lead to the inaccuracies or uncertainty errors. It is important to note that the thermal processes depend on the function of each zone, its position with respect to the exterior and the method used to condition the space (Raftery et.al. 2011). Residential buildings, especially multi-storied ones, are dynamic in terms of operational schedules and occupancy. The occupancy density and energy load per floor area also varies from house to house and largely depends upon the socio-economic profile, tenure of stay etc. It is more challenging to calibrate buildings with such profile as compared to the commercial buildings where operational schedules and occupancy load remains the same all-round the year and, therefore, simulation models can be calibrated using typical schedules. Also, control of all the building systems is centralized in commercial buildings where in residential buildings personal preferences and occupancy behavior plays an important part in operational schedules of various energy-intensive appliances. It is observed in this study that it is important to assign the schedules on a zone to zone basis rather merging the zones (most preferred approach in commercial buildings).Therefore, the occupancy schedules, lighting loads and conditioning type are assigned on a zone-to-zone basis in this study.

The section below explains the operational schedules that are assigned for the simulation model (refer Table 3):

Lighting

A list of lamp types and number of lamps per zone is created to estimate the lighting power density of each zone. In most of the cases, the usage was predominantly around the late evening hours. In the present study, the schedule for lighting system is assumed to be running from 7am to 9am and 5p.m. to 12a.m (a standard family time when the occupancy is high and also the lighting is essential). It is notable that the lighting schedules vary in a domestic setup. Therefore exemptions made for the typical cases:

- During winters, with the early sunset and late sunrise, the lighting use varies.
- People who work late at night require a specific lighting schedule.

Occupancy

The number of occupants in each building is graphically presented in Figure 2 which shows that more than 60% of the houses have 2–4 occupants per DU. It must be noted that the unoccupied dwelling units are also identified using records of monthly utility bills and different schedules were assigned. The occupancy density per zone is estimated using number of working and non working occupants.In this study, each dwelling unit has one or two non working members (mostly elderly members of the family or the housewives) which explains the continous schedules used in the energy models. The houry usage of most of the appliances (like air conditioners, heaters, lighting systems etc.) were based on the inputs received from the field survey during monthly visit. It is important to note that the schdeules are phased (i.e if only 80% of the lights were on at a given it may change to 100% or 20% in later part of that day).

Fan, A/c, Heater/Blower, Hot water Geyser

Based on the data collected during monthly visits, running hours of each equipment is noted and schedules are assigned. The number of appliances and running hours varied for some cases as the disposable income level and the social stature varied for few of the surveyed occupants. But it is not marked enough to make any considerable changes within a building. Table 4 shows the running hour details of all the buildings.

Other daily-use appliances

The average running hours of Air Conditioners (A/c's), Instant Water Heaters (WH), Standalone Heaters (H), Computers (C), Laptops (L), Televisions (T.V) and Washing Machines (WM) for each of the building is summarized in Table 4. It must be noted that appliances with the constant wattage, like refrigerators, are not occupancy dependent where as daily use appliances like Televisions, Fans, A/C's, washing machines etc. are occupancy dependent. In case of refrigerators (with 24x7 hours usage), only the operation cycle varies throughout the day (depending upon the cooling load or indoor thermal load). The schedule for refrigerators are phased i.e. its operation cycle is high in the afternoon hours and low in the morning and evening hours of a typical day (predominantly in summer months). Also, the rate power per equipment is assigned on the basis of equipment labels or internet product searches.

Table 3 Operation schedules for each zone in a DU

Occupancy/Lighting	Assumed Schedules
Bed Room	7p.m to 7a.m & 9p.m to 6a.m
Living Cum Dining	9a.m to 7p.m
Kitchen	7a.m to 9p.m
Lighting	7a.m to 9a.m (Summer) 5p.m to 11p.m (Winter)

Table 4 Average Hourly Consumption of Appliances

	A/c	Fans	WH	H	C	L	T.V	WM
CV	2	9	1	1	1	2	3	5
HV	3	9	1	2	1	1	4	2
BMD	2	9	1	1	1	2	5	4
TR	2	10	0	2	1	1	5	3
GMR	2	10	1	1	1	2	4	4

** A/c: Air Conditioner; WH: Instant Water Heater; H: Standalone Heaters; C: Computer; L: Laptop; T.V: Television; WM: Washing Machine*

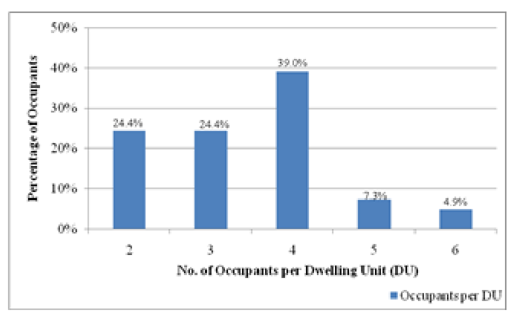

Figure 2 Distribution of number of occupants per dwelling unit (DU)

RESULTS AND DISCUSSION

Model Validation

The monthly energy-use curve of the calibrated model has closely resembled the contours of the curve created by the metered values (Figure 3 a, b, c, d & e).

However, to check for the accuracy of the simulation results, calibrated models needs to be validated based on its compliance for statistical indices within acceptable tolerances. The criteria generally vary for monthly or hourly measured data. The simulation model is created using input data collected from the year under study and the average of two years data is used to. Table 5 outlines the acceptable tolerances defined by the international standards. In this study, following three statistical indices are used to validate the calibrated baseline models: Percentage (%) Error; Coefficient of variance of the root mean squared error (CV RMSE) and Normalized Mean Bias Error (MBE%).Equation (1),(2) and (3) are used to calculate the Percentage (%) error, CV(RMSE) & MBE %

$$\% \text{ Error} = (y_{\text{simulated}} - y_{\text{measured}})/y_{\text{measured}} \times 100 \quad (1)$$

$$\text{CV RMSE} = 1/\bar{y}_{\text{measured}} \times \{\sqrt{[\sum(y_{\text{simulated}} - y_{\text{measured}})^2] / (n-p-1)}\} \quad (2)$$

$$\text{MBE (\%)} = [\sum(y_{\text{measured}} - y_{\text{simulated}})/\sum y_{\text{measured}}] \times 100 \quad (3)$$

where:

$y_{\text{simulated}}$ = monthly energy consumption (simulated value)

y_{measured} = monthly energy consumption (measured value)

$\bar{y}$= mean of monthly energy consumption

p= number of predictor variables

Table5 Acceptable tolerances defined by Guideline Standards

INDEX	ASHRAE 14 (%)	IPMVP (%)	FEMP (%)
CV(RMSE)	± 15	-	±15
MBE	± 5	±20	±5

(Coakley et.al, 2014)

The estimated percentage error of energy consumption between calibrated model and metered utility value is observed to be within the acceptable tolerance of ±25% for monthly data (refer Fig 4 a & b), as suggested in a similar study previously (Reeves 2012). The positive values indicated that the simulations have overestimated the results whereas the negative values mean that the simulations have underestimated the results as compared to the measured data. The CV (RMSE) and MBE% for the monthly electricity consumption is obtained within the acceptable tolerances (i.e. ±15% for CV(RMSE) and ±5% for MBE%), as defined in the ASHRAE Guideline 14-2002. Fig 5 illustrates the estimated CV (RMSE) and MBE(%) for the calibrated model of all the surveyed buildings.

Simulation output of the physical variables of the indoor environment are also compared with the spot measurement data (air temperature,Ta) and estimated data (radiant temperature,Tr). It is observed that the % error for Ta and Tr is within the acceptable limits for summer months and have significantly crossed the tolerances for winter months (especially November & December), refer Figure 6a&b. CV (RMSE) and MBE% of Ta and Tr of simulation model is also compared with the actual data. Table 6 clearly shows that CV(RMSE) for GMR, BMD and TR have marginally crossed the tolerance limit while it is within the acceptable limit for HV and CV. This difference is due to the varied use of standalone heaters within the dwelling unit during winter months. The spot measurements are taken in the living hall and most of the time there was no heater operating in the space, as occupants prefer to use it at evening/ night time. It is recommended that the level of details for baseline models should be framed as per the requirement of the study (i.e. only energy load or detailed heating/ cooling load).

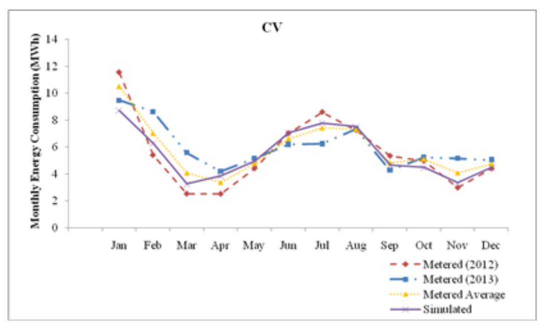

Figure 3 a Energy-use curves of calibrated (simulated) models vs metered utility value , CV

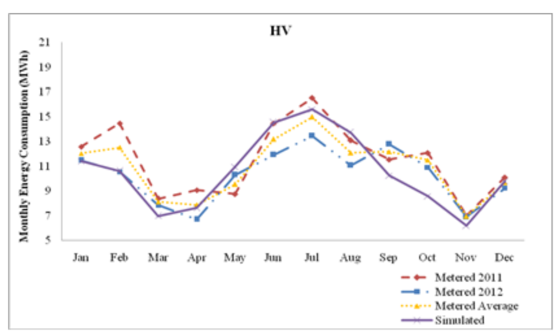

Figure 3b Energy-use curves of calibrated (simulated) models vs metered utility value, HV

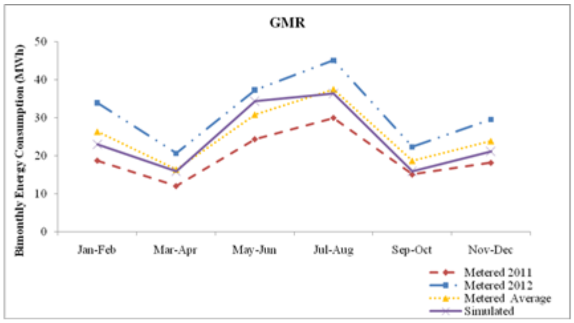

Figure 3c Energy-use curves of calibrated (simulated) models vs metered utility value, GMR

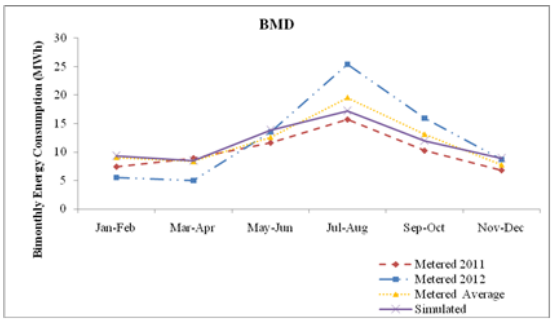

Figure 3d Energy-use curves of calibrated (simulated) models vs metered utility value, BMD

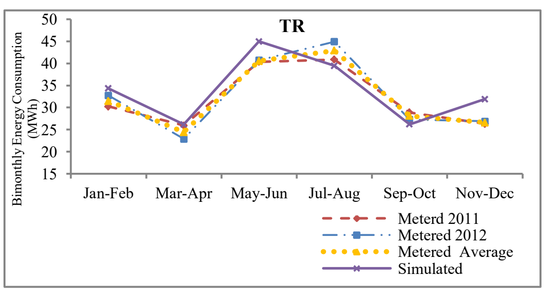

Figure 3e Energy-use curves of calibrated (simulated) models vs metered utility value, TR

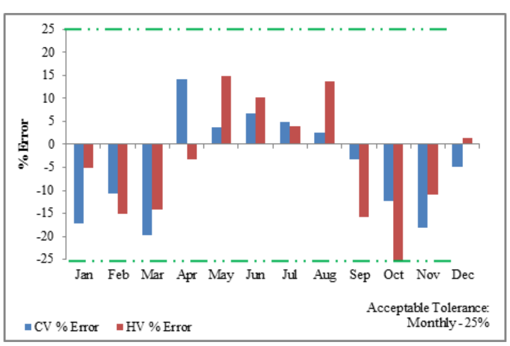

Figure 4a Percent (%) Error for energy use (HV & CV): monthly data

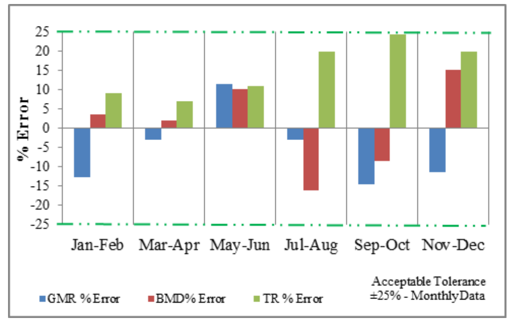

Figure 4b Percent (%) for energy use (GMR,BMD & TR): monthly data

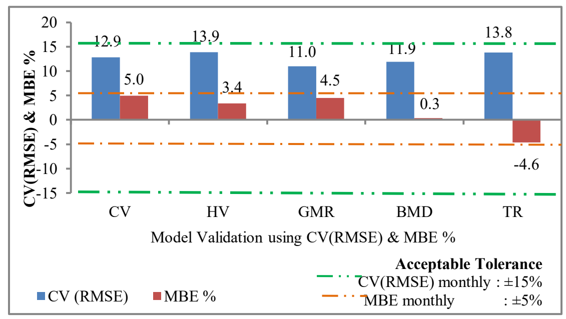

Figure 5 CV (RMSE) and MBE% of energy use: monthly data

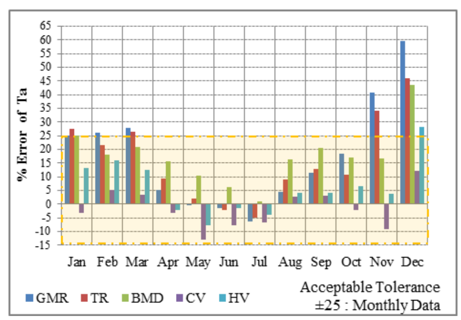

Figure 6a Percentage (%) Error of Air Temperature(Ta) : monthly data

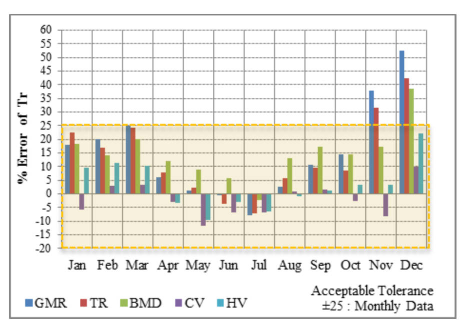

Figure 6b Percentage (%) Error of Radiant Temperature (Tr): monthly data

Table 6 CV (RMSE) of Ta and Tr

	Air Temperature (T_a)	Radiant Temperature (T_r)
GMR	19.4	16.9
TR	16.7	14.7
BMD	17.4	14.9
CV	7.6	6.8
HV	8.7	7.5

CONCLUSION

Evidence based manual calibration approach is adopted to calibrate five mixed-mode multi-storied apartment buildings in composite climate of India using Design Builder software. For evaluating the model accuracy, percentage error, normalized mean bias error (MBE%) and the coefficient of variation of the CV (RMSE) were calculated and found to be consistent with ASHRAE guideline 14 limits. Results have shown that measured values fairly calibrates the energy consumption of the existing buildings, however, physical variables of indoor thermal environment (Ta and Tr) has shown discrepancy for winter months. There are no set guidelines available to calibrate simulation models of multi-family buildings. The calibration approach used in this study, though requires lot of time and effort, but has proved to achieve acceptable tolerances for uncertainty. Considering the complexities (like occupancy behavior affecting the energy usage, varying energy load and occupancy density per zone etc.) and limitations (like consent and participation of the home dwellers, availability of metered values of the electricity usage in bimonthly period in some regions, cost etc.) involved in a domestic set-up, this calibration approach is well suited to Indian residential buildings for the early stage and has much scope of improvisation. For future studies data loggers and smart meters can be employed to record the hourly readings and this will not only improve the data accuracy but also ease the data collection process.

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Fig1a BhaimataDas Apartments (BMD)

Fig1b Growmore Society (GMR)

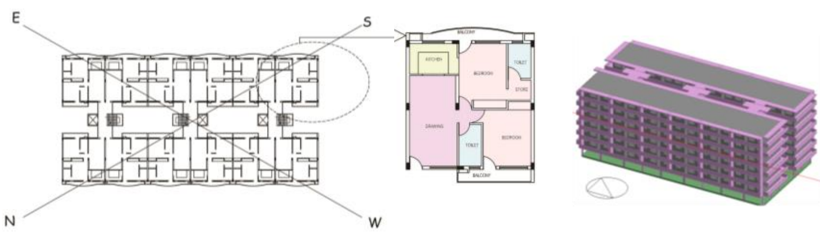

Fig1c Trishla Apartments (TL)

Fig1d HillView Apartments (HV)

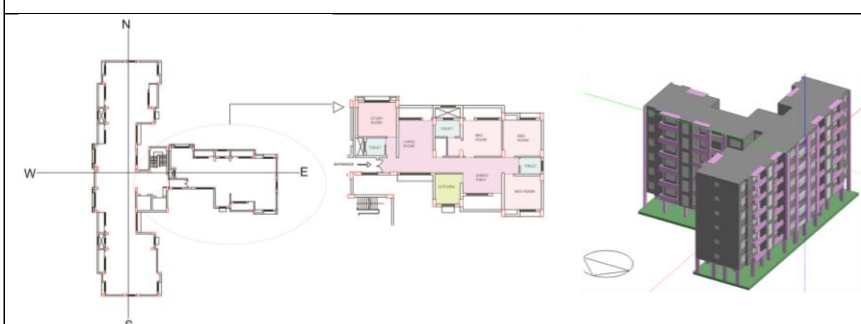

Fig1e Canal View Apartments (CV)

Bed Room
Living Room
Kitchen
Toilet