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Adaptive use of natural ventilation for thermal comfort in Indian apartments

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ABSTRACT

Thermal comfort research in India is in its nascent stage. Indian codes specify uniform comfort temperatures between 23 and 26 °C for all types of buildings. About 73% of energy in Indian residences is consumed for ventilation and lighting controls. Therefore, a thermal comfort field survey was conducted in apartment buildings in Hyderabad, which included information on the use of building controls. The present analysis is based on this database. Due to the poor availability of adaptive opportunities, 60% of the occupants were uncomfortable in summer. The comfort range obtained (26.0–32.5 °C) was way above the standard.

The occupants adapted through clothing, metabolism and the use of various controls like windows, balcony and external doors and curtains. The subjects operated the controls, as the indoor temperature moved away from the comfort band. At comfort temperature, maximum use of openings was found, which correlated robustly with indoor/outdoor temperature and thermal sensation. Use of controls was critically impeded by lack of privacy and safety and non-availability of controls. Several design and non-thermal factors, such as operation and maintenance of controls, mosquitoes, noise, and occupant's attitude, age and tenure impacted the occupant's adaptive behaviour and thermal comfort significantly. The building's '*restrained adaptive opportunity*' seriously hampered the occupant's thermal satisfaction and adversely affected the sensation vote.

1. Introduction

The indoor environment in naturally ventilated (NV) buildings greatly depends on the local climate and the way environmental controls are used. The severity of the effect of outdoor climate can be modified by the use of controls. Common controls like openable windows, blinds, doors, lights and fans offer the occupants some opportunity to modify the thermal environment, in their pursuit to comfort.

It was demonstrated in ASHRAE's RP-884 [1] research across several continents that, occupants of naturally ventilated buildings were comfortable in a wider range of temperatures than occupants of buildings with centrally controlled HVAC systems. Brager et al. [2] conducted field surveys in naturally ventilated buildings, where occupants had varying degrees of control over the windows. They concluded that personal control of operable windows and other controls improved local thermal conditions and occupant comfort [2–9].

Energy consumption in Indian residential buildings is the highest among Asia Pacific Partnership countries [10]. About 73% of the energy consumed in Indian residential buildings is used for lighting (28%) and ventilation controls (fans – 34%; Air coolers – 7%; A/c – 7%) to provide thermal and visual comfort indoors [11]. For a populous nation like India, the ramifications of this high energy use are serious. Moreover, environmental controls are important in reducing the need for high energy solutions, [12,13]. Behavioural use of controls links the physiology/psychology of the body and the physics of the building [2]. It is thus, a major link in the dynamic interaction between buildings and their occupants. Use of controls is also a key element in linking dynamic simulations of the human body and the simulation of buildings.

The use of controls is part of a feedback loop, the result of a very complex behaviour and is never an isolated action. While Nakaya et al. [14] observed that, "the use of one control, may change with use of another (e.g., closing windows and turning on fans)," Nicol and Humphreys [5] identified that, the perceived usefulness of a particular control will change from time to time depending on conditions.

These feedback mechanisms embodied in the adaptive principle create an order in the relationship between outdoor climate and comfort temperature in a NV building [5]. On the other hand, this order is broken in a HVAC building as outdoor climate is decoupled with the indoor environment. The database for most of the research, on the use of controls is obtained from all over the world, through

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field studies in office environments, [1,2,8,15,16]. Conceivable, the use of controls, and the triggers, for occupant behavioural action in dwellings are quite different. However, there are very few studies on the use of controls in residential environments [14,17] and also in comparison to the office environments in Asian countries [18,19]. There is little reported from India on the use of controls [20,21]. To fill this gap, a thermal comfort field study was conducted in NV apartments in Hyderabad, for three months in 2008 [22]. Key findings of the research can be found in Indraganti [23].

The "*adaptive opportunity*" provided by the building is difficult to quantify [5] and it decides the ability of the occupants to remain comfortable [12]. Interestingly, use of controls defers the use of higher level of controls like air-conditioners, as shown by Nakaya et al. [14], to a higher temperature level in hot climates. The way occupants use controls cannot be predicted exactly, but is a stochastic (probabilistic) process, driven by the efforts of the occupants to avoid discomfort.

Windows and doors connect the indoors with the outdoors physically, visually and spatially, by allowing natural ventilation, views and light into the interiors. Balconies, especially acting as shaded semi outdoor spaces, provide the much needed thermal relief to the occupants of flats during the hot seasons [24]. Nicol and Humphreys [5] propound that, the mere existence of a control does not mean that, it is used or improves the buildings' adaptive opportunity. Hence, it was necessary to observe the availability and adaptive use of these systems used as controls. Therefore, an investigation into the possible linkages between the use of controls and the thermal sensation of occupants of apartments in Hyderabad was carried out.

The present paper will present the main results of the thermal comfort field study [22,23]. This paper also explains (1) the way these controls were used by the occupants in apartments, (2) the investigation of various design aspects of an apartment which affect of the thermal behaviour of occupants in using (/non-use of) various controls and (3) the impediments the occupants faced, in using them adaptively.

2. Methods

Hyderabad is situated in the Deccan plateau of India and is the State capital of Andhra Pradesh. Hyderabad, lies on 17°27′N latitude and 78° 28″E longitude and is classified into 'composite climate' with four distinct seasons: winter, summer, monsoon and post monsoon [11]. The survey was carried out in summer (May) and monsoon months (June and July) in the year 2008.

2.1. Measurement of indoor and outdoor data

Outdoor temperature and humidity data for all the days of survey were procured form the local meteorological station. Mean minimum outdoor temperatures during summer and monsoon sample periods were 27.3 °C and 24.1 °C, respectively. Mean maximum outdoor temperatures of the summer and monsoon sample periods were 40.4 °C and 34.2 °C, respectively. Over the summer study period, the mean 8:30 h and 17:30 h relative humidity (RH) were 38.6% and 26.7%, respectively. The relative humidity in the monsoon period was relatively higher. The mean 8:30 h and 17:30 h relative humidity (RH) were 66.1% and 46.7%, respectively.

Five small to medium sized apartment buildings, having three to six floors, named KD, SA, RA, KA and RS, located in central and eastern parts of Hyderabad city were chosen for the study. These are reinforced cement concrete post and beam structures with 115–230 mm cement plastered brick walls. Excepting KA and RS, all these buildings have stilted ground floors, used mostly for car/scooter parking. The top floor concrete roof slabs of these buildings are seldom protected from excessive solar heat gain. A few of them are provided with false ceiling, which is used mostly for its ornamental purpose. No other capacitative/convective insulation or radiant coating is provided on these roofs. Typical floor plans of the buildings are presented in (Appendix 1–5).

Sample sizes of a maximum of 113 subjects with 38 males and 75 females were achieved in summer and monsoon surveys, respectively (about a 100 most of the time). Although the same sample was retained in all the surveys, the sample size varied slightly in each month as some subjects refused to participate. A total of 3962 sets of data were provided by a maximum of 113 respondents, of whom 35% were men and 65% were women. The average age of all subjects ranged between 35 and 50 years across all buildings. The average age of male subjects was slightly lower and the average age of all subjects was 42 years (Table 1).

The survey was conducted in forty-five flats located in various floors in the five apartment buildings [22]. Indoor environment was recorded using calibrated digital instruments, following class – II protocols for field study. A mobile tripod with instruments at 1.1 m form the floor level (Fig. 1) was used onsite, in all the apartments to collect measurements of the indoor atmospheric environment. The instruments showed concurrent physical data (air temperature, RH, globe temperature, air velocity), representing the immediate environment of the subject. A minimum time interval of 2 h was maintained between two consecutive readings taken in any single apartment. The survey was conducted during the day, slightly slipping into the night. (7 am–11 pm) Hence, no measurements/observations of behavioural adaptation could be noted down during night time.

The surveys were conducted in two levels: transverse and longitudinal. Most of the subjects participated in both the surveys that spanned 33 days. The transverse survey was conducted on a single day, followed by four days of longitudinal survey, in each month in all the apartment buildings. The questionnaires were designed based on McCartney et al. [25]. Both transverse and longitudinal questionnaires had six sections: Basic identifiers, thermal responses, clothing level checklists, metabolic activity checklists [26], personal environmental controls being used and skin moisture and productivity. In addition, the transverse survey also had questions on tenure, sensation and preference (TP) for other environmental parameters, behavioural and structural adaptation methods adopted and impediments in using various controls.

Table 1
Comprehensive profile of investigated subjects - longitudinal surveys.

Month	Subject (Nos)	Gender	Weight (mean) kg	Weight (SD) kg	Height (m) (mean)	Height (SD)	Body surface area (mean) m^2	Body surface area (SD) m^2	Age (years) mean	Age (years) SD
May	32	Male	71.46	14.47	1.71	0.09	1.81	0.20	40.14	14.00
June	35		71.58	14.14	1.72	0.09	1.81	0.19	41.38	14.12
July	37		70.62	13.55	1.71	0.09	1.80	0.18	41.92	13.92
May	61	F.Male	59.36	9.62	1.60	0.05	1.63	0.12	40.40	10.69
June	63		60.52	10.89	1.61	0.05	1.63	0.13	42.52	11.00
July	66		60.06	10.44	1.61	0.05	1.63	0.12	43.24	11.65

SD = Standard Deviation; Body surface area, $S = 100.315 \cdot W^{0.383} \cdot H^{0.693}$ where, S = Body Surface Area (m^2), W = Weight (kg), H = Height (m).

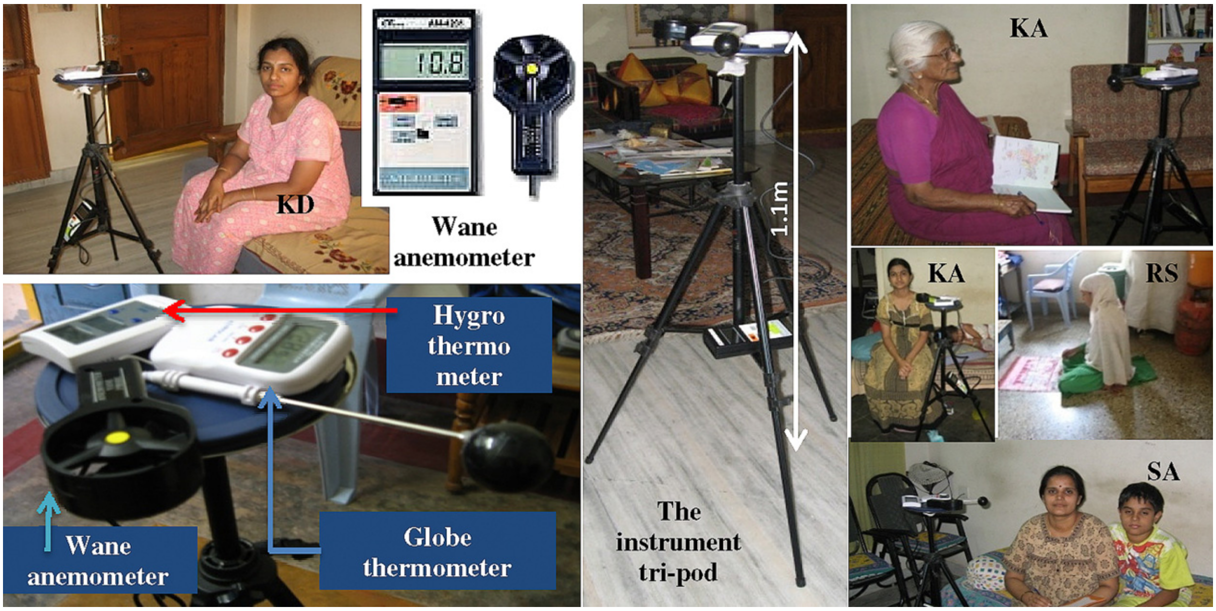

Fig. 1. The survey environment, instruments and the instrument setup.

The thermal sensation scale was the ASHRAE seven-point scale of warmth ranging from "*cold* (−3) *to hot* (+3) *with neutral* (0)" in the middle. Nicol's thermal preference scale asked on a five-point scale whether, the respondent would like a change in the thermal environment. Possible responses were "*much cooler; a bit cooler; no change; a bit warmer* and *much warmer*". Thermal preference was measured as a binary input (1 = *unacceptable*; 2 = *acceptable*).

Clothing garment checklists were adapted to the regional customs prevailing in Andhra Pradesh and compiled from the extensive lists published in ASHRAE hand book [26]. Where near equivalent ensembles in the standard lists were not found, for ex. clothing insulation for Indian ensembles like sari was estimated based on the equation [27]. $\mathbf{I_{cl}} = 0.00103 \cdot \mathbf{W} - 0.0253$; where, $\mathbf{I_{cl}}$ = Clothing Insulation (clo) and **W** = weight of the sari in grams (g). To the I_{cl} value obtained using the above formula, the clo value of a petticoat (0.15) was added, giving the total I_{cl} value of the ensembles of cotton and polyester saris to be 0.54 and 0.61 respectively. All the $\mathbf{I_{cl}}$ values were added 0.04 clo for undergarments. In addition, upholstery insulation of 0.15 clo was added when the subject was seated or found resting [1].

Metabolic rates were assessed by a checklist of residential activities and were based on the detailed databases published in ASHRAE hand book [26]. The metabolic rates ranged between 0.7 Met (sleeping) and 2.0 (standing working) in this study. Body surface area was estimated using the formula [28]: $\mathbf{S} = 100.315 \cdot \mathbf{W}^{0.383} \cdot \mathbf{H}^{0.693}$; where, **S** = Body Surface Area (m^2), **W** = Weight (kg), **H** = Height (cm). Fanger's PMV [29] values were estimated using ASHRAE comfort calculator [30]. Absolute humidity (kg/m^3), wet bulb temperature (°C) and vapour pressure (Mbar) were estimated using a humidity calculator [31]. The detailed description of sample, buildings and questionnaires are presented in [23].

3. Results and discussion

3.1. Subjective thermal responses and neutral-temperature

Table 2 presents the summary of indoor climatic data, subjective thermal evaluation and calculated indoor climatic and thermal comfort indices. In this survey only about 40% of the subjects voted comfortable (voting within +1 to −1) on the sensation scale, preferring a temperature on the cooler side of the neutrality, despite accepting their thermal environments in May, (mean **TS** = 1.8; mean TP = 1.3). This was due to the poor adaptive opportunities available to the occupants of apartments to cope with the harsh thermal conditions encountered in summer.

As the apartments were least protected from excessive solar heat gain in summer, the indoor temperature often reached much higher levels from the skin temperature, especially in the roof exposed flats. For example, structural roof treatments like double roofs, reflective paints, thicker roofs etc., were seldom provided. Intense direct solar gain from the roof in summer further exacerbated the thermal conditions indoors. In addition, the occupants also had very little access to shaded semi-open cooler spaces to '*adaptively move about*' during the hot period. Thus, poor adaptation in apartments had resulted in a majority feeling uncomfortable in summer. However, thermal sensation, preference and acceptance have improved in June and July as temperature receded. As the temperatures were moderate, the adaptive measures were just adequate, to result in a near neutral vote in these months, similar to the findings of Heidari [32]. Therefore, the adaptive thermal comfort model is the first step, in the development of sustainable thermal comfort standards. It includes various environmental, behavioural and psychological adaptations and thus assumes great importance. These adaptations are known to affect the thermal acceptance of an environment [33].

A complex relationship was found between thermal sensation, preference and acceptance. Subjects voting beyond the central categories have also accepted the thermal environment, while some subjects voting within (−1 to +1) have also voted the environment unacceptable. Similar results were obtained by Han et al. [34].

A subject is said to be comfortable if he/she votes within the three central categories of the sensation scale. The distribution of comfort was approximated using the polygonal regression analysis against the indoor globe temperature. It was found that, little or no discomfort was experienced by 80% of the subjects, when the mean indoor temperature was between 28.7 and 32.5 °C. Thermal sensation vote was regressed against indoor globe temperature, which yielded the relation, $\mathbf{TS} = 0.31\boldsymbol{T_g} - 9.06$, with a moderate

Table 2
Summary of indoor climatic data, subjective thermal evaluation and calculated indoor climatic and thermal comfort indices; Thermal sensation was rated on ASHRAE's seven-point scale (−3: *cold to* +3: *hot*) preference on Nicol's five-point scale (−2: *much warmer to* +2: *much cooler*) and thermal preference on a nominal scale (1 = *unacceptable*; 2 = *acceptable*).

Season (Month), Sample size	Descriptive statistic	Air temperature (°C)	Relative humidity (%)	Wet bulb temperature (°C)	Air speed (m/s)	Globe temperature (°C)	Thermal sensation (measured) (TS)	Thermal preference vote (TP)	Thermal acceptability (TA)	TSI (C)	PMV
Summer (May), 1405	Mean	**34.7**	**27**	**23.1**	**0.5**	**34.5**	**1.8**	**1.3**	**1.7**	**32.0**	**3.9**
	SD	1.6	9	0.7	0.5	1.8	1.0	0.6	0.5	2.1	0.9
	Maximum	39.3	63	26.4	4.0	42.0	3.0	2.0	2.0	37.8	7.8
	Minimum	26.7	14	17.8	0.0	26.7	−2.0	−1.0	1.0	23.2	0.1
	r	0.46	−0.31	−0.03	0.08	0.42	–	0.53	−0.37	0.28	0.42
Monsoon (June), 1334	Mean	**30.9**	**53**	**23.2**	**0.5**	**31.2**	**0.5**	**0.7**	**1.9**	**29.9**	**2.3**
	SD	1.2	6	1.6	0.4	1.2	0.8	0.6	0.2	1.2	0.6
	Maximum	33.8	76	28.2	2.2	34.1	3.0	2.0	2.0	32.7	3.7
	Minimum	27.4	39	13.9	0.0	26.6	−2.0	−1.0	1.0	24.5	−1.6
	r	0.42	−0.15	0.08	−0.04	0.40	–	0.60	−0.31	0.34	0.38
Monsoon (July), 1223	Mean	**30.3**	**55**	**20.4**	**0.4**	**30.7**	**0.4**	**0.6**	**2.0**	**28.8**	**2.1**
	SD	1.1	6	1.4	0.4	1.1	0.7	0.6	0.2	1.1	0.5
	Maximum	33.8	68	26.7	2.0	34.7	3.0	2.0	2.0	32.6	3.7
	Minimum	25.8	39	10.7	0.0	28.0	−1.0	−1.0	1.0	24.4	−0.6
	r	0.20	−0.23	0.01	0.01	0.25	–	0.61	−0.25	0.19	0.25

SD = Standard deviation; r = Correlation with thermal sensation; TSI = Tropical summer index; PMV = Fanger's predicted mean vote.

coefficient of correlation of 0.65 ($p < 0.001$). A neutral-temperature of 29.2 °C and a comfort range (voting within −1 to +1) of 26.0 °C and 32.5 °C was thus obtained. This range is much higher than the comfort range of 23–26 °C, specified in the Indian Codes [35]. Fanger's predicted mean vote (PMV) was found to be always higher than the actual sensation vote. As PMV does not take into account the adaptation and acclimatisation of the occupants, PMV was higher and had a higher correlation with globe temperature ($\boldsymbol{T_g}$), ($r = 0.93$, all data), similar to Nicol et al. [15].

3.2. Adaptation through clothing and metabolism

The total clothing insulation values ranged between 0.19 and 0.84 clo in all the three months. Female clothing insulation was slightly higher (mean = 0.62, SD = 0.124, range = 0.19–0.80), while the average male clothing insulation was found to be slightly lower (mean = 0.53, SD = 0.117, n = 1358 range = 0.27–0.84). This suggests that, the personal clothing adjustments in women were limited by socially and culturally acceptable minimum clothing practices, more so in middle aged women. A similar observation was made by Cena and de Dear [36]. For example most men during the summer midday were found wearing only shorts/*Lungi* (a 2 m × 1.2 m long white cloth wound around the waist), as part of clothing adaptation.

Adaptation through slowing down of metabolic activity, together with clothing adaptation was also evident. Preferred activity during summer midday was post- meal siesta (0.7 Met) in lighter clothes (0.15–0.3 clo), if possible. Interestingly, there was a good negative correlation observed between, clothing and metabolic activity, ($r = -0.42$, all data). Most subjects preferred to wear lighter clothing, (for ex: long gown (women), clo = 0.29) when engaged in high metabolic activities like kitchen work etc.

3.3. Adaptation through the use of physical controls in the room environment

All the investigated spaces had openable windows and external doors as the study was conducted in the living rooms, although few of them lacked balconies. Whilst most of the windows were fitted with curtains/blinds, a few of them lacked these. The use of various controls was noted down as binary data, (0 – closed; 1 – open). As the focus was on opening and closing behaviour, percentage of open area in a window/door could not be measured. Physical controls like windows, external doors, curtains and blinds and balcony doors were investigated, in conjunction with the changes in the indoor environment.

Assumable, the thermal sensation of the occupants was higher during the midday in summer, and was found to be closely related to the pattern of the use of controls; rather they both formed a feedback loop in the residential environments studied. The proportion of open windows (POW) and the proportion of open balcony doors (POB), varying with the time of the day (Fig. 2), suggests the same.

It can be observed that most of the windows and balcony doors remained closed during the most overheated period in summer (May), when the outdoor temperatures were very high and humidity was at its lowest. As wind was blown from the hot exterior, opening windows and balcony doors during such hours, added only to the dry heat discomfort, convective and radiant gains.

It can be further observed that a lesser proportion (POW = 35%) of windows remained open, towards the midday, while slightly a higher percentage (POB = 50%) of balcony doors remained open. This was partially due to the fact that, most of the windows were fitted with sunshades (width 450 mm–600 mm) and opened into the exterior directly, while the balcony doors opened into a shaded

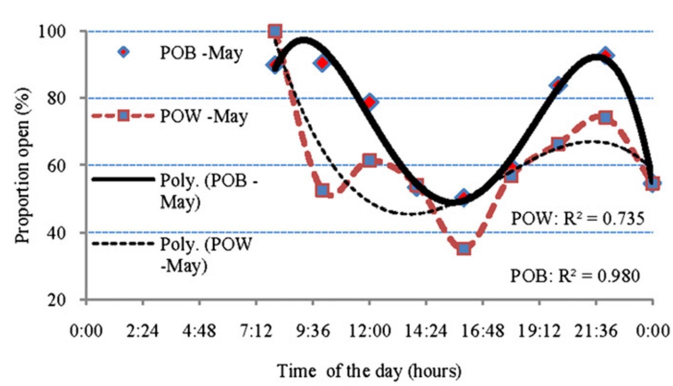

Fig. 2. Time dependency of proportion of open balcony doors and windows, (May – All data).

semi enclosed space. These were further examined in the subsequent sections in detail.

3.3.1. Adaptive use of windows

All the environments surveyed were fitted with openable wooden/aluminium windows. The size of the window varied between 1.0 and 6.0 m^2. The subjects in all the flats adaptively opened and closed the windows to maintain comfortable conditions indoors. The analysis of proportion of open windows with the mean outdoor temperature, indoor globe temperature and thermal sensation revealed the same. It can be noted that the proportion of 'open window' (POW) increased with outdoor mean temperature ($\boldsymbol{T_o}$) until $\boldsymbol{T_o}$ reached 31–32 °C, and thereafter the percentage of open windows (POW) slowly reduced. Thus, it resulted in a robust negative correlation between the POW and the $\boldsymbol{T_o}$ ($r = -0.74$, all data), (Fig. 3). This is in confirmation to the findings of others [15–17,37].

The summers in Hyderabad are hot and dry, marked with low humidity and high outdoor temperature with high diurnal swings. As $\boldsymbol{T_o}$ increased, the occupants adapted through closing the windows, as open windows would add to the dry heat discomfort. The subjects then adaptively used fans and other electrical controls, for air movement, necessary at such high temperatures. It was found that the use of coolers was beginning when the outdoor mean temperature ($\boldsymbol{T_o}$) was at 28.5 °C and A/c s were found in use when $\boldsymbol{T_o}$ was above 31.3 °C.

Fig. 3 shows the relationship of proportion of open windows with outdoor, indoor temperature and thermal sensation. While there were small individual differences in the POW in various buildings, it was generally observed that POW reached its average of ∼60% when $\boldsymbol{T_o}$ was close to 31.5 °C. While the total POW is highest in KD (75%), it is lowest in RS (37%). POW in RA has not changed much with the outdoor temperature. The POW remained around the average value of 58%. This was primarily due to the fact

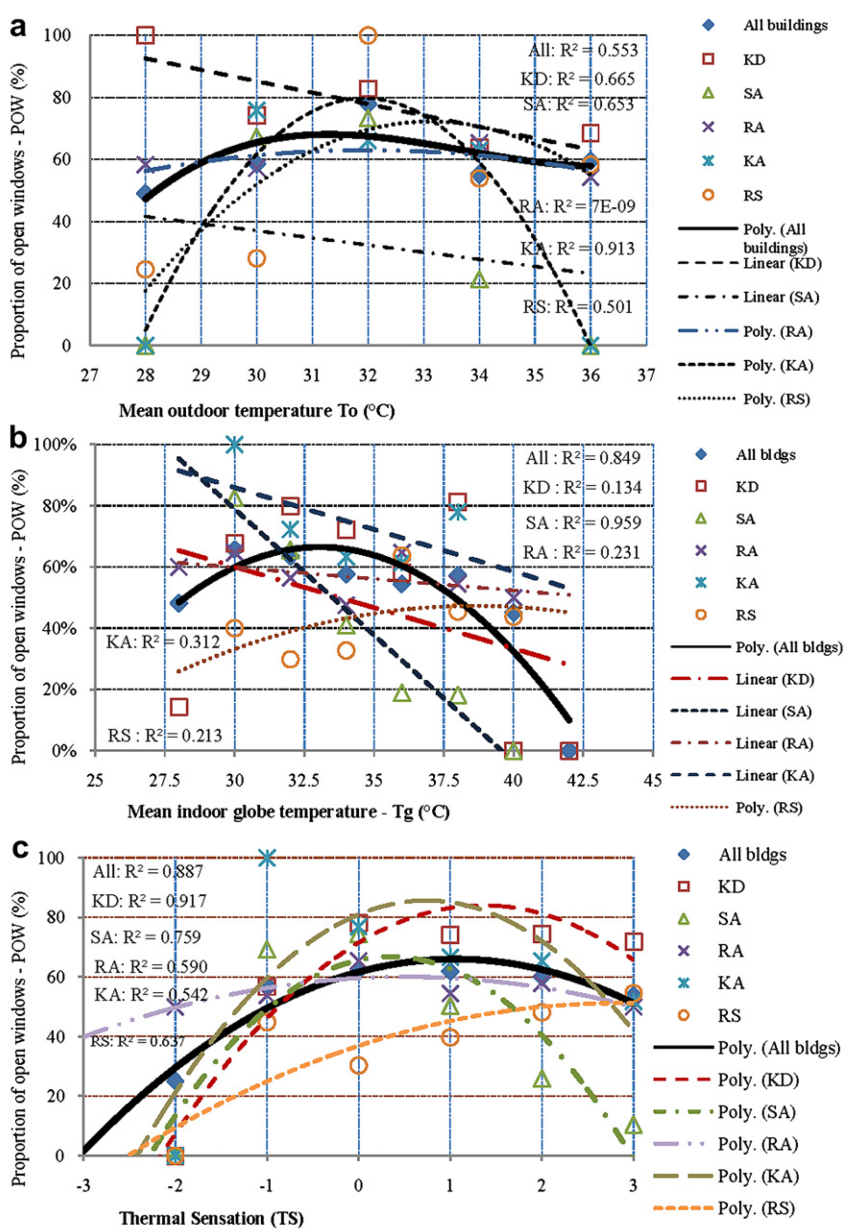

Fig. 3. Distribution of proportion of open windows with (a) outdoor mean temperature; (b) indoor globe temperature; (c) thermal sensation (All data).

that, the window opening behaviour was also affected by various other factors such as privacy, convenience, safety, sun penetration, attitudes, etc., as explained in the subsequent sections.

Nevertheless, at high $\boldsymbol{T_o}$ values, POW had stabilised in most of the buildings, while in some, it increased. Window opening behaviour was more dependent on the indoor globe temperature [6], which represented the immediate environment of the subject, than the outdoor mean temperature. This was because; window opening/closing resulted, in direct response to the growing indoor discomfort, as part of a feedback loop of thermal comfort. That is, as the subject experienced the increased indoor temperature, he/she responded immediately to the stimuli, by closing or opening the windows. Thus, people opened the windows in response to the increase in the indoor and outdoor temperatures [16,17]. Explaining this phenomenon, Raja et al. [38] observed that the indoor climate, the outdoor climate and a mixture of both might drive the use of controls. Barlow and Fiala [39] noted that, opening windows was the most favourite adaptive opportunity [33], followed by controlling solar glare, turning lights off locally and controlling solar gain. Conversely, Hellwig et al. [40] find poor but significant correlation between window opening behaviour and room temperature in schools in summer, possibly due to several impediments in opening the windows.

As shown in the scatter plot between POW and indoor globe temperature (Fig. 3b), the subjects operated the windows as the indoor temperature moved away from the comfort band [6]. At comfort temperature, usually the highest POW was recorded, as observed in all the buildings. This clearly explains the occupants' adaptive behaviour, as open windows often produced cold drafts at lower temperatures. At higher temperatures, they resulted in dry heat discomfort coupled with high radiant heat gain, usually experienced in hot summers.

It is important to note that, occupants' sensitivity to air movement became very sharp as the subjects moved away from thermal neutrality. Understandably, most of people voting beyond the central three categories on the thermal sensation scale also found the air movement inadequate. An analysis of thermal sensation with the proportion of open windows further revealed interesting facts (Fig. 3c). It can be inferred that, the proportion of open windows increased from TS '*slightly cool* to *slightly warm*' in most of the buildings, as the warmth increased. The POW remained stable (at its maximum value), when the thermal sensation was between *slightly warm* and *warm*," where the effect of cross ventilation through open windows was most desirable. Importantly, at thermal sensation of *hot*, most subjects preferred closing the windows to avoid heat gain, and hot breezes, as explained earlier. Moreover, when the windows were oriented towards the east/west aspect, as in RA, they permitted direct solar radiation deep inside the interior, further increasing the discomfort. Noticeably, the shading devices (450–600 mm deep) were inadequate to give sun protection. Conceivable, when the occupants voted on the cooler side of thermal discomfort, POW was low, as it prevented cold drafts.

There is further evidence to explain the adaptive use of windows as the discomfort increased. As shown in the scatter plot between POW and time of the day (Fig. 4), the POW was highest in the morning and lowest at 40% during midday in May, (coinciding with the most overheated period). In addition, it can also be observed that POW fluctuated most (100%–40%) in May (TS $= -1 \sim +3$), moderately in July and least in June. This can be attributed to the changes in the humidity and temperature in these three months and the changing air movement requirement.

In May, as elucidated earlier, higher discomfort was mainly due to the hot – dry conditions and higher cross ventilation during the overheated period added only to the heat gain and discomfort. Closed

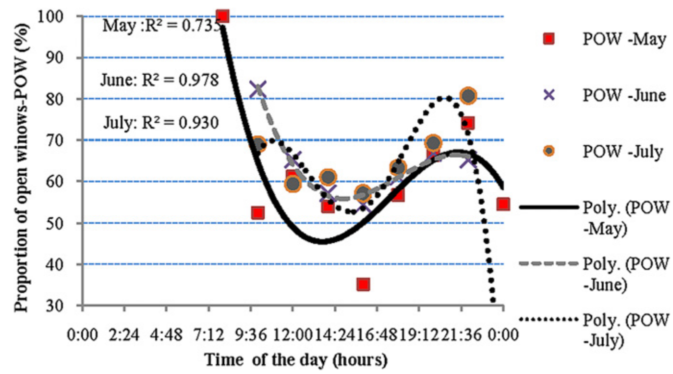

Fig. 4. Scatter plot showing changes in proportion of open windows with time (All data, May, June and July).

windows contain heat gain in hot summers [3]. In this survey, a lower POW was found, at high temperature and discomfort (at TS $= 3$).

On the contrary, in June, the indoor temperature was around the skin temperature and humidity was relatively higher. In these conditions, thermal relief was obtained by higher ventilation. This was reflected in higher percentage of open windows found throughout the day in the month of June. In July, the temperature was below the skin temperature and increased ventilation was not much desired, unless the subject was in high metabolic activity. Much as expected, the diurnal variation in POW was moderate in July. Umemia et al. [41] find that, the window opening behaviour related closely with outdoor relative humidity in their Japan study.

3.3.2. Balcony doors

As the survey was conducted in the living dining rooms, most of the flats have balconies attached (99%). It was noted that the use of balcony doors also contributed substantially to indoor comfort. The proportion of open balcony doors (POB) varied with the mean outdoor temperature and indoor temperature in a similar manner as that of open windows. The POB correlated robustly with globe and outdoor mean temperatures (Fig. 5). Similar to POW, in all the buildings, POB has also recorded a lower value as the discomfort has increased, as analysed earlier. However, it is important to note that, a higher percentage of balcony doors remained open (58%–86%) than the windows (37%–75%).

This was due to the fact that, most of the windows opened directly into the exterior of the building or into a public corridor, which strongly affected the window opening behaviour. On the other hand, the balcony doors opened into a semi covered private open space, mostly under the private realm. Thus, balcony doors offered better privacy and glare protection to the interior, resulting in higher usage.

However, there are differences observed, among individual buildings, in the way the balcony doors were adaptively operated. For example, in RS, a higher percentage of balcony doors were kept open, even at very high indoor temperatures. It was noted that, individual tolerance limits to hot breezes, subject's thermal history of air conditioner usage, frequency of power breakdowns and availability of other electrical controls have also affected the adaptive use of windows and doors. It is important to note that, subjects in RS faced power shortages most, and did not have A/c s at home. They depended more on natural air movement indoors, because some of the subjects in RS were able to tolerate high temperature wind drafts also.

It was observed that, the POB recorded its maximum value at an indoor temperature range, close to indoor comfort temperature. Thereafter, POB dropped, similar to POW. It can also be inferred that, POB slightly increased from TS '*neutral*' to TS '*slightly warm*', where

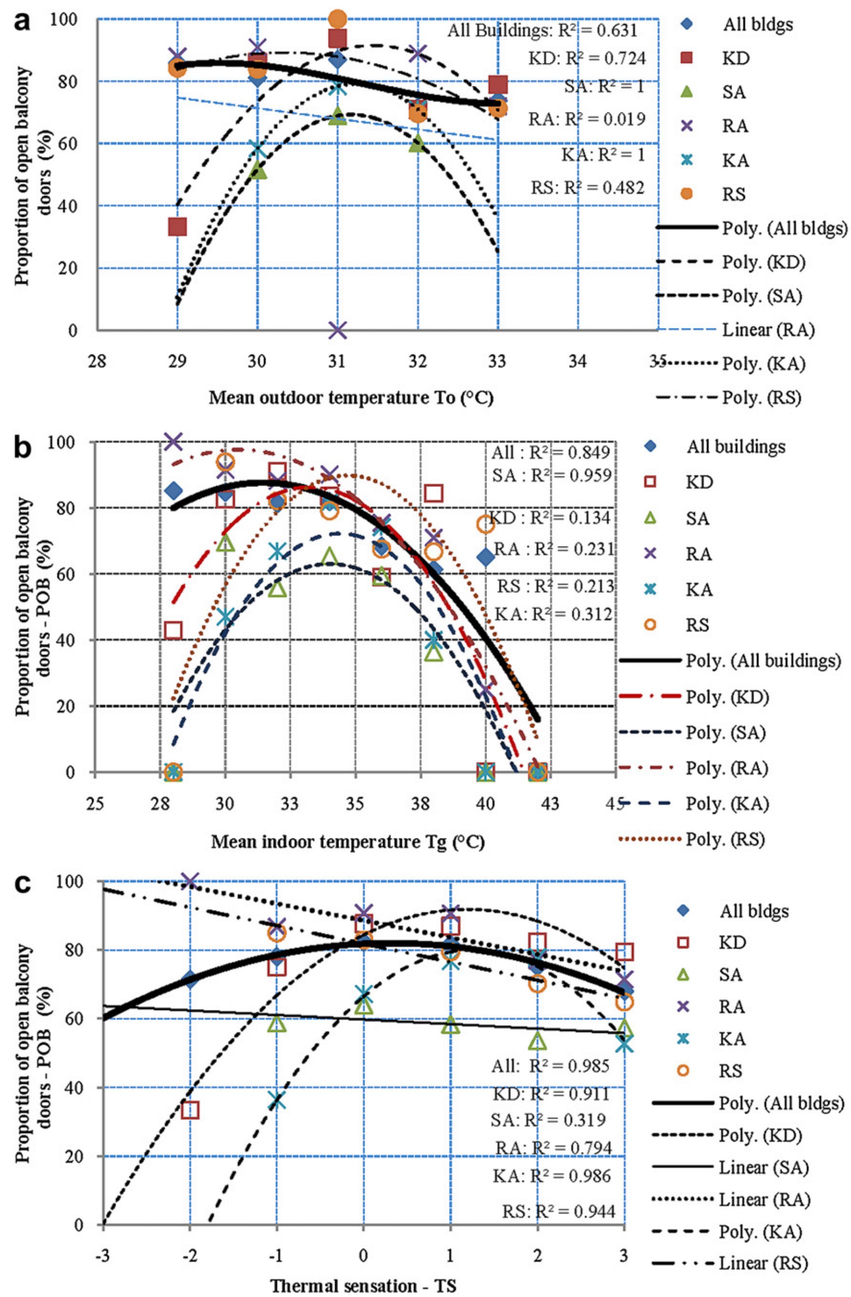

Fig. 5. Distribution of proportion of open balcony doors with (a) outdoor mean temperature; (b) indoor globe temperature; (c) thermal sensation (All data).

the effect of ventilation in restoring thermal comfort is very effective. It usually coincided with the indoor temperature of 32–33 °C. This point of POB inversion has changed slightly from building to building. It is also observed that, in buildings where the use of AC is high, this point of inversion is towards the lower side of the temperature. Rijal et al. [16] observe that the temperature band between opening and closing windows (the "*dead band*") is about 4 K.

Thermal sensation and percentage of open balcony doors correlated robustly, ($r = -0.99$). Balcony door opening behaviour was very much similar to that of window opening behaviour. That is, as the occupant's sensation vote moved away from the central three categories, the adaptive closure/opening of balcony doors increased. The balcony door opening behaviour was dominated by the thermal sensation and air movement requirement at the hour of voting, with most balcony doors remaining open when the subjects were at neutrality. As the discomfort increased, up to about TS = 2, the percentage of balcony doors, remaining open had increased, suggestive of adaptive adjustment to permit higher air movement. Percentage of open balcony doors remained the lowest at the highest levels of discomfort in KA.

3.3.3. *Curtains and blinds*

When bright diffused or direct sunlight through the windows caused discomfort at high temperatures, it resulted in the adaptive use of curtains ($r = -0.87$, all data), as seen in all the buildings (Fig. 6). The materials used for curtains were light to medium weight cotton and polyester, which were opaque in nature. Very little natural air movement and light were permitted by these curtains when drawn. A few apartments were also fitted with semi-transparent polyester lacy curtains, which permitted some light even when drawn. In addition to the excess daylight penetration and other thermal requirements, adaptive operation of curtains

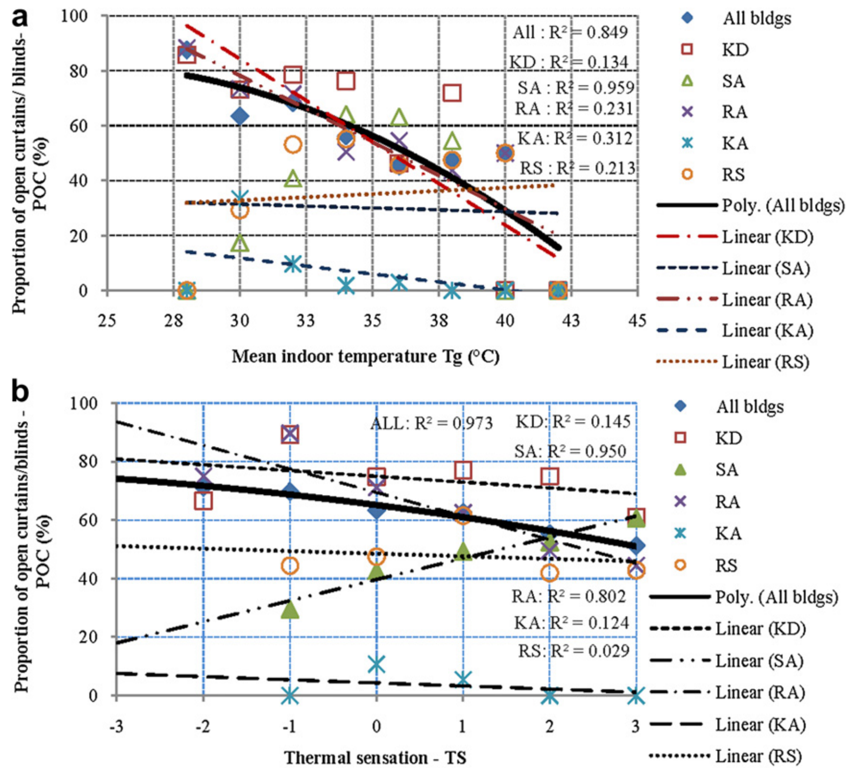

Fig. 6. Distribution of proportion of open curtains/blinds with (a) indoor globe temperature; (b) thermal sensation (All data).

was also affected by the requirements of privacy, attitudes, and other such non-thermal aspects as seen in the subsequent sections. It was also observed that, the orientation and shade factor of the window and sky conditions affected the adaptive curtain opening [6]. For example, in SA, the windows faced the eastern aspect and the curtains remained closed even at low indoor temperatures, as they would allow a lot of direct light causing discomfort glare. Similarly subjects with large windows as in KD have closed the curtains adaptively during the day in summer to avoid glare and diffused light from the exterior. Nicol and Humphreys [6] found a relationship between proportion of blinds closed and external illuminance and also sky influence.

In apartments KA and RS, the availability of curtains as an adaptive control measure was found to be limited, due to economic and other reasons and the subjects hung bed sheets and other textiles over the windows adaptively, to avoid direct sun and glare during the most overheated period of the day. Adaptive closure of curtains/blinds, where available increased, as the occupant's thermal sensation had increased from -1 to $+3$. At TS of $+3$ (*hot*), it was observed that, the curtains have been drawn, as the bright light induced glare, which aggravated the discomfort. In addition, the subjects had a psychological feeling of '*coolth*' associated with dim light in hot seasons (especially, during the hot midday in summer). Moreover, when the subjects adapted through, slowing down of their metabolic activity, like sleeping during the day, low light was preferred, and it resulted in drawing of curtains. Similar to POW and POB, POC was observed to be at its maximum when the subjects were comfortable, as observed in all the buildings. As TS moved beyond the comfort band, towards the warmer side, a higher percentage of blinds were closed. Nicol et al. [6] find that, the use of blinds varied with the external illuminance, and there is a significant ($p < 0.001$) difference in the frequency of use of blinds in air-conditioned (30%) and naturally ventilated (41%) buildings. They further find that, whilst lighting is most probably being used to offset low external illuminance, the use of blinds is more linked to the weather. Blinds are more likely to be used to offset the glare and heat on sunny days. The open windows and doors lower the indoor temperature through cross ventilation, while the blinds and curtains cut down the direct solar radiation and glare [42][1] .

3.3.4. External doors

The occupant behaviour on the use external doors was much similar to that of windows and balcony doors (Fig. 7). As noticed in the case of other controls, the proportion of open external doors was at its maximum when the TS vote is within the comfort zone. As explained earlier, when the subject was uncomfortable (TS beyond the comfort zone), he/she displayed a tendency to close the external doors as open doors would bring in hot breezes indoors. Interestingly, there are individual differences in buildings, on the way external doors were adaptively. Although thermal sensation correlated poorly with open doors in the UK study of Raja et al. [38] there was robust correlation with open windows and it was the most effective means of control.

The behaviour of external door opening was also affected by the aspect of privacy, habits and attitudes in addition to the other thermal factors, such as protection from direct solar radiation etc. For example, when the external doors opened into the open corridor exposed to the direct solar radiation, it resulted in a low value of POD, as in the case of SA, RA and KA. The detailed floor plans of buildings are presented in [23]. Conversely, in RS and KD, as all/most of the external doors have opened into the covered interior corridors, the subjects have preferred to keep a higher percentage of the external doors open as the TS vote increased from *neutral*.

[1] Developed a window opening algorithm based on the field study findings.

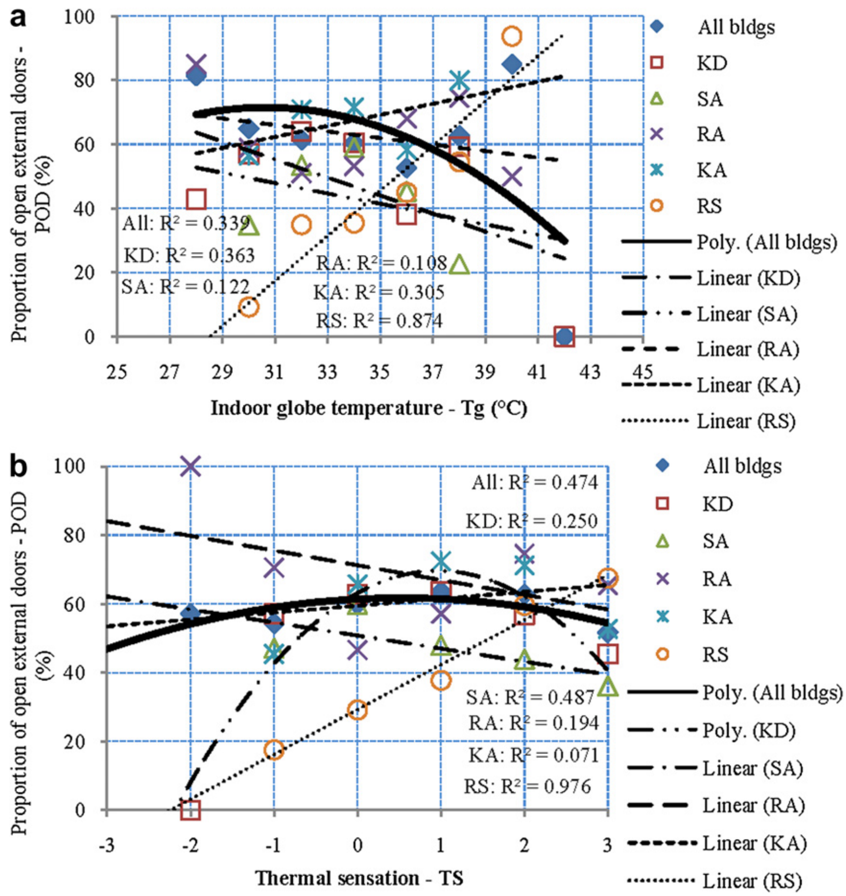

Fig. 7. Distribution of proportion of open external doors with (a) indoor globe temperature; (b) thermal sensation (All data).

3.4. Impediments in using the controls

3.4.1. Attitudes

The adaptive use of physical controls like windows, balcony doors, external doors, blinds and curtains in the room environment was also observed to be affected by the attitudes, habits, privacy and security aspects, in addition to the thermal necessities. Some subjects have displayed an attitudinal indifference towards the adaptive use of windows. This was particularly observed, when fans were available to provide air movement necessary in warm - humid months (June and July): for example, in RA and RS. This sluggishness to operate the physical controls was also observed, when high efficiency environmental controls like A/c s were easily available to the subjects in their bedrooms, as in KD.

On further investigation, it has been found that, some older subjects, due to their lower mobility, could not operate the windows and doors adaptively, while in some cases the hardware necessary to keep the shutters in position was dysfunctional. It has also been pointed out that the windows opening into a narrow public corridor (SA, RA, and RS) often interfered with the movement of building users, which in turn forced some of the subjects to keep the windows and doors shut.

Table 3
Effect of privacy on the window opening behaviour and mean indoor globe temperature (T_{gm}): Month wise distribution of proportion of open windows in the public and private realms (all data). Higher indoor mean temperatures were recorded in the interiors with windows opening into the public realm, as they were used less adaptively.

Month	Realm	Open windows									Indoor Globe temperature (°C)					
		All			LF			RE			All		LF		RE	
		POW (%)	FOW (n)	FTW (n)	POW (%)	FOW (n)	FTW (n)	POW (%)	FOW (n)	FTW (n)	Mean	SD	Mean	SD	Mean	SD
May	Public	**50**	388	772	**50**	280	562	**51**	108	210	**34.5**	1.1	**34.9**	1.4	**35.8**	1.4
May	Private	**63**	401	633	**68**	220	325	**59**	181	308	**33.7**	1.6	**34.0**	2.0	**34.3**	2.4
June	Public	**51**	298	588	**50**	215	426	**51**	83	162	**31.0**	1.1	**31.3**	1.2	**32.2**	1.1
June	Private	**72**	536	746	**81**	356	441	**59**	180	305	**31.0**	1.2	**31.2**	1.2	**31.5**	1.1
July	Public	**61**	356	586	**61**	246	406	**61**	110	180	**30.6**	1.0	**30.7**	1.0	**31.1**	0.9
July	Private	**66**	421	637	**71**	272	381	**58**	149	256	**30.3**	1.0	**30.5**	1.0	**30.9**	0.9

Realm = The Realm, windows open into: Public = 0, Private = 1, FOW = Frequency of open windows (n); FTW = Frequency total of windows (n); POW = Proportion of open windows (%); Tgm = Mean globe temperature; SD = standard deviation; All = All flats; LF = Lower floor flats; RE = Roof exposed flats.

Fig. 8. Image showing closed windows and doors. Windows/doors opening into the public realm (corridors) and without proper sun protection were seldom used adaptively, due to restricted privacy and safety.

Interestingly, subjects in higher economic groups (KD) preferred to use electric lights during the day, on closing the curtains. This was partially to have glare-free light and also to display certain social status.

3.4.2. *Effect of privacy on window/door opening behaviour*

The occupants in roof exposed (RE) flats are exposed to harsher environments due to high solar exposure. The importance of availability and use of adaptive controls to achieve thermal neutrality at high temperatures, in roof exposed (RE) flats is explained in Indraganti [23]. The window opening realm (WOR: public: 0, private: 1) was noted down in all the field surveys, as binary data. An analysis of use of controls revealed that, the adaptive behaviour of operation of controls was strongly affected by the realm into which the control opens, *viz*: public or private.

Therefore, the proportion of open windows in both the realms has been analysed month wise in both lower (LF) and roof exposed (RE) floors. From this analysis it was inferred that, the aspect of privacy impeded the adaptive opening of windows significantly. In all the cases considered, the percentage of open windows was lower, if the windows opened into the public realm. Window opening realm (WOR) and the proportion of open windows correlated robustly ($r = 0.841 - 0.53$) and is significant statistically ($p < 0.01$) when tested at 5% level of significance. Naturally, this affected the indoor globe temperature adversely. In all the cases studied, higher mean indoor temperature was recorded in environments with windows opening into the public realm, due to the lower POW (Table 3).

As explained in the Section 3.3.4, door opening realm affected the external door opening behaviour also, since it determined the privacy of the interior space. Thus, use of controls was restricted by design, which in turn, adversely affected the indoor comfort, especially in summer (May). It is also imperative to note that, a higher indoor mean temperature ($\boldsymbol{T}_{\mathbf{gm}}$) was recorded in flats with windows opening into the public realm. Interestingly, this

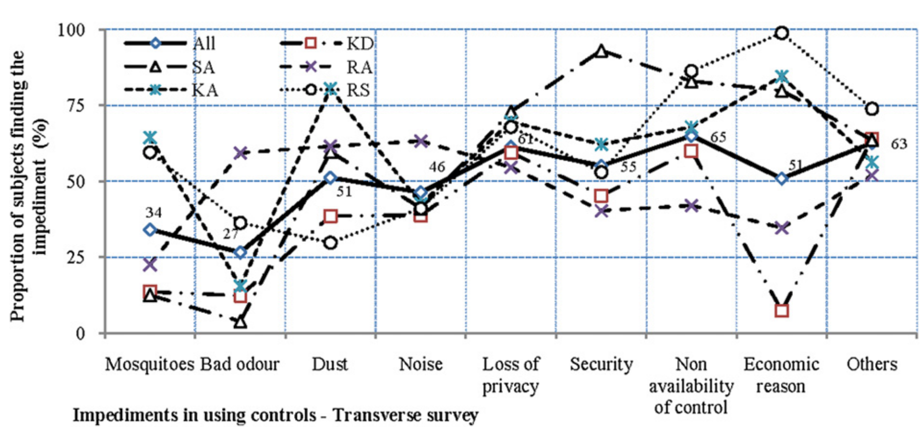

Fig. 9. Proportion of subjects finding various impediments in using the controls adaptively in various buildings and on all data – Transverse survey.

Fig. 10. Some adaptive interventions applied to windows, doors and balconies to promote higher adaptive use, as found in KD, KA and RS. (A, B): Bamboo blinds hung on balcony openings and (C) Planter box extension to windows to reduce glare and sunlight and curtains and to improve privacy, (D, E, F) : Metal grill gates to main doors and metal grill enclosures to balconies to improve safety, privacy and cross ventilation. (G) Additional door shutters with mosquito screens and vents for improved cross ventilation, (I) RCC *Jalis* applied to corridors for safety, sun control and cross ventilation.

difference was not very prominent in other months as POW had lesser effect on $\boldsymbol{T}_{\mathbf{gm}}$ in other months. Similarly, the aspect of privacy affected the way external doors, balcony doors and curtains were adaptively operated (Fig. 8). On the contrary, it was also observed that the balcony doors were opened and closed adaptively in KA, even though most balcony doors opened into the public realm ($R^2 = 0.98$).

The subjects in the transverse survey were asked to choose from a list of possible impediments, the occupants usually face in using the controls adaptively. Free answer responses were also solicited. These were recorded by the author in the field note book separately. On analysis, it was inferred that, loss of privacy, security and non-availability of control were the major impediments, in addition to several others cited by the subjects, like bird and stray animal (monkeys, dogs and cats) menace (Fig. 9). As explained earlier, the windows and external doors opening in the public realm seriously hindered the usage of controls and almost negate adaptive opportunity available. For example, in RA and SA the windows opening in to the public realm were rarely opened (see Appendix 2 and 3), despite the thermal necessity. Moreover, improper shading devices, dysfunctional latches and bolts fitted to the windows and doors also have deterred the subjects from using these controls adaptively.

While economic reason was the major impediment in KA, RS and SA, security in SA, bad odour and noise were found to be major impediments in RA. These impediments were analysed in conjunction with contextual features of the neighbourhood. It can be further comprehended that, these contextual features have in fact, impeded the adaptive use of controls by the occupants: for example, RA is ensconced by construction activity and obnoxious smells from Husain Sagar, a highly polluted lake, in close proximity.

Similarly, mosquitoes were found to be a major impediment in using the controls in KA and RS as both these neighbourhoods were pervaded by a lot of mosquitoes and the flats were not fitted with mosquito screens due to economic reasons. Dust was found to be a major impediment in KA (80%) as all the entrance corridors were laid along the busy urban street, also with construction activity around. Similarly, Raja et al. found that there were many non-thermal factors that dominated the door opening behaviour, like privacy, safety and noise [38], shading, views [8]. Anderssen et al. [17] further add that the perception of the environment and factors concerning the dwelling also impacted the window opening behaviour.

A majority of subjects especially in roof exposed floors considered '*non-availability of controls* and *the economic reasons*' as major impediments in achieving thermal comfort. Important among the other reasons cited by the occupants as impediments, were stray animals and birds, hardware problems connected with the operation of the controls, lack of knowledge about the control, tenancy status, operational difficulty etc. It is important to note that, tenure affected the way controls were used. Owners letting out apartments seldom undertook the necessary modifications required for entrance doors, windows and balconies to improve their adaptive usage. Therefore, modifications such as, additional metallic grill shutters to external doors, planter boxes to windows, grilled enclosures to balconies, mosquito screens etc., were seldom provided in tenant occupied apartments (Fig. 8: RS). Fig. 10 presents some adaptive interventions applied to windows, doors and balconies to promote higher adaptive use of openings, as found in KD, KA and RS. Interestingly, all these were fitted in owner occupied tenements. These additional fitments were found to improve safety, security and privacy of the interior space, which in turn improved the adaptive usage of the controls, especially in summer. Therefore, availability of controls and their appropriate use is primordial to better performance of the building and for improving occupant satisfaction [38].

4. Conclusions

The thermal environment and comfort responses of residents of Hyderabad, lying in composite climatic zone were investigated. A field survey was conducted in May, June and July in the year 2008. The use of environmental controls like windows, doors and curtains and comfort responses of about 113 occupants of 45 flats in five apartment buildings were studied. Both psycho-physical and attitudinal impediments and hindrances in the use of adaptive controls have been investigated into. A total of 3962 datasets were collected in longitudinal and transverse surveys conducted in summer and monsoon seasons, for a total of 33 days. Indoor and outdoor environmental data were obtained, following ASHRAE class – II protocols for field studies and from the local meteorological station respectively. Outdoor temperatures in May were very high coupled with low humidity. In June and July moderate temperature and high outdoor humidities, marked with occasional summer showers were recorded. Indoor environments in all the apartments followed the outdoor conditions closely, with minor differences in individual buildings.

The following are the conclusions:

1. Due to the poor adaptive opportunities available, about 60% of the occupants were uncomfortable in summer. However, as the adaptive opportunities were just adequate in the monsoon season, subjects voting comfortable increased to 93%. Thermal acceptance vote depended on several non-thermal aspects as well and was found to have a complex pattern.
2. A neutral-temperature of 29.2 °C and a comfort range (voting within -1 to $+1$) of 26.0 °C and 32.5 °C was obtained through regression analysis. This range is much higher than the comfort range of 23–26 °C, specified in the Indian Codes.
3. The occupants have well adapted through clothing and metabolic activity, as the temperature increased in summer. Personal clothing adjustments in women were limited by socially and culturally acceptable minimum clothing practices, more so in middle aged women.
4. On analysis of the physical environmental controls like windows, balcony doors, external doors and curtains, it was found that, the subjects adaptively used them in their quest to better comfort. The subjects operated the windows/doors/curtains as the indoor temperature moved away from the comfort band. At comfort temperature, usually the highest percentage of open windows/doors was recorded, as observed in all the buildings. As summer in Hyderabad is predominantly hot and dry, at high temperature, windows/doors/curtains were closed to contain heat gain, glare and hot breezes. The subjects were found to use fans and other electrical controls for air movement necessary for thermal comfort at high temperatures.
5. Proportion of open windows/doors showed a robust correlation with the outdoor and indoor temperatures and thermal sensation, in confirmation with the earlier studies by others. However, Window opening behaviour was more dependent on the indoor globe temperature, which represented the immediate environment of the subject, than on the outdoor mean temperature.
6. It was observed that, adaptive opening of balcony doors was higher than windows, as balcony doors offered better sun protection, glare control and privacy. This was due to the fact that, most of the windows were fitted with small sunshades (width 450 mm–600 mm) and opened into the exterior aspect or corridor directly, while the balcony doors opened into a shaded, semi enclosed private space. Understandably, this '*restrained adaptive opportunity*' posed by the buildings, seriously hampered the occupant's thermal satisfaction and adversely affected the sensation vote.
7. Curtains were found to be adaptively used as the temperature and discomfort increased. Their adaptive use depended on daylight penetration, orientation and shade factor of the window. In addition, it was also affected by the requirements of privacy, attitudes and other such non-thermal aspects.
8. Restricted mobility due to age, attitudinal indifference and sluggishness in various groups of subjects was found to hamper the adaptive behaviour and the use of controls, especially, when other easier controls like fans, coolers and A/c s were available to the subjects. However, the air coolers and A/c s were beginning to be in use when the mean outdoor temperature was above 28.5 °C and 31.3 °C respectively.
9. It was inferred that, lack of privacy critically impeded the adaptive use of openings and significantly influenced the indoor comfort in turn. In all the cases considered, the percentage of open windows was lower, if the windows opened into the public realm. In addition to privacy (realm), lack of safety and non-availability of control were found to be the major impediments. Besides these, operation and maintenance of controls, mosquitoes, stray animals and birds, noise, tenure of the apartment and several contextual issues critically impeded the use of controls and impacted the occupant's adaptive behaviour.
10. Additional fitments such as (a) additional metallic grill shutters to external doors, (b) planter boxes to windows, (c) grilled enclosures to balconies, (d) mosquito screens etc., were found to improve safety, security and privacy of the interior space, which in turn improved the adaptive usage of the controls, especially in summer. These were seldom provided in tenant occupied apartments.

4.1. *Suggestion for better adaptive use of environmental controls*

1. It is therefore suggested that, in residential environments in addition to the provision of operable controls,
   a. the aspect of '*open-ability and operability*' of a window/opening shall be given the top priority in the design process, while deciding its position or placement *vis a vis* a public space.
   b. provision of appropriate additional fitments/features to improve the adaptive use of controls be made mandatory, as it would improve the occupant's adaptive behaviour, to yield significant energy savings. (Some possible examples are presented in Fig. 10).

It is also suggested that the codes be modified to make certain mandatory provisions for effective solar heat control through the roofs of top floor apartments to contain direct solar gain; (for ex. capacitative roof insulation with high time lag, double roofs, etc).

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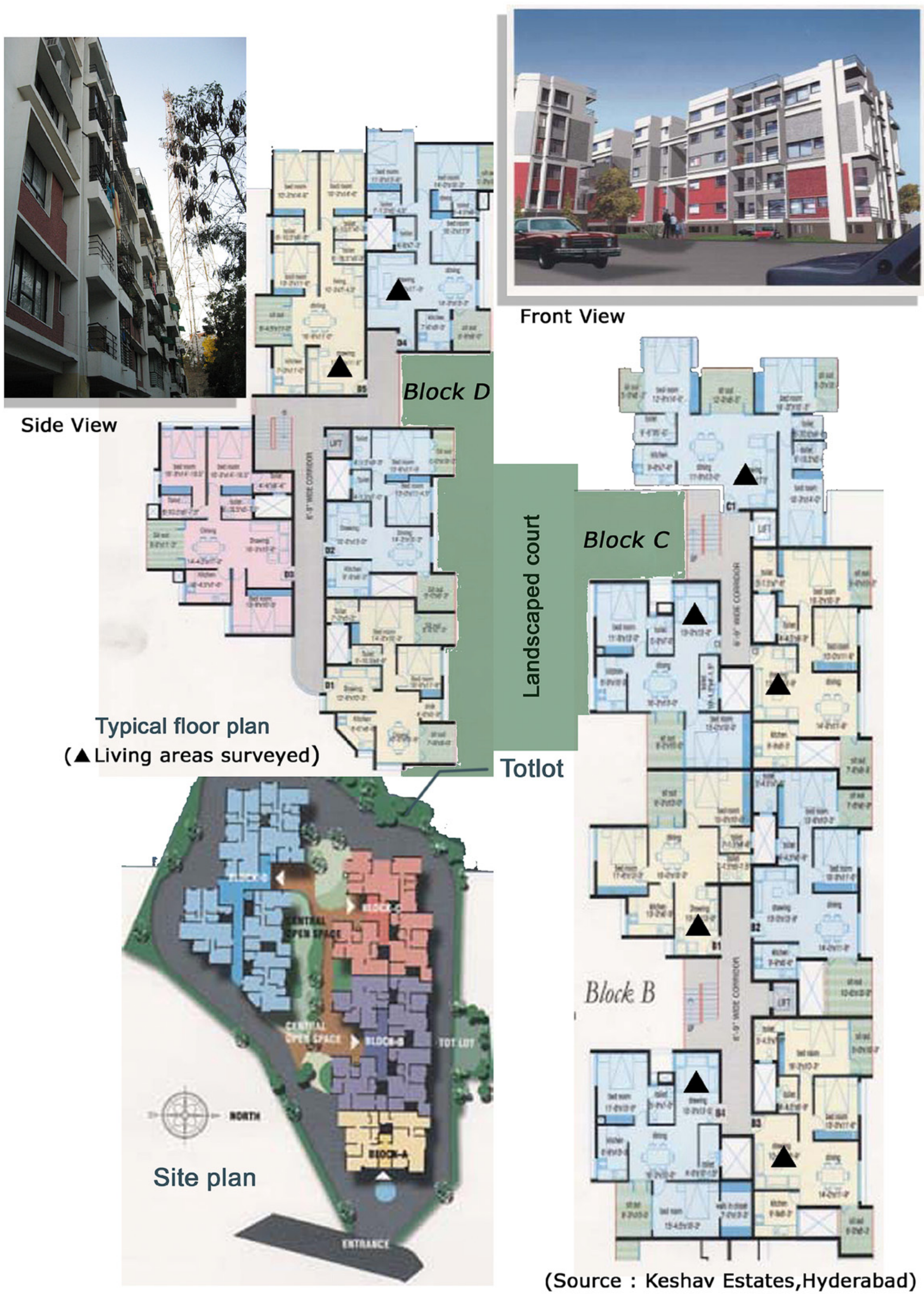
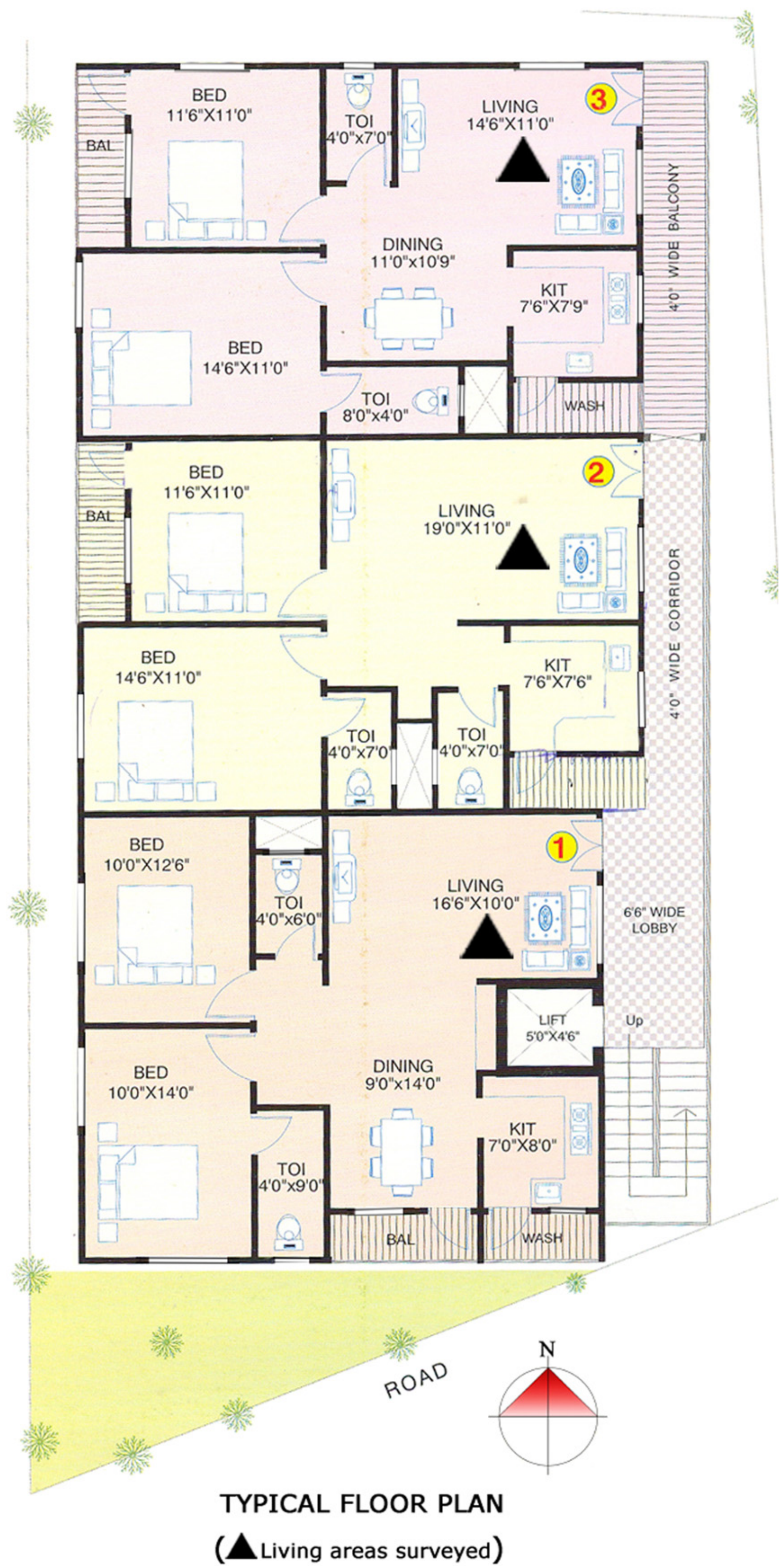
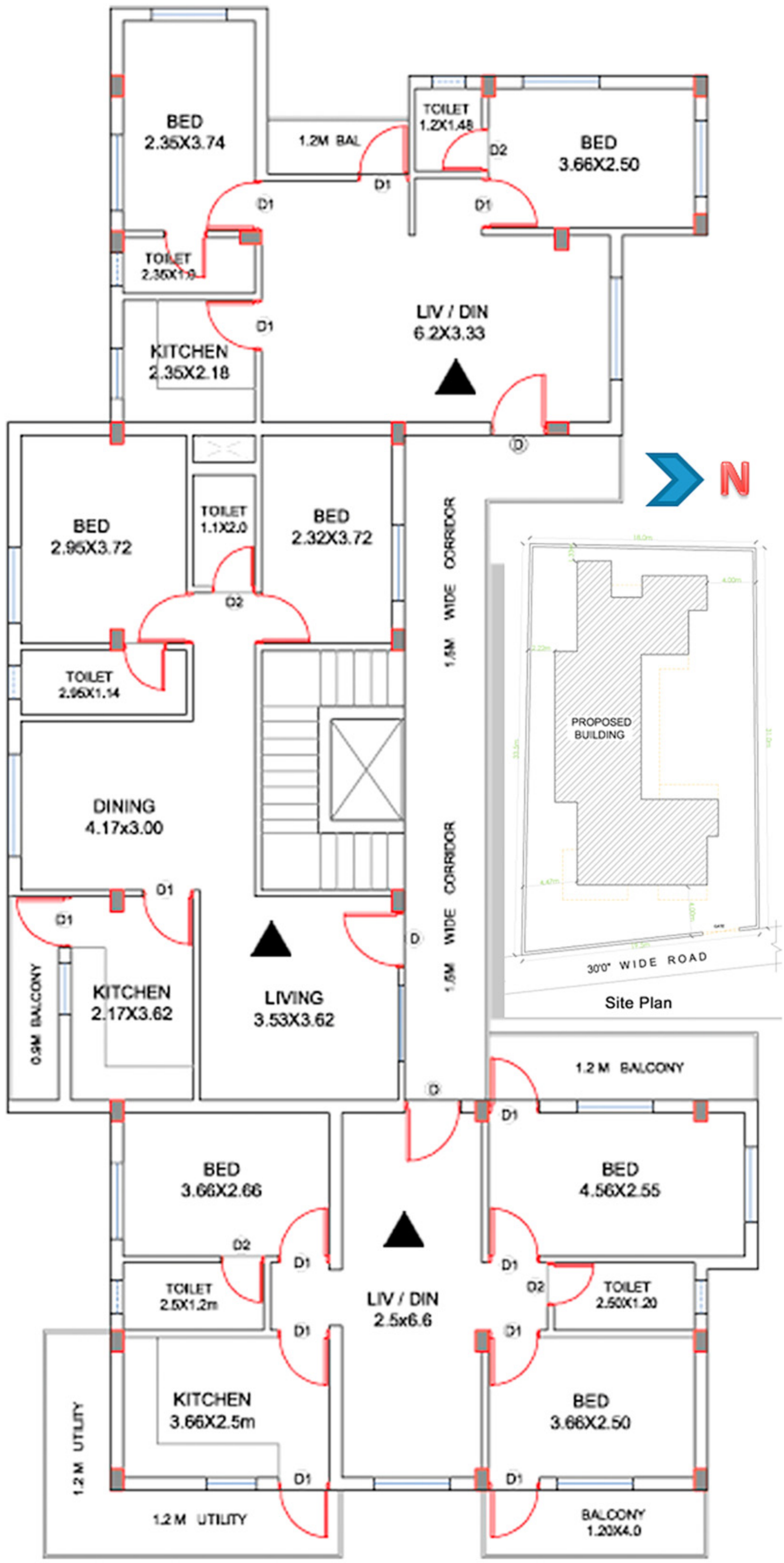
Appendix 1. Typical floor plan of KD



Appendix 2. Typical floor plan of SA

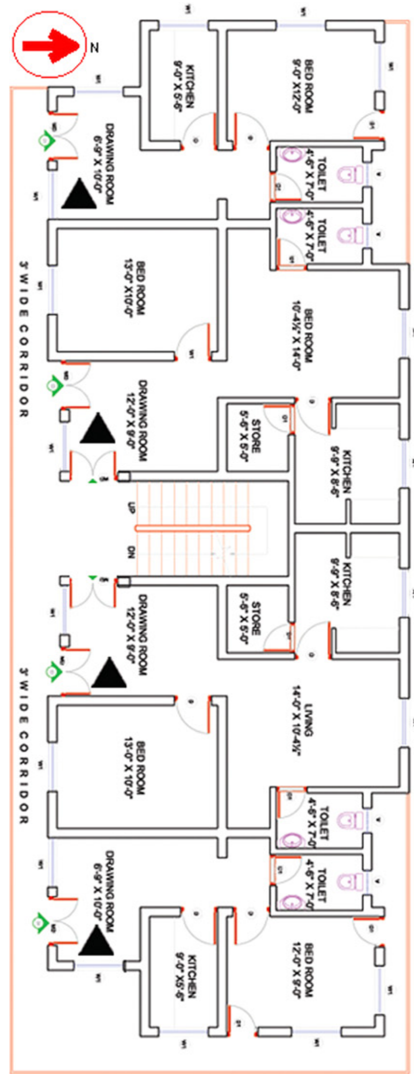


Appendix 3. Typical floor plan of RA

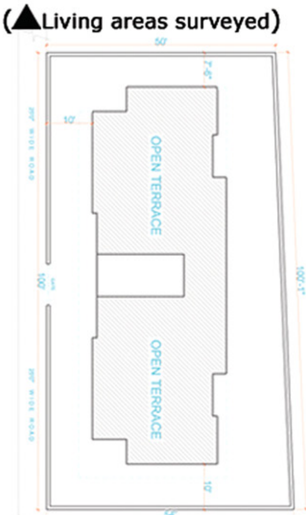


Typical Floor Plan
(▲ Living areas surveyed)

Appendix 4. Typical floor plan of KA

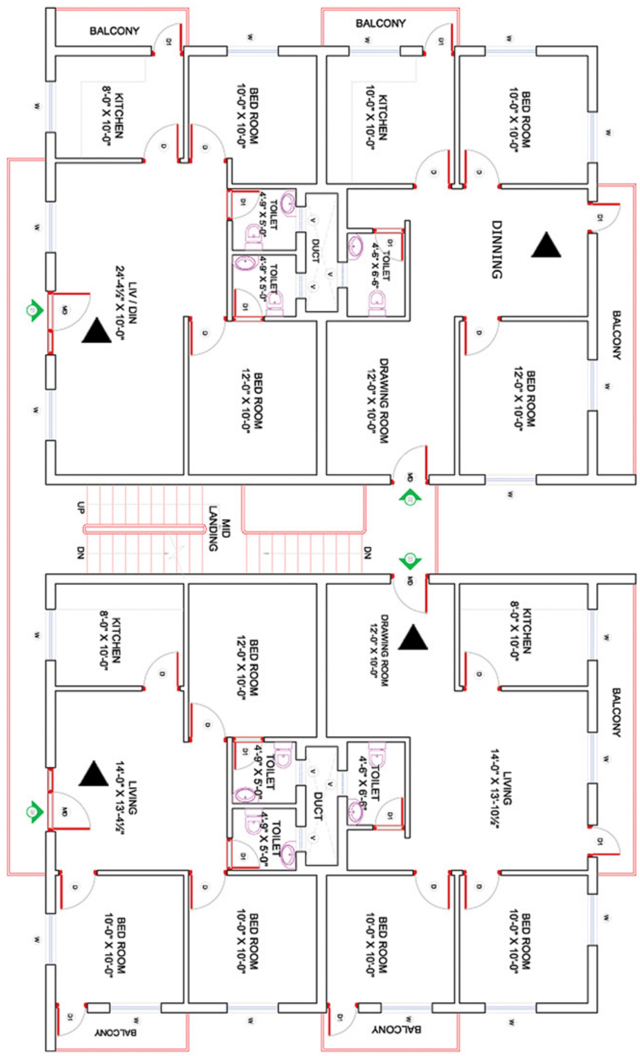


Typical Floor Plan
(▲Living areas surveyed)



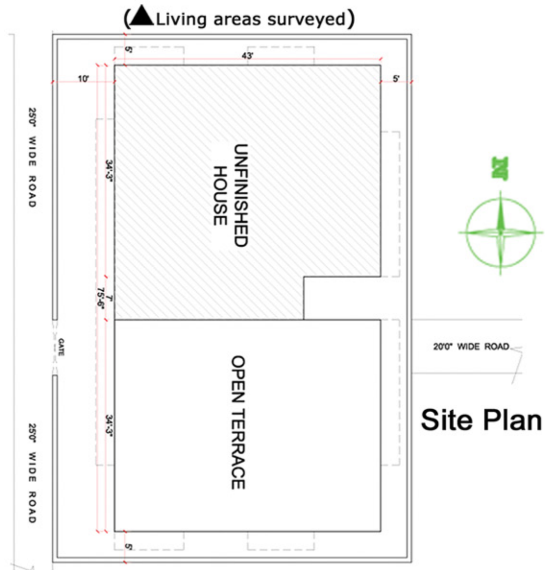
Site Plan

Appendix 5. Typical floor plan of RS



Typical floor plan

(▲Living areas surveyed)



Site Plan

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