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Towards daylight inclusive bye-law: Daylight as an energy saving route for affordable housing in India

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ABSTRACT

Building sector in India consumes about 33% of total electrical energy use, out of which 25% is accounted by the residential sector. This can be effectively reduced by utilizing daylighting as an essential component of building design strategy. Indian building codes lack specific daylight-inclusive design guidelines, which can provide policy support in reducing the energy consumption. In this study, energy sustainability through daylighting is studied with respect to daylight performance of a middle income, residential apartment in the city of Mumbai. Useful Daylight Illuminance (UDI) is used as the performance metric. The effect of built components like window-to-wall ratio (WWR) and orientation on the UDI ranges was studied. Occupancy behavior was modelled using an UDI threshold of 500 lx, and an energy management matrix (EMM) was derived. It has been found that at south-east orientation and at 20% WWR, the base-case building would save up to 26% lighting energy. Finally, a methodological framework for developing a policy toolbox using EMM was proposed as a route towards designing daylight inclusive building bye-law.

Introduction

Rapid urbanization in India, is pushing the energy demand at an unpreceded rate of 8% per annum (Yu et al., 2014). The sprawling of compact multi-storied high rise buildings, currently an archetype to meet urbanization demands, is increasingly putting pressure on urban energy needs. Moreover, non-stringent building bye-laws and lack of solar legislation add to the burden. While such development is better from the point of minimizing energy usage for transportation, the close proximity of the high-rises limits the sky-component and daylight penetration (Bardhan et al., 2015a). This in turn affects the quality and the quantity of daylight received, especially at the lower floors, and puts pressure on artificial lighting needs. Especially, in a country like India which has prolonged sunlight hours it seems imperative to have regulatory norms that integrate daylighting into the housing sector. The building bye-laws of Indian cities prescribe that every habitable room should have one or more apertures like windows, opening to external environment such that in no case the glazing to floor ratio be less than 10% of all habitable spaces (Kolkata, Gazzette. Orders and Notifications by the Governor of West Bengal, the High Court, Government Treasury, 2007) and the prescribed minimum distance between buildings is based on the “sustained vertical angle requirements” as per NBC-2005 Part 8 Sec 1 (BIS, 2005). These laws were first developed in the UK, primarily for low rise terraced houses, which assume that all windows receive a fairly good amount of “sky component” and that there is a constant angle of obstruction among the buildings. Given that Indian cities are growing taller and the windows have varying skyline obstruction, these laws become less effective. The building design itself suffers with no guarantee on daylight availability and performance. This situation calls for remedial measures in building bye laws that can meet with the contemporary demands in the growing residential sector.

One of the critical characteristic of India is its low socio-economic class driven urbanization (Bardhan et al., 2015b). This has led to a huge deficit of affordable housing in India. As a remedial measure, the Government of India has formulated the scheme of “Housing for All-2022”, which aims to build 20 million affordable houses in the next seven years (MHUPA, 2015). Under this pretext it would be judicious to propose daylight inclusive building bye-laws for this upcoming housing stock.

Hence, this study intends to propose a route towards daylight inclusive building bye-law and policy formulation. First, the study describes the gaps in current bye-laws and then estimates the daylight performance of an existing building. It then suggests the metric of Usable Daylight Illuminance (UDI) for evaluating the energy saving capability of residential buildings. Finally, an energy management matrix is designed as a method for formulating daylight inclusive building bye-laws.

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The specific objectives of this study are

- To understand the current lacuna in the current building bye laws with respect to daylight legislation for naturally ventilated residential houses.
- To examine and establish applicability and suitability of existing metrics as a way of energy saving in the affordable housing stock in India.
- To determine the energy saving potentials by varying the window to wall ratio (WWR) and orientation.
- To develop a method for design guidelines for including daylighting at early design stages of affordable housing.

Indian context

Building sector in India consumes 33% of total energy, out of which 25% accounts for residential sector whereas 8% is consumed by the commercial sector (Kumar et al., 2009). In the residential sector, there is a growing trend of single person households, especially in the metropolitan cities, which is more likely to push this energy consumption and demand upwards. Thus the energy consumption in the building sector might become a challenge, if not arrested at this stage. India needs to orchestrate design guidelines especially for the residential sector to make it energy efficient and climate resilient.

Energy Conservation Building Code-2011 (ECBC), which defines norms and standards for the energy performance of the buildings and their components based on the climate zone in which they are located, states that 80% of the energy in commercial building is due to lighting and air conditioners (ACs), whereas the major energy use in the residential buildings is due to lighting and fans (Kumar et al., 2009). The energy consumption break up in the residential sector for 2011 was as follows: 28% of energy use is in lighting, 34% in fans, and 13% in refrigeration (Centre for Science and Environment (CSE), 2014). In 2010, the room air conditioner saturation among Indian urban households was only 3% which is likely to grow to 60% by 2030 (NSSO, 2012). However, given the current status of India's building stock it is only one-fourth of the total estimated building stock of 2030 i.e. 70% of the houses are yet to be constructed (Centre for Science and Environment (CSE), 2014; The World Bank, 2008). Therefore, it is evident that one way for energy saving for Indian residential conditions is by harnessing while assessing the residential energy consumption in India; it was reported that in 2030, about 45% of the energy savings can alone be achieved by optimizing the lighting technology (Planning Commission Government of India, 2014).

Hence, for a country like India where the majority of the population lives in the middle or low income group, estimating energy savings from lighting becomes more practical than focusing on reducing cooling loads from ACs in the residential sector. Moreover, according to Roychoudhury (as seen in Burke, 2015) "Indian buildings do not need air conditioning for 365 days, 24 h a day" and although architects are resorting to means for ensuring better lighting, air movement, and shading, but to realize it as an energy saving option needs policy support. The peak summer months of June and July demands the highest cooling needs through ACs (Rawal and Shukla, 2014). Therefore, Rawal and Shukla (2014) recommend building energy efficiency in India which can be achieved by using smart devices to acquire energy data from buildings, energy efficient household appliances, policy road map for implementing energy efficiency measures for residential buildings and by developing a climate based residential building energy code. Moreover, much of the building energy is wasted because of "poor design, inadequate technology and inappropriate behaviors" and that government intervention in design is required to transform the building energy scenario especially in developing countries like India (WBCSD, 2009). It is suggested that the building energy use decision making should be "bottom-up" approach to identify the barriers for energy-efficiency and the means to overcome them. One of the essential means identified is the building design.

Currently in India two such building codes exist which are a national instrument for providing guidelines for building construction activities and aim to create sustainable practices. These are namely the National Building Code of India (NBC) — 2005 (BIS, 2005) and the Energy Conservation Building Code (ECBC) —2011 (Kumar et al., 2009). However, these are more of a blanket recommendation than regulatory norms. They are mostly used to adjudge the performance of a completed building and are seldom used as guideline for designing the house at the early stages of design.

NBC-2005 and ECBC-2011 do not explicitly specify any building byelaw that can foster the usage of natural lighting in place of artificial lighting. For instance: Section 5.2 (e) of NBC-2005 which deals with the planning, design and development, mentions "*Emphasis on daylight utilization, natural ventilation, shielding, and window area and its disposition; daylighting to be supplemented with an integrated design of artificial lighting*", similarly Section 5.2 (f) mentions, "*Optimum utilization of renewable energy sources duly integrated in the overall energy system design; with consideration of active and passive aspects in building design including thermal performance of building envelope*". Part-8 Section 1 of NBC-2005 (also IS 3646-Part I 1992) covers the requirement for lighting and ventilation in buildings which deals with daylight thresholds required for various indoor functions. However, these are yet to become building legislation. The building permission authorities, which give sanctioning for construction of buildings, also lack any standard metric to adjudge the daylight performance of a building design, with respect to energy saving potential.

Similarly, Chapter-4 of ECBC-2011 which primarily sets the guidelines for building envelop, fails to specify any essential code or guideline for integrating the daylighting component in the building envelope. It only 'prescribes' skylight and a cool roof as alternative methods of energy efficient building. Moreover, for a warm and humid climate zone ECBC recommends use of wind towers, courtyard-type construction, ventilated roof construction and cross-ventilated openings as the key cooling strategies through natural ventilation (see ECBC-4.3.1.1). However, in order to improve thermal comfort levels in the residential buildings ECBC recommends use of de-humidifiers and desiccant cooling (Kumar et al., 2009). Section 5.2.1 of ECBC-2011 and Part 8, 5.4.3 and 5.7.1 of NBC-2005, specify the usage of natural ventilation for cooling purposes either by wind action or through stack effects. The fans are inherently integrated in these guidelines. Chapter-7 of the ECBC guidelines deals with the lighting controls for mostly commercial buildings. It fails to integrate daylight compliance guidelines or building byelaws for the residential sector.

Hence, the housing sector in India needs passive solar building byelaws that can integrate daylight as a key strategy for the creation of sustainable built environment. Moreover, in India, where the annual sunshine hour ranges between 2300 and 3200 h, well day-lit buildings can boost the energy efficacy of sustainable housing to a greater extent and perhaps it becomes imperative to consider utilization of daylighting as an integral part of building industry both in policy and practice (Harinarayana and Kashyap, 2014).

Under this purview, this study aims to analyze the energy saving potential in a naturally ventilated house using daylight and propose a policy toolbox that can enable daylight inclusive building bye-laws to ascertain a sustained energy saving in the context of growing urbanization. The novelty of this work lies in the methodological framework for incorporating daylight metric as an energy saving indicator in a naturally ventilated residential house and formulation of policy toolbox to frame daylight inclusive building bye-laws.

Study area and base-case scenario

A typical residential building for a middle income household within the city of Mumbai is chosen as a base-case model for the study. This building is built as per existing building bye-laws. Mumbai is one of the densest cities in the world, which has a diverse mix of culture and socio-economic entities. More than 80% of the city's population belongs to the middle and the low income groups (Bardhan et al., 2015b) where electricity is not available 24 × 7. Given Mumbai's urbanization trend, the majority of this population lives in a densely packed high rise building with zero or limited accessibility to daylight. However, with appropriate building design, preferably through bye-laws, these houses could avail a significant amount of daylighting. Thereby, impacting health and contributing to energy savings.

The occupancy of the space during the daytime also influences energy savings through daylighting. In the context of India, occupancy can be related to the prevalent family structure and strong social ties of the *joint family* system. This becomes dominant as one moves to the lower socio-economic cohorts, including the middle income groups (Bardhan et al., 2015b). The larger family size can be attributed to having elderly (age 60 and above) who are mostly restricted indoors (Anand and Rademacher, 2011). Moreover, given the low proportion of women labor participation in the service sector most married women are housewives, who spend a majority of their time within the house. Hence, there is at least two to three occupants within the house and the house is never absolutely empty during the daytime. The sun also plays a significant role in social customs and daily activities. Thus using daylight for illumination during the daytime can contribute significantly to the energy savings.

A ground floor apartment of a typical middle income, residential housing, located in the Mumbai city was chosen for this study. The climate of Mumbai is warm and humid. Geographically, the case study building is located at 19.14N, 72.92E. The floor plan consists of four identical apartments mirrored to each other (see Fig. 1) covering an entire floor area of 839.63 m^2. The choice of ground floor for analysis pertains to the observed phenomenon of least exposure of sunlight on the lower floors of high rise buildings in dense metropolitans like Mumbai (Mardaljevic et al., 2011a,b). The building is oriented in the north–south direction with a generic WWR of 17%. The internal space configuration of the apartment is as follows: it has 2 bedrooms, 2 toilets, and a living room with a balcony as illustrated in Fig. 1. The building is completely naturally ventilated with a total lighting load of 240 W in each apartment. There were 6 occupants with a minimum three members staying in the apartment during the daytime.

The occupants used heavy curtains as the active control measure towards perceived daylighting glare in the living space, at the working plane (based on field reconnaissance study). This caused the room illuminance levels to fall below 500 lx, which stimulated switching to artificial lighting. The occupants showed variation in the perception of the glare. Most of the time, glare was the approximation of the illuminance contrast by the occupants. This behavioral paradigm was also reported by Kleindienst and Andersen (2009), where they used four typologies of illuminance sources: the classroom model, the skylight model, the frame model and the Simple Corbusier model. In case of residential building, the illuminance source is replicable to the frame model, where glare was largely due to luminance contrast.

Data and methodology

In this study, daylight simulations were performed on a typical residential housing of a middle income family. The simulations were carried out to assess the daylight performance of the functional space of the apartment with respect to UDI values. UDI values of 200–1000 lx were taken as the determinant for energy saving potential, which was further simulated with varying orientation and WWR while keeping the functional space constant. This kind of approach is distinctive to the conventional box model approach for daylight simulations. Constraints such as keeping the functional space intact while varying other building components like WWR and orientation were maintained throughout the simulation so that a certainty of realism of the built environment can be sustained in the study. Such assumptions were necessary to the main coherency with the objective of this study of creating an alternate route for energy saving through daylight inclusive bye-laws in India. The methodology adopted is illustrated in Fig. 2.

UDI as the daylight performance parameter

The dynamics of daylight space is highly influenced by the climate of the region, which makes UDI as a suitable daylight performance metric (Nabil and Mardaljevic, 2006). Numerous field studies have shown that UDI is more realistic in modeling daylight performance of buildings as it gives more flexibility in addressing the usable illuminance levels in

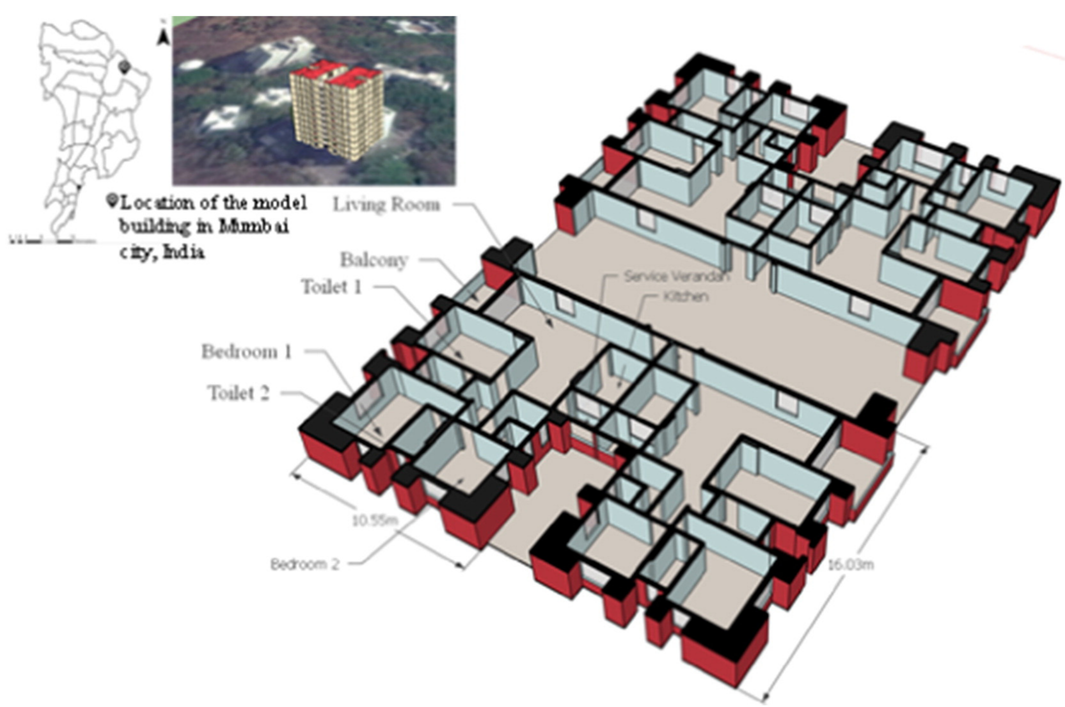

Fig. 1. The base-case model of the residential building.

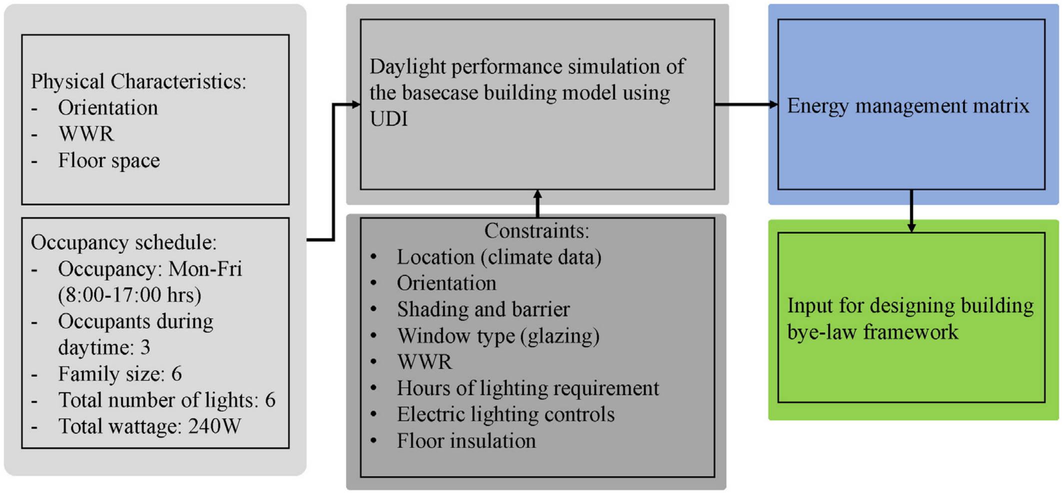

Fig. 2. Adopted methodology.

space (Mardaljevic et al., 2011a, 2011b; Nabil and Mardaljevic, 2006; Reinhart, 2005; Reinhart and LoVerso, 2010). Such experimental studies have also reported that illuminance levels between 300 and 3000 lx are considered to be most visually ambient for doing paper based tasks especially for the office environment (Mardaljevic et al., 2011a,b, 2012). Mardaljevic et al. while defining UDI had divided UDI 100–200 (%) into UDI-supplementary and UDI-autonomous, and stated that UDI-supplementary ranges from 100 to 200 lx where artificial lighting may be needed, whereas in case of UDI-autonomy (200–2000 lx), it is most likely that artificial lighting may not be needed (Mardaljevic et al., 2012).

The simulated apartment has an occupancy of a minimum three members during the daytime on weekdays, of which two members are above 60. Thus, considering the age induced visual strain, 500 lx was assumed to be the minimum threshold during simulations. This is coherent with the recommendations of NBC-2005 (Part 8-Sec 1) and also with the recommendation of various human-environment interaction studies (Hughes and Neer, 1981; Knez and Kers, 2000).

Table 1
Main input parameters of the daylight simulations.

Parameters	Values
Luminous efficacy model	Perez
Sky illumination model	Perez all weather
Sky Condition	CIE clear sky
Weather file	Mumbai ISHRAE
Apartment height	3 m
Desk level height	0.85
Illuminance requirement	500 lx
Hours of lighting requirement	8:00 to 17:00 h
Daylight saving time applied	April 1st to October 31st
Lighting and blind control	Manual 'on/off'
Static shading	Overhangs (500 mm) above openings
Dynamic shading device	None
Simulation parameters	
ab (ambient bounce)	5
ad (ambient division)	1000
as (ambient super samples)	20
ar (ambient resolution)	300
aa (ambient accuracy)	0.1
DIVA materials	
Floor	0.20 reflectance
Ceiling	0.80 reflectance
Walls	0.50 reflectance
Exterior ground	0.20 reflectance
Glazing	0.76 transmittance

Modeling and simulation

The modeling involved developing of a detailed 2D layout drawings and its corresponding 3D rendering in Google Sketchup v8.0. The 3D rendered model was then imported in Rhinoceros v5.0 with Design Iterate Validate Adapt (DIVA v3.0) plug-in for daylighting analysis (Jakubiec and Reinhart, 2011). DIVA yields illuminance value inside the building envelope. It is also capable of predicting brightness and glares inside the building. In this study, DIVA is used to calculate the light metrics of UDI inside the room using a time based simulation (see Table 1 for input parameters). DIVA performs daylight analysis with the integration of DAYSIM and radiance engine (Jakubiec and Reinhart, 2011). Such engines are widely used for climate-based daylighting simulation studies (Jakubiec and Reinhart, 2013; Mardaljevic et al., 2012). In order to arrive at UDI levels within the building space photo sensor points were created at a grid space of 0.5 m in a planar surface at a desk height of 0.85 m from floor level. This planar surface was then added to the simulation model using DIVA v3.0 for Rhinoceros as illustrated in Fig. 3. The inbuilt Radiance engine in the DIVA uses validated ray tracing technique for the calculation of the daylight metrics: UDI and Annual light exposure (Kämpf et al., 2010; Ng, 2003; Roy, 2000). Moreover, obstruction in the form of a 2 m high wall surrounding the floor at a distance of 8 m was created to account for real life obstructions like trees and street shops. Also, as per building bye-law side and rear open space of minimum 3 m has to be kept between the buildings. This was also incorporated in the model.

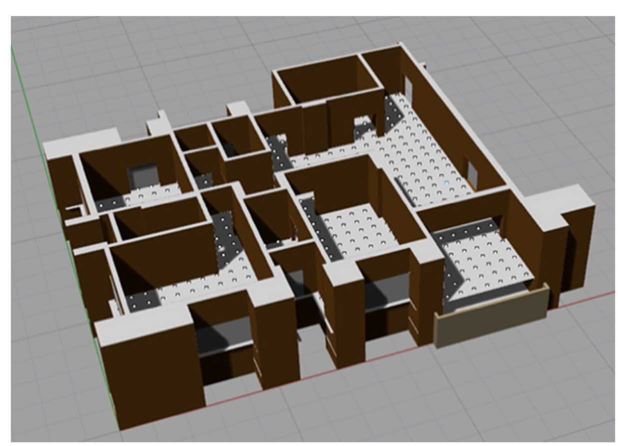

Fig. 3. Photo sensor points for simulation.

Table 2
Specifications of the base-case indoor lighting system.

Specifications	Values
Manufacturer	Philips
Type	T12
Brightness	2325 lm
Estimated year energy cost	$4.82 (based on 3 h/day, 11 cent/kWh cost depends on rates and use)
Life expectancy	21.9 years (based on 3 /day)
Light appearance	6500 K (daylight)
Energy used	40 W
Lumens per watt	58.1
Recommended use	General residential purpose: kitchen, bathroom, living space

(Source: adapted from (Philips India Limited, 2016)

Lighting control using DIVA

DIVA gives the users the ability to schedule artificial lighting inside buildings. In order to use this feature, a one-zone volume for energy analysis was constructed based on the existing detailed architectural geometry. Schedules generated by the daylighting analysis are then automatically imported to the energy simulation engine. This method reduces the complexity of simulating models through multiple exports to different software; as it allows rapid visualization of daylight and its corresponding energy performance simultaneously (Jakubiec and Reinhart, 2011).

DIVA uses DAYSIM engine for its Daylight Autonomy profile generation, shading scheduling and electric lighting schedule generations, which are automatically generated based on the kind of user shading behavior chosen and the annual illuminance profile generated at the

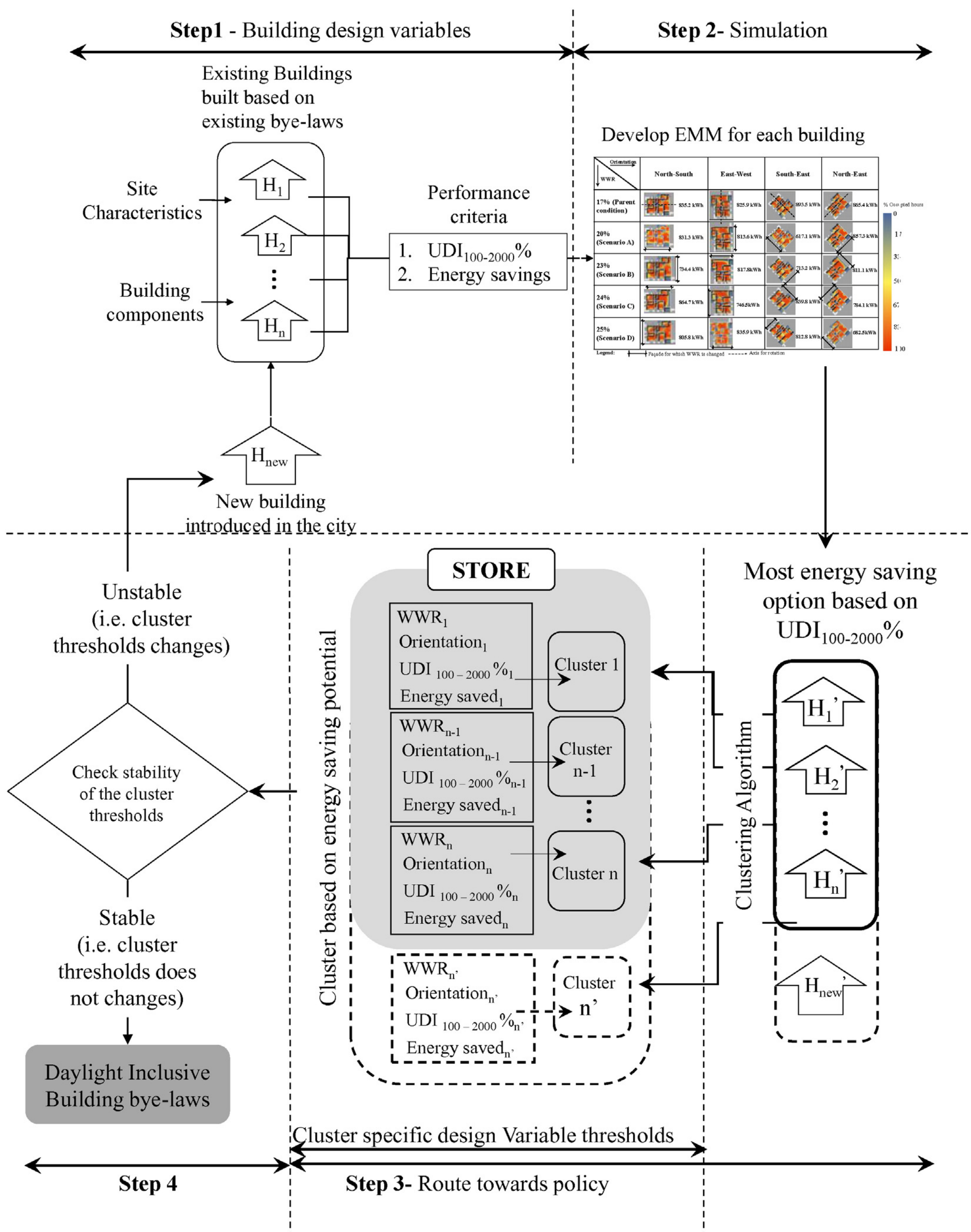

Fig. 4. Proposed policy toolbox for daylight inclusive building bye law.

selected photo sensor nodes (Jakubiec and Reinhart, 2011). Here, the energy performance for varying UDI with respect to orientation and WWR was studied and the lighting schedule was modeled by considering manual 'on–off switch mode' for artificial lights. The installed electrical lighting power was taken to be 240 W for the entire apartment (see Table 2). Simulation results were generated in the form of a comma separated value (.csv) file which was further used to generate an energy management matrix for design decisions and policy recommendations with respect to the constraints in terms of orientation and WWR.

Proposed framework for designing daylight inclusive building bye-laws: creating the policy toolbox

A linear stepwise framework is proposed here as a way towards designing daylight inclusive building bye law (see Fig. 4). UDI is used as the daylight performance metric for estimating energy savings from daylight. Step 1, involves the creation of a system data using various typologies of existing residential buildings within an urban area. In step 2, these buildings are estimated for acceptable UDI levels (100–2000 lx) and subsequent energy reduction potential. The energy saving potential can be a white box process which will calculate the availability of ambient light levels in the functional space and its effect on the manual lighting controls by the occupants. Thus, capturing the energy saving potential in the form of a matrix is known as energy management matrix (EMM). Such matrix will represent the built characteristics of the building and its corresponding energy management potential.

Step 3 includes the development of building clusters based on the output from an EMM. The buildings will be categorized into clusters, such that each cluster represents a different combination of built characteristics and energy saving potential. These clusters can be stored in a virtual warehouse or a "STORE" which acts as the decision making box and can be used for building a policy toolbox.

The policy toolbox will be considered stable once the energy saving potential corresponding to a set building component thresholds do not change upon the introduction of a new building within the toolbox. Until then, this STORE will be reiterated for the cluster specific thresholds with each new building introduced in the urban space. Finally, after several runs once the STORE cluster thresholds become stable, that is the values of the building components of a specific cluster do not change, it can be used to formulate regulatory daylight inclusive building bye-law for improved energy efficiency. Fig. 4 illustrates the proposed policy toolbox.

The energy management matrix (EMM)

The EMM is a representation of built environment characteristics and its corresponding energy saving potential with respect to the incident daylight. The base-case model was simulated for UDI and manual lighting scheduling i.e. it was assumed that whenever the light levels inside the functional space fall below 500 lx, users switched to artificial lighting. This estimated the corresponding energy saving potential for the base case scenario.

The base-case model was then rotated to the following cardinal orientation along the original axis of north–south direction: east–west (EW), south-east (SE) and north-east (NE). They were re-simulated for the UDI ranges, while simultaneously varying the WWR for four devised scenarios, namely A, B, C and D, where A, B, C and D pertained to increasing the window width horizontally for façade 1, 2, 3 and 4 respectively. Such increase let to an overall change in WWR for scenarios A, B, C and D by 20%, 23%, 24% and 25% respectively (see Fig. 5). These values of WWR were the maximum limits that could be achieved without structural failure of the building or affecting the privacy of the interior space with respect to its intended function. All windows were kept at the original design height of 0.9 m from the floor level. The facades which had the highest propensity of sunlight exposure in each orientation were re-simulated to understand the impact of increased sunlight incidence with respect to different WWRs. Hence, a matrix comprehending the propensity of a building to save lighting energy during the daytime with respect to its permissible limit of WWRs and various orientations is constructed.

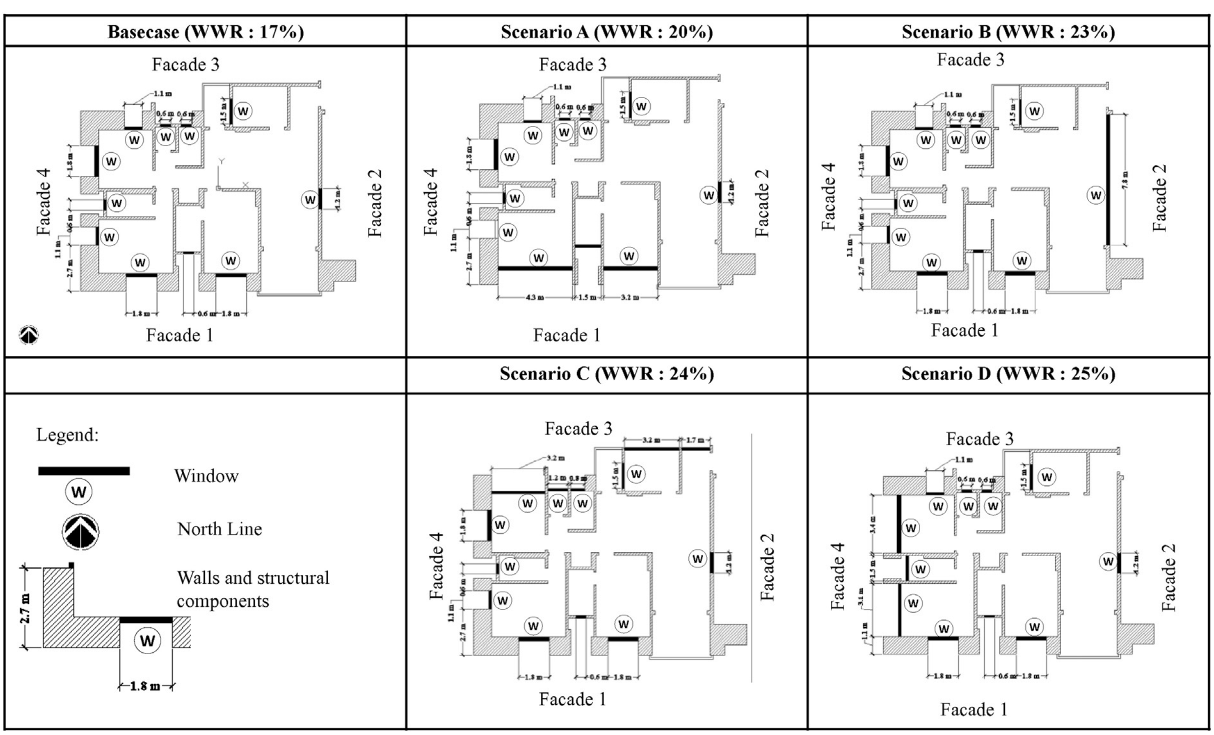

Fig. 5. Variation in WWR based on the building facades.

Table 3
The energy consumption of the apartment with respect to different orientations.

Orientation	Lighting energy consumption per annum (kWh)
NS	835.3
EW	825.3
SE	893.5
NE	865.4

Results

Energy saving from lighting controls in varying orientation and WWR

One of the objectives of this study was to analyze the energy saving potential of a building when UDI is considered as a daylight performance parameter. Lighting scheduling was used to calculate energy saving potential such that each of the orientation and WWR values had a minimum illuminance threshold of 500 lx (see Fig. 2 and Table 1). The annual lighting energy consumption of the studied apartment was 835.30 kWh with 17% WWR and at north–south orientation (base-case scenario). The energy consumption of the apartment with respect to different orientation is illustrated in Table 3.

EMM is the kernel process of the proposed energy management route for daylight inclusive building bye-law, which aims at reducing lighting energy consumption in the residential sector. The lighting manual controls of the base case scenario are represented in Fig. 6.

Here, 500 lx is considered as the minimum illuminance level in the living room for a visually ambient and productive environment, for the intended occupants. Although, occupants' behavior is highly unpredictable in a real life situation, we adopted a deterministic model based on the primary survey of the human-space interaction in the apartment during the daytime.

Lighting controls through manual switches of different orientations and WWR values are shown in Fig. 7. The ‘black’ regions in graphs are moments when the occupants switched ‘off’ the artificial lights, whereas white indicates the switch ‘on’ state. Table 4 shows the energy saving potential at different orientations and WWR values.

Positive values in Table 4, represent possible lighting energy savings whereas negative values represent lighting energy consumption in the apartment. The key inferences from Table 4 are:

- At 20% WWR, the SE orientation of the living room (assumed functional space) receives illuminance beyond 500 lx throughout the day. Thus, 26.11% of energy can be saved. Similarly, at NE orientation can save up to 18.20% of energy by not switching on artificial lighting.
- However, at 17% WWR, the south-east and the north eastern orientation of the living space consumed 6.98% and 3.61% more lighting energy respectively. This means that the occupants have to use artificial lighting sources more in such orientation during the daytime.

This energy saving-consumption paradigm is represented in the form of EMM, as illustrated in Fig. 8.

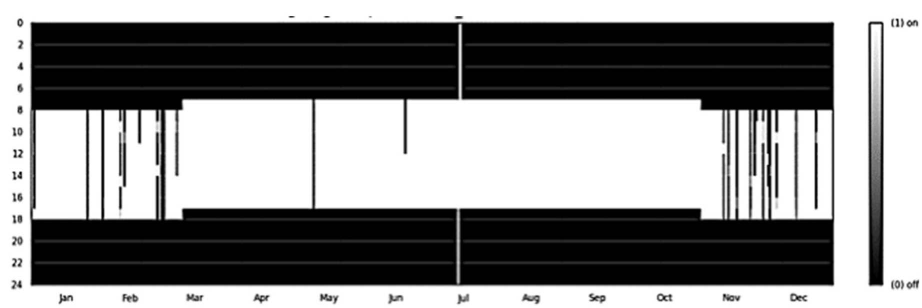

Fig. 6. Lighting controls in the base-case model by the occupants.

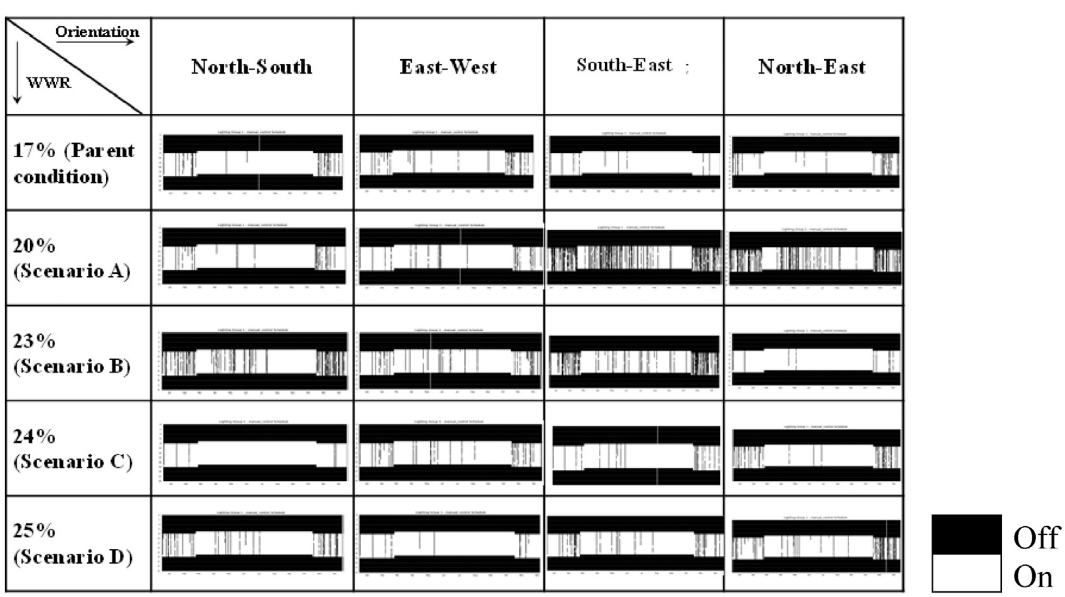

Fig. 7. Lighting manual controls based on different orientations and WWR values.

Table 4
Energy saving potential based on various orientations and WWR values.

WWR	North–south	East–west	South-east	North-east
17%	835.2 kWh (base-case)	1.11%	−6.98%	−3.61%
20%	0.46%	0.00%	26.11%	18.2%
23%	12.06%	2.58%	14.6%	−2.64%
24%	−3.53%	2.08%	−0.55%	2.88%
25%	3.52%	10.62%	2.62%	6.11%

Discussion

This study aimed at developing a way for designing a daylight inclusive building bye-law using UDI as a metric for energy saving in the residential sector of a developing metropolis. The primary motivation of this study was to provide i) all buildings with equal opportunity to have energy saving through daylighting, and ii) design guidelines for buildings to include daylighting at an early design stage. An EMM is proposed as a way towards building the policy toolbox. The EMM was derived from climate based daylight performance simulations of a building whose built components were varied (see Fig. 8). Inputs of the EMM are building design variables such as WWR and orientation along with occupancy pattern and lighting system data. Daylight performance simulations were performed for EMM using UDI as a metric. It was found out that the base-case model (originally at 17% WWR and north–south orientation) showed energy saving potential which was higher at 20% WWR and south-east orientation (see Figs. 5 and 8 scenario A). The highest energy saving option from the EMM relates to the abundance of visually ambient illuminance in the functional space throughout the day. EMM inputs were carefully chosen such that the structural and functional integrity of the space remains intact. Most daylight simulations use a box model for analysis where parameters like structural and functional stability is not considered, while EMM integrates such real life constraints. Therefore, EMM can justifiably act as a route for designing of daylight inclusive building bye-law.

The proposed policy toolbox (see Fig. 4) takes the output of the EMM as inputs for clustering the buildings based on their built components and response to energy saving potential. Clusters thus generated contain the specific threshold for each design variables like WWR, orientation, room widths, material of the building envelope and the UDI thresholds. For policy formulation, this route from EMM to cluster-generation needs to be repeatedly iterated by introducing new buildings into the toolbox system data. For each new building introduced within the system, EMM would provide different outputs resulting in cluster restructuring. The threshold values of the design variables in restructured clusters might vary from the previous. As mentioned earlier, this loop of reiteration must be continued until the cluster structure does not change and the threshold values of design variables and energy saved stabilizes. Only after stabilization these values can be used to draw statutory codes for drafting daylight inclusive building bye-laws. In reality, this process of stabilization might take time. For example: if Mumbai wants to adopt daylight inclusive building bye-laws for its upcoming building stocks, the existing building stocks need to be simulated to generate the cluster thresholds for the 'STORE' (see Fig.4). These thresholds would then be a marker for the next generation buildings to adopt design guidelines to improve their energy efficiency at an early design stage. Therefore, this eventually improves the energy sustainability of the whole building stock.

Conclusion

This study summarizes and outlines building bye-laws in India and its lack of specific design guidelines for incorporating daylight in architecture as an energy saving metric. The study demonstrated that the relationship of daylight metric like UDI with building design parameters like WWR and orientation is sufficiently robust and has the potential to formulate building bye-laws i.e. using the UDI to devise an energy management matrix which in turn can enable in finding a context specific preferred solution. The methodology proposed here is essentially "operationalized proof of concept" which can also be applied to other developing cities. The policy toolbox, using EMM suggested here, is a simplified method and can easily be adopted for policy planning, as the existing building database already exists with the building authorities. The next steps of analysis would involve parametrization and sensitivity of other building design elements to be incorporated in the EMM and derive the EMM for all the possible typologies of housing stock (which spans across socio-economic status) for the city of Mumbai. The proposed policy toolbox can cope with the growing

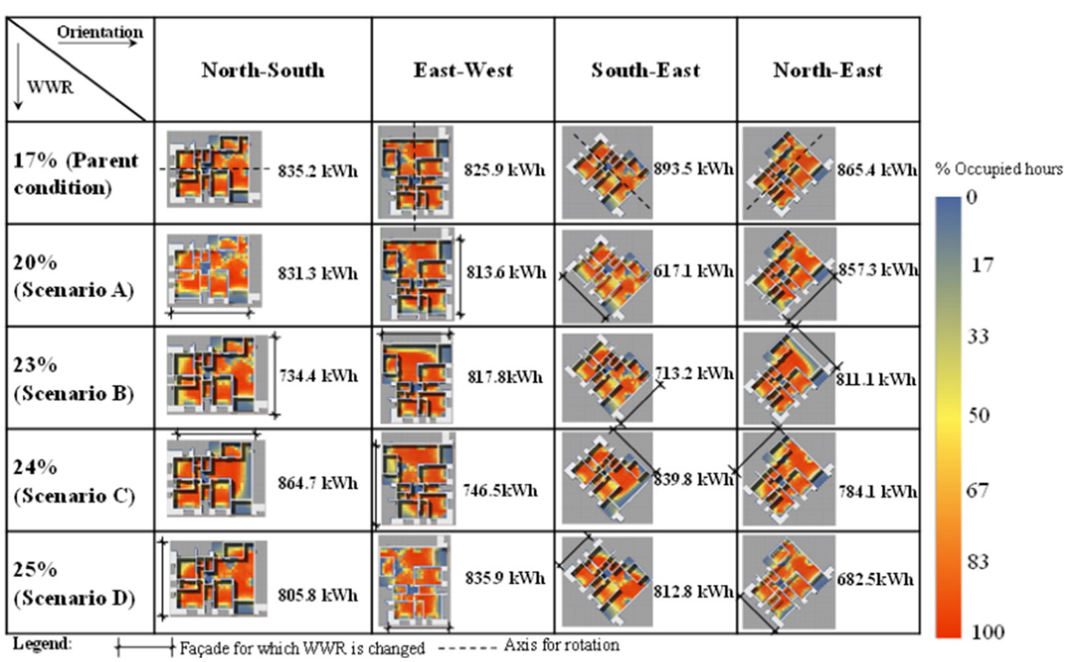

Fig. 8. Energy management matrix (EMM).

energy and housing demand of India and can contribute in enhancing the building energy efficiency, especially for the proposed 20 million affordable housing stocks.

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