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Re-imagining Energy Efficiency in Open-Plan Offices Using Micro-Zonal Occupant Centric Control: Protocols to be Considered

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Highlights

- Need to integrate micro-zoning, thermal zoning and spatial planning of open-plan offices
- Protocols for micro-zoning outlined
- Planned micro-zones save 44% of HVAC energy consumption

Abstract

Air-conditioning energy consumed in buildings can be reduced by cooling only occupied regions. With modern open-plan offices being adaptable with flexible work hours, there is a need to virtually divide thermal zones based on varying thermal requirements. Micro-Zonal Occupant-Centric Control (MZOCC) saves HVAC energy by creating micro-comfort zones around occupants through independent diffuser control. However, research gaps exist between thermal zoning for HVAC design and micro-zoning. There is a lack of clarity on the method of micro-zoning and factors to be considered, such as size and shape of micro-zones. The aim of this study is to delineate protocols for micro-zoning and evaluate the benefits of planned micro-zones. Characteristics of existing Indian open-plan offices are studied, and a method for micro-zoning is delineated. Results indicate that planned micro-zoning saves 44% of energy. The micro-zonal layout acts as the starting point for optimising diffuser allocation and airflow control, which will further improve energy savings.

Keywords: Energy-efficiency, Thermal-zones, Micro-zones, Open-plan offices

Introduction

Micro-zonal occupant centric control (MZOCC) has emerged as a significant method to improve energy efficiency in open-plan offices. This creates micro-comfort zones around occupants, enabling a reduction of energy wastage in conditioning unoccupied regions within a thermal zone. MZOCC acts as an alternative to personalised ventilation (PV) that uses personal fans or air handling units placed very close to occupants. Though PV creates a micro-comfort zone around the occupants, it requires a high initial investment to lay ducts and equipment for bringing airflow to the occupant's face and body [1]. This also causes intrusion to occupants [2], and the conditioned air is concentrated in a very small area [3]. Most importantly, this does not allow flexibility in changing architectural layouts. Hence, there is a need to improve standard HVAC systems so that micro-comfort zones can be created by virtually dividing the thermal zones.

The potential of such virtual sub-zoning to improve energy efficiency [4][5], thermal comfort [6], and air quality in open-plan offices is established in the literature. However, there is a lack of clarity on how micro-zones are to be planned. There is a research gap between micro-zoning and thermal zoning. Current methods of thermal zoning do not consider the parameters required for micro-zoning. In addition, most studies on micro-zoning have chosen arbitrary sizes for micro-zones as per convenience, and inter-micro-zonal interactions are either modelled using steady state models [5] or transient empirical models [4]. Previous studies that used transient CFD models for MZOCC indicated that unplanned micro-zoning can lead to energy wastage and thermal discomfort due to inter-micro-zonal interaction. It can lead to the merging of cool air jets from adjacent diffusers or the clinging of cool air to walls and surfaces, creating heavy thermal gradients [7], [8]. In this regard, there is a need to develop protocols for micro-zoning such that HVAC energy can be saved without violating thermal comfort. The aim of the study is to explore the considerations in micro-zoning by giving recommendations on the size of micro-zones, the shape of micro-zones, the distance between diffusers, etc., and evaluate energy savings due to micro-zonal air-conditioning with respect to standard zone-based air-conditioning.

Literature Review

The method of creating micro-comfort zones for reducing energy wastage has been of great interest to researchers. Personalised ventilation, personal comfort systems [9], and task ambient systems are used to attain comfortable air temperatures around occupants even when the zone is at a higher air temperature. Personalized ventilation (PV), which creates a micro-comfort zone around the occupant by supplying fresh air to the breathing zone of occupants, saves 50%-60% of air conditioning energy [10][11] [12]. The type of airflow and micro-comfort zone created depends on the air terminal device (ATD) used. A few common ATDs are moveable panels (MP), which throw air through a personal air handling unit (AHU); computer monitor panels (CMP), which throw air through an AHU above the computer monitor; vertical desk grill (VDG), horizontal desk grill (HDG), which throws air from an opening near the desk [13], personal environmental modules (PEM) which are placed on partitions [14] [15], air blowers on headsets [2] or their seat [13] etc.

Airflow from each diffuser type can further be controlled by altering air temperature, mean velocity, turbulence intensity, direction of supply air, area of supply vents, the targeted area of supply, activities, and ergonomics of the space [9]. Since PV vents are placed very close to the occupants, the supply air has a higher temperature and lower velocity (approximately 0.25m/s) compared to standard HVAC systems [16]. This restricts the spread of air jets from PV and cools only a small area around the occupant. But this also leads to discomfort due to thermal asymmetry and gradients for occupants who are not near PV vents [3]. Hence, PV is usually operated along with a standard room air conditioner, which maintains a higher setpoint temperature. Strategies linking the control between the micro environment due to PV and the macro environment due to room HVAC systems are developed [17]. Personal comfort systems have cooling mechanisms integrated to personal equipment such as personal chairs, coolers, blankets, mattresses [18], and clothing [9]. The boundary of the micro-comfort zone of PV varies based on the properties of the ventilation system, such as temperature, mean velocity, turbulence intensity, direction of supply air, area of supply vents, and the targeted area of supply. Factors such as occupant movement [19], furniture design and arrangement [14], and other spatial elements in the zone also influence the boundary.

Virtual zoning of thermal zones into sub-zones and controlling airflow in each sub-zone using occupant centric control has emerged as an alternative to PV. Such virtual sub-zoning is mostly done by dividing the thermal zone into geometric grids, with each grid having one air node [5] [4] [6]. 'Fine grained zoning' [20] [6] divides the thermal zone into finer grids of size 7.2mx7.2m. The grid boundaries are considered virtual with a constant air exchange flow, and the grid size is chosen based on separations on the façade[6]. However, with variations in heating and cooling in each fine zone, the thermal coupling between adjacent micro-zones varies; hence, assuming a constant flow may lead to errors. Further, it was observed that while fine grained zoning reduced comfort violations, energy consumption increased in a few cases.

Thermal interactions through the virtual boundary have been modelled in studies that aimed at exploring HVAC energy efficiency using sub-zoning. A steady-state CFD model was developed to model the thermal interaction between the virtual boundary of a zone of size 7mx6.6m divided into two sub-zones of 2.9mx6m [5]. The study leveraged on thermal coupling to cool adjacent sub-zones and was able to reduce 10% energy consumption. To capture the transient variations in thermal coupling, a mathematical model with bi-directional airflow was developed in a study on a co-working office in India [4], [21]–[24]. This model was used to predict the indoor temperature at each sub-zone for a given time in order to allocate workspaces to occupants based on their thermal preferences. The size of each sub-zone was 10mx15.25m. The set-point temperatures of the occupied sub-zone are decided based on the requirements of the users in the sub-zone. But it is also seen that, several unoccupied sub-zones are to be conditioned to reach setpoint in the occupied sub-zones. This is because airflow through the diffusers in the occupied sub-zones is not sufficient and requires thermal coupling from adjacent sub-zones. This highlights the need for connected control of diffusers.

For a detailed understanding of thermal interactions through virtual boundaries, recent studies by the authors used experimentally validated transient state CFD models for MZOCC [7], [8], [25]. These revealed that uncontrolled intermicro-zonal interactions could lead to increased energy consumption due to the merging of adjacent air jets and lead to a deflection of air jets away from occupied regions. Two factors are found critical in controlling this merging: (1) relative location of diffusers and (2) supply velocity [25]. When two supply diffusers were placed at a distance of 2m, air jets were found to merge and move away from the occupied micro-zone. The merging is due to the attraction induced by the low-pressure region created between the diffusers. Low velocity jets were found to deflect towards high velocity jets due to the reduced momentum of the former. The presence of surfaces such as walls or furniture also causes the deflection of air jets due to the Coanda effect [8]. Thus, the diffusers placed in corner regions produce smaller micro-zones than those in the centre of the room. Air movement is also influenced by the type of furniture and height of partitions [8] [26]. Considering the aforementioned properties of air jets, two strategies for controlling air movement and inter-micro-zonal interactions are proposed. (1) setback flow – maintaining a low velocity flow and (2) setback temperature – maintaining a higher setpoint temperature. These are maintained in either all unoccupied micro-zones or only the micro-zones adjacent to the occupied micro-zones such that thermal gradients and draft are minimal with maximum energy savings. MZOCC using setback flow and setback temperature-based control strategies can bring about 60% energy savings [8].

Several strategies for thermal zoning are discussed in the literature, but there is a research gap between thermal zoning and micro-zoning. Thermal zones or HVAC zones are regions with uniform thermal requirements and catered by a single thermostat [27] [28]. The common assumption is that the thermal conditions within a zone are uniform at any point of time. This assumption is used in simulation zoning, where the building is discretized into regions of uniform thermal conditions to reduce model complexity [29]. For zoning in early design stages when room separations or interior loads are unknown, the standard core-perimeter model is used [30] such that externally and internally heated spaces are separated. The prescribed perimeter depth varies in different standards, with a range of 3m to 6m, with 4.5m to 5m being the most commonly used. Further, the cardinal zones are separated as the intensity of solar radiation varies. Thus, the 5 zone model is the most basic form of zoning and is used in several automatic zoning algorithms [29] [31]. Most studies consider room-based zoning, where physical partitions form the zonal boundaries, to be the most granular thermal zoning [32]. In between room-based zoning and core perimeter zoning, several methods of grouping spaces into zones, such as grouping based on function [32], function and orientation [32], thermal loads [29] [33], adjacency of rooms, and similarity in HVAC requirements [34] have been explored. Recently, a cluster-based method of thermal zoning has been proposed, where a large space is divided into finite grids and grouped based on transient heat gained [35].

From the literature, the parameters that influence thermal zoning can be simplified as transient heat gain and source of heat (external or internal), function and activities, schedule of usage, and adjacency of spaces. On the other hand, in microzoning, parameters such as the location of diffusers, inter-micro-zonal interaction, partition heights and air movement, variations in thermal preferences, etc., are important. There is a need to merge this gap between thermal zoning and microzoning and outline a method of micro-zoning. Further, from the literature on micro-zones, it is observed that micro-zonal sizes were decided arbitrarily, with each study having its own grid size. It is suggested in the cluster-based zoning method that the minimum grid size will depend on the area required for the activity and the area catered by a diffuser [35]. In continuation, there is a need to explore minimum grid sizes for common activities and diffuser types found in open-plan offices. In this regard, there is a need to study considerations in the spatial design of open-plan offices from literature as well as built spaces.

Open-plan offices originated with the idea of designing spaces for free communication without the barriers of walls [36]. Important parameters to be considered by planning open-plan offices are work patterns [37], activities [38], organizational hierarchies [39], and the needs of the occupants [40]. The guide on planning open-plan offices prepared in 2010 highlights relevant functional, technical, and financial factors to be considered while planning open-plan offices [39]. Modular planning, plug facilities, and flexible ceilings/partitions upgrade a standard open-plan office to a 'flexible' office [41]. Attempts to improve office atmospheres have also led to the emergence of 'activity-based' offices, which provide a variety of work settings for occupants to choose from as per the requirement of the assigned work [38].

From literature, the common office types can be categorised as into 5: (1) Bullpen, which is a full open-plan office with no partitions [40], (2) caves and common design [42], where individual cabins surround open workspaces, (3) Team enclosures [40], where each team occupies an open-plan office, (4) flexible offices, which contains a mixed of dedicated workspaces and shared areas [41] and (5) activity-based offices [38]. Similarly, in terms of work culture, open-plan offices can be divided into four [37]. (1) Hive, where one works independently with minimum interaction with the colleagues,

(2) cell, some amount of interaction is present, but most work is done independently, and the worker also works remotely; (3) Den, which requires a highly interactive environment to accommodate group work; and (4) club, which has both concentrated work and group work. A survey of Indian open-plan offices is conducted in this study to explore whether Indian offices follow such characteristics.

Several strategies to improve open-plan layouts to facilitate better communication [43], reduce sedentary time [44], and make the space livelier [45] are discussed in the literature. Inadequate air-conditioning [46], over-conditioning, and lack of control over the thermal environment [37][38] can cause dissatisfaction among occupants. As discussed, this also increases energy wastage. Hence, customisation of the thermal environment with a perceived sense of control is important in open-plan offices. Spatial attributes such as social density (number of occupants in the space) [46], spatial density (size of the space) [46], and office space occupation (number of occupants per enclosed office) [47] are important while creating such personal thermal environments. This gives an estimate of how many people each diffuser serves and how many diffusers are required to serve each activity. This is important in deciding the minimum size of micro-zones.

Listing the common activity spaces and occupant densities (the ratio of social density and spatial density) in open-plan offices for each activity, commonly used air conditioning diffusers, furniture types, and clusters helps in planning microzones. Open-planned offices are often tightly packed to reduce facility costs. Indian offices have occupant densities of 6-8m^2/person [48], indicating crowded work spaces [49]. Further, the occupant densities can vary for different spaces in the open-plan office, such as workspaces, corridors, activity-based work areas, and leisure spaces. Hence, the air conditioning requirement in each region can be different.

To summarise, the location of diffusers, furniture in the space and their arrangement, activities, occupancy in the zone, and other spatial features influence micro-zoning. The need to find optimal virtual boundaries to place thermostats within micro-zones is highlighted in previous studies [7], but there is a need to develop a method for the same. At this point, it is imperative to have guidelines to plan the appropriate size of micro-zones, diffuser location, minimum distance of diffusers from walls, minimum distance between diffusers, furniture height, and arrangement basis the activity and requirement of micro-zones before OCC is implemented in MZOCC. Open-plan offices are diverse, with a variety of activities, and require varying levels of air-conditioning in different regions. Though few studies have proved the efficiency of MZOCC, there is a disconnect between micro-zoning and thermal zoning. The aim of this study is to give guidelines on planning micro-zones in open-plan offices. In this matter, open-plan offices in India are studied to explore how similar these offices are with respect to the characteristics observed in the literature. This also gives insights into the additional factors to be considered for MZOCC. The novel contribution of this study is that it identifies the considerations in micro-zoning Indian open-plan offices, gives guidelines on appropriately planning micro-zones, and evaluates the energy savings due to possible micro-zonal divisions. While previous studies have arbitrarily divided thermal zones into micro-zones [6] or divided considering function planning of the zone [50], this study establishes that planning micro-zones considering the aforementioned spatio-temporal characteristics of the office saves more energy compared to micro-zoning based on function alone.

Method

The study follows a three-stage approach as outlined in Figure 1, wherein the first stage, considerations for micro-zoning open-plan offices, are identified from the literature, following which existing open-plan offices in India are surveyed to identify the similarities of these offices from the ones observed in the literature. From these, considerations for micro-zoning Indian offices are identified.

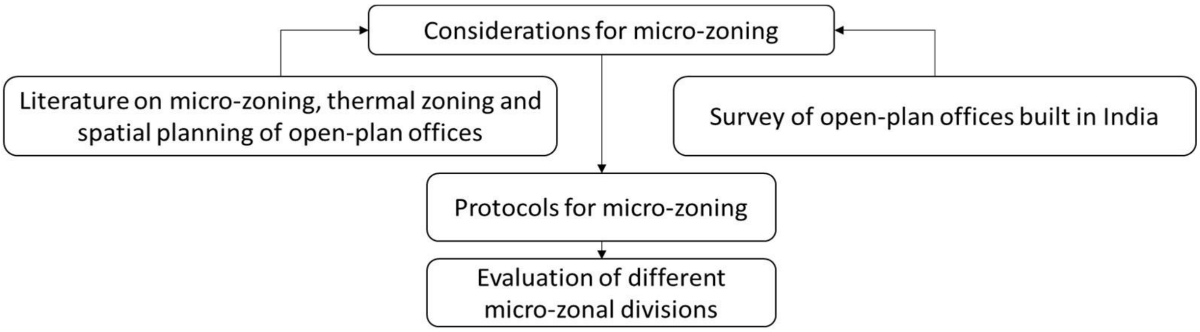

Figure 1: Methodology

A variety of open-plan offices built in the last decade are surveyed to explore the characteristics and existing conditions of Indian open-plan offices. The objective of the survey is to include all possible varieties of open-plan offices to have a holistic understanding. Hence, sampling is terminated when all varieties are studied. Forty-two offices, with a total of 116 open-plan office rooms, are studied, and 65 varieties of open-plan office layouts are observed.

To analyse the characteristics of these offices, the distribution of area of the floor plate, area of open-plan offices, aspect ratio, occupancy, occupant density, activity types, furniture used and their arrangements, etc., are analysed. The additional features in 'flexible' offices and 'activity-based' offices that need to be considered while sizing micro-zones are also explored. The existing conditions in these offices are evaluated in terms of thermal zoning and diffuser allocation. For each activity and diffuser type, the minimum size of micro-zones as per existing office layouts are delineated. In the second stage, protocols for micro-zoning are outlined based on the observed considerations.

The cooling load in the hour with the peak demand is considered the design load. The variations in energy consumed due to changes in occupancy are computed separately after estimating the cooling load. The Radiant Time Series (RTS) method is used to estimate cooling load. The RTS method considers the time delay due to conductive heat gain from building surfaces and delay in radiative heat gain to convert to cooling load [51]. The radiative heat gain absorbed by the interior surfaces adds to the cooling load when it is transferred to room air by convection. Conductive time series (CTS) is used to calculate conductive heat gain at the exterior using equation (1)

$$q_{i,q-n} = UA(t_{e.q-n} - t_{rc}) \quad (1)$$

Where,

$q_{i,q-n}$ is the conductive heat input for the surface n hours ago, (W)

U is the overall heat transfer coefficient for the surface, (W.m^2.K)

A is the surface area, (Wm^2)

$t_{e.q-n}$ is the sol-air temperature n hours ago (K)

t_{rc} is the presumed constant room temperature, (K)

Table 1: U values assumed in the study

Type	Material	U (W/m^2.K)
Roof	4 inch lightweight concrete	1.275
Exterior Wall	8 inch lightweight concrete block	0.8108
Interior Walls	Frame partition with ¾ gypsum board	1.4733
Ceilings	8 inch light weight concrete	1.3610
Floors	Passive floor	2.9582
Slabs	Uninsulated solid	0.7059
Doors	Metal	3.7
Exterior windows	Large double-glazed windows	2.914

Sol air temperature at an hour is calculated using equation (2):

$$t_e = t_o + \alpha E_t / h_o - \epsilon \Delta R / h_o \quad (2)$$

α is the absorptance of the surface for solar radiation

E_t is the total solar radiation incident on surface (W/m^2)

h_o is the coefficient of heat transfer (W.m^2.K)

t_o is the outdoor temperature in K

ϵ is the hemispherical emittance of the surface

ΔR is the difference between long-wave radiation incident on the surface from sky and surroundings and radiation emitted by a blackbody at outdoor air temperature (W/m^2)

The weather conditions are input using weather station data. The U values for different materials are assumed as given in Table 1. The overall U value is estimated by adding the reciprocal of the R-values of the materials.

Hourly conductive heat gain is computed from the conductive heat gained in the past 23 hours using equation (3)

$$q_q = c_o\, q_{i,q} + c_1 q_{i,q} + c_2 q_{i,q} + \cdots + c_3 q_{i,q} \quad (3)$$

q_q is the hourly conductive heat gain for the surface, (W)

$q_{i,q}$ is the heat input for the current hour (W)

c_o, c_1 is the conduction time factors (CTS values for wall and roof are followed as per ASHRAE 2017 [30])

Heat gain through surfaces from adjacent zones is computed using equation (4)

$$q = UA(t_b - t_i) \quad (4)$$

q is the heat transfer rate, (W)

U coefficient of overall heat transfer between conditioned and adjacent space, (W.m^2.K)

A is the area of separating section (Wm^2)

t_b is the average air temperature in the adjacent space (K)

t_i is the indoor temperature

Popular energy simulation tool energy-plus is used to calculate the cooling load, and inter-micro-zonal interactions are modelled using an airflow network [52] with a constant air exchange value of 10 exchanges per hour, as given in previous studies [6]. Though assuming a constant air exchange may overlook the transient variations in inter-micro-zonal interactions, the assumption is made as the objective of this analysis is to plan micro-zones to have a good starting point to further optimize airflow control. Computing inter-micro-zonal interaction using CFD simulations is computationally extensive and is not required at this stage. While planning airflow control, the air jet trajectories can be traced using CFD simulations to further improve MZOCC. The supply air temperature is set at 12 °C, and the setpoint is at 23 °C. It is assumed that the zone is conditioned using a variable air volume system (VAV). On computing the cooling load required in each micro-zone for the peak hour, the total cooling energy consumed for a day is estimated using equation (5)

$$E = \sum (CL_{mz} * Occ) \quad (5)$$

CL_{mz} is the cooling load in each micro-zone, and Occ is the percentage of occupants in a micro-zone at a given hour. It is assumed that the diffusers in the micro-zones are operated following MZOCC protocols formulated in this study.

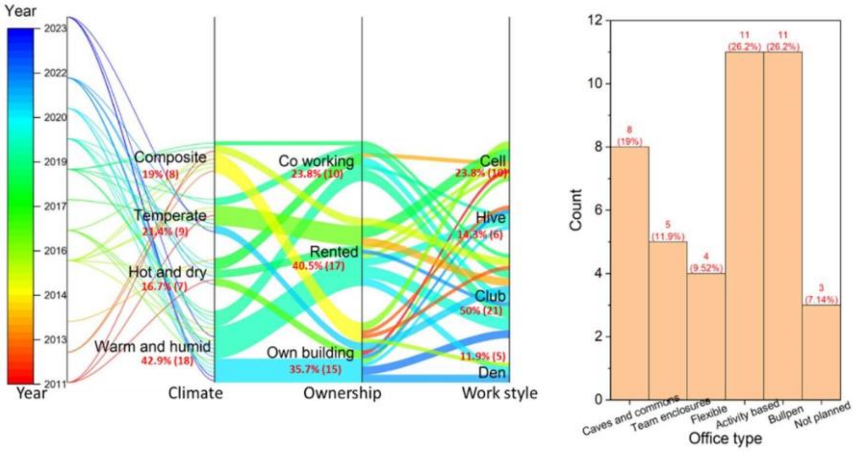

Figure 2: Distribution of year of construction, climate, ownership, work style and office type

Results and Discussion

Stage 1

Characteristics of open-plan layouts in Indian offices

The distribution of climatic zones, building types, work patterns, and layout types of surveyed offices are shown in Figure 2. Offices were surveyed through physical inspection by studying the layouts and interactions with office staff.

The area of floor plates ranges from 15-15000 sqm. The percentage of area allocated for open-plan offices ranges from 8%-90%. Figure 3 shows the distribution of floor plate area, percentage of open-plan offices, and aspect ratio of floor plates. Indian offices are observed to have similar characteristics to those observed in the literature on open-plan offices.

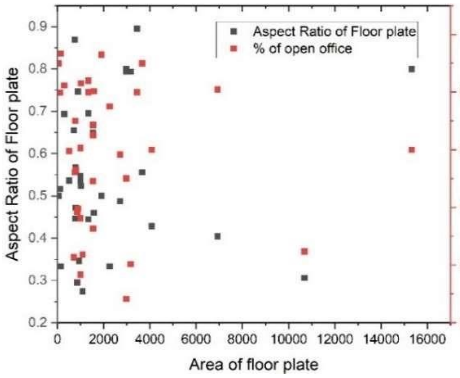

Figure 3: Distribution of office characteristics

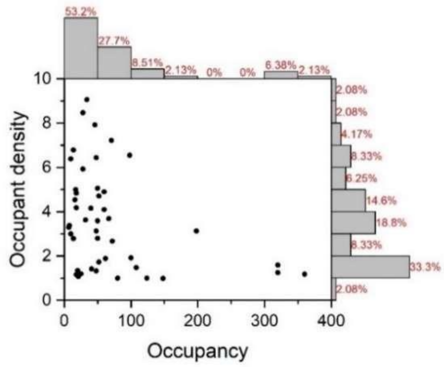

Figure 4: Plot of occupancy vs occupant density

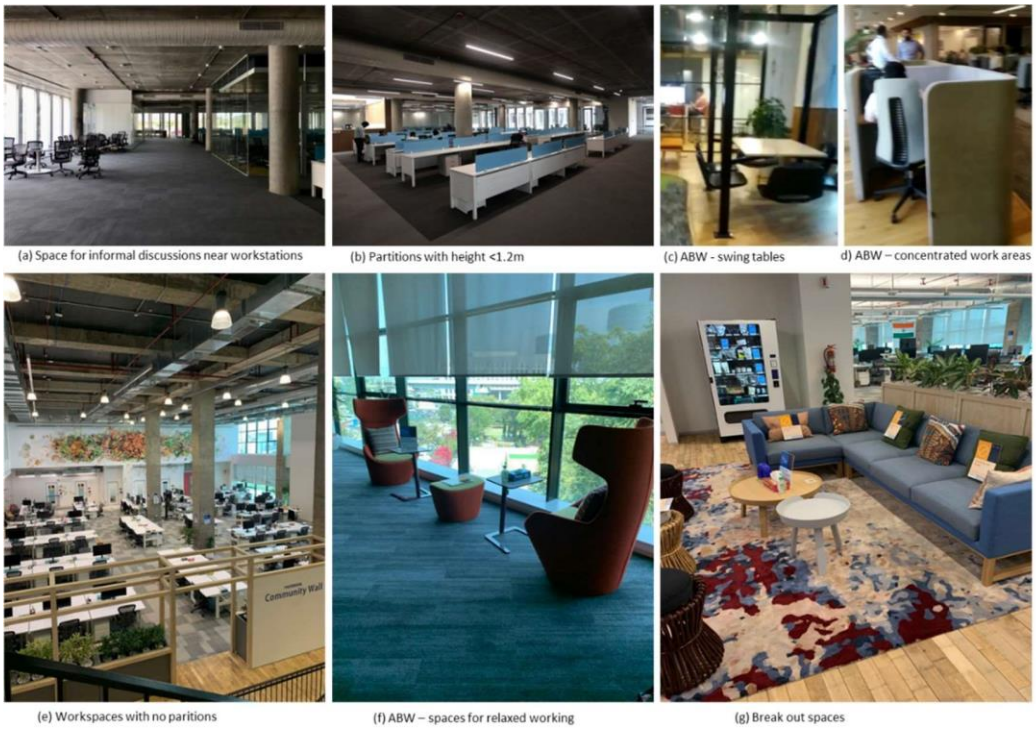

Figure 5: Photos of a few surveyed spaces

Figure 4 shows the distribution of the area of each open-plan office room with the occupant density in the room. The offices where interior layouts are not planned are removed from the distribution. It is observed that more than 50% of the offices have occupant density less than 4, i.e., very low area available per occupant. This contrasts the assumption of taking 6-8 m^2/person in Indian offices [48]. Customising thermal environments in such crowded spaces is challenging. More number of people need to be served by a single diffuser. Thus, people and activities will have to be grouped based on thermal preferences. Most of the offices have rectangular tables (72%), followed by L-shaped tables (18%). Circular tables and other customized furniture types are also seen. On analysing partitions, 3.28% of furniture have partition heights above 1.65m, 47.5% have part partitions between 1.65m and 1.2m, and 49.2% have partition heights below 1.2m. A variety of activity-based work (ABW) environments, leisure spaces, break-out areas, informal discussion areas, spaces with active furniture (e.g., tables with adjustable heights), etc., are found in the offices. Glimpses of a few offices are shown in Figure 5. In a few offices, the common work areas have double-height ceilings with cool air thrown from the ceiling, as shown in Figure 5e. The efficiency of MZOCC under such circumstances has not yet been explored. Considering the spread of jets and the diffusion of air, it can be asserted that MZOCC is challenging under such work settings, and the creation of micro-comfort zones will require personalised ventilation (PV).

Thermal zoning and HVAC systems in Indian open-plan offices

The zoning strategies in each of the floor plates are examined, and the spaces present in the core and perimeter and their distributions are plotted in Figure 6. It is observed that for more than 50% of offices, even the standard core-perimeter zoning strategy is not followed. This indicates that external heat gained is heterogeneous within these offices. Further, for the offices where the perimeter is separated, it is observed that perimeter depths are greater than 10m for cases where open-plan offices are located in the perimeter (as shown in Figure 7). This shows there is a gap between the literature and the implementation of thermal zoning for energy efficiency in open-plan offices.

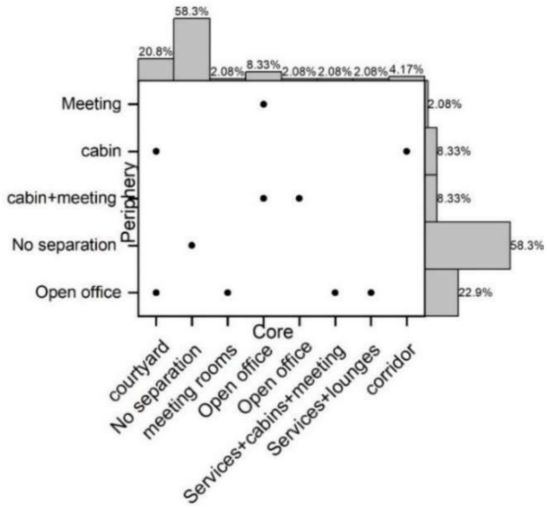

Figure 6: Spaces observed in core vs perimeter

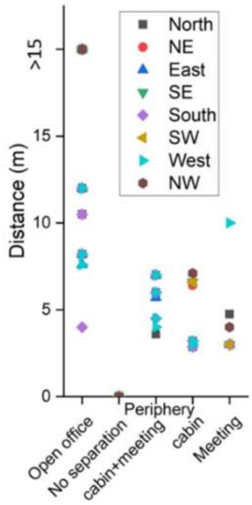

Figure 7: Depth of perimeter zones

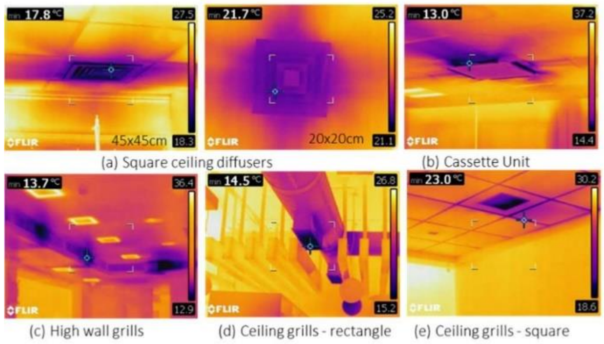

Figure 8: Thermal images of common diffusers

Table 2: Throw of each diffuser type

Diffuser Type	Grid
4-way square ceiling diffuser	3x3
Cassette units	6x6
Rectangular grills	1x4
Circular diffusers	radius of 1.5m

About 95% of the offices have centralised control. Occupants were casually asked how they felt about the thermal environment. Two occupants stated that overcooling is common, and occupants adapt to the thermal environment by carrying jackets to be worn inside the office, even on summer days. This indicates a clear wastage of HVAC energy and discomfort among occupants. Around 4% of office rooms had diffusers with independent control, such as cassette Acs. But in an office that allowed independent control of diffusers, an occupant was observed to relocate to avoid over-cooling. On enquiring, the occupant stated that he feared disturbing other senior staff in the office and hence, decided to adapt to the thermal environment. Though these observations cannot give general conclusions about the office behaviour of occupants, it is observed that MZOCC is needed to maintain thermal comfort in these offices. Most open-plan offices have ducted systems with the throw from either the ceiling or the top portion of the walls. There were instances where diffusers were placed very close to each other. This would lead to air jets hitting each other. Thermal images of the most common diffuser types found in surveyed offices are shown in Figure 8. It is observed that the size of diffusers, CFM, diffuser features, and the presence of a false ceiling, lights, or other installations in the ceiling all influence the throw. Spaces such as corridors are designed to have setback flow or a low-velocity flow. Side grill diffusers have a linear throw, where the region above the occupied zone (above 1.8 m) is at a lower temperature than entrained air in the occupied zone. Hence, these are not suitable for MZOCC. The minimum area catered by various ceiling diffusers is given in Table 2.

Area required for each activity

Common activity spaces found in surveyed open-plan offices are workstations, formal and informal meeting areas, collaborative spaces, waiting areas, queuing areas, lounges, activity-based workstations (ABW) such as couches to work, work cafes, swings with work tables, garden tables, low height seating, furniture with adjustable heights, etc. The unit area required for work station varies based on the furniture type and cluster. Hence, a non-uniform grid prioritizing the activity spaces must be developed. Dimensions of the lowest grid possible for workstations from the survey are plotted in Figure 9. The minimum area required for other activity spaces, as observed from the survey, is given in Table 3. In the absence of a furniture layout, a grid size that can accommodate the planned activity must be used. When furniture layouts are available, the grid should not be overly customized for a given layout, as this will prevent future adaptations. Hence, an optimal grid size, which is also flexible to accommodate other activities in the future, must be chosen.

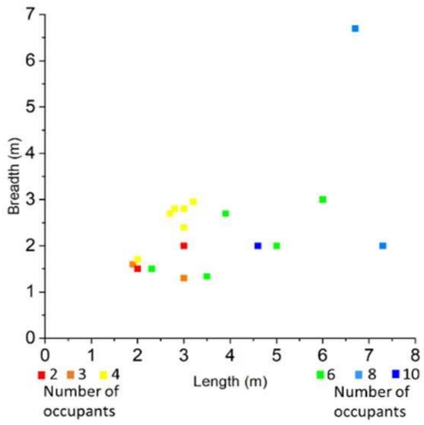

Figure 9: Minimum grid-size for workstations

Table 3: Minimum grid size for each activity

Activity Type	Grid (m)
Rectangular or circular workstations (4seater facing each other)	3x3
Workstations attached to walls or pillars	offset of 2m from surface
Meeting spaces – 12 people	5x4
Collaborative spaces	2x1.5
Waiting area	2x2
Lounges	2x2
ABW – Individual Couches	3x1.5
ABW – Work cafes	6x9
ABW – Swing tables	4x4

Stage 2: Protocols for micro-zoning

Based on the observations so far, an outline of the protocol for thermal zoning can be framed as:

1. Start with standard thermal zoning separation of core-perimeter (perimeter depth can vary from 6m-8m depending on the solar radiation and activities assigned in the perimeter)
2. Further, divide into micro-zones based on planned activities
3. Choose the micro-zonal grid size based on activities. (Table 2 can be used as a reference in this process)
4. Select diffuser type. (Table 1 can be used as a reference for this)
5. Alter the grid size based on area catered by diffusers, minimum distance between diffusers (e.g., at least 3m for 4-way square ceiling diffusers), and minimum distance of diffusers from walls (at least 2m). This has to be further altered while planning airflow control.
6. Alter the grid size to account for flexibility and future activities
7. Choose the grid size and diffuser that gives minimum energy consumption

It is to be noted that this micro-zonal division will not be the optimal one, but a good starting point for further evaluation. This is because transient factors such as occupancy schedule, thermal preference, inter-micro-zonal interaction, air movement, etc., are assumed at this stage observed in the literature. The optimal division will be such that occupied microzones are conditioned without the unwanted merging of air jets, thermal gradients, and drafts. Hence, after micro-zoning and initializing airflow, CFD simulations must be done to adjust micro-zones. This process will be an interesting future study.

Stage 3: Evaluation of micro-zoning in an existing office: A case study

The importance of micro-zoning is evaluated considering an existing open-plan office. The office is located in Hyderabad and is designed for hot and dry climates. Energy consumption under seven zoning layouts is evaluated. Zoning type 'a' is the typical HVAC zoning that currently exists in the studied office space. The entire open-plan office is zoned into a single thermal zone. The meeting room, which is separated by physical partitions, is zoned separately. Since the room has no external walls, core-perimeter zoning is not considered. Micro-zoning layouts 'b' to 'g' are shown in Figure 10. Zoning type 'b' divides each activity space in the open-plan office into different micro-zones. As discussed, the occupancy schedule and thermal preferences for each activity space are different. Hence, they need to be virtually separated. The occupancy in different activity spaces at the given hour is assumed, as shown in Figure 11. A setback temperature of 26 degree C is assumed for the corridors. Zoning type 'c' further divides functional micro-zones into large grids. This division is along the circulation paths observed in between workstations. The occupant density, schedule, and thermal requirements in each micro-zone are updated for cooling load estimation. In zoning type 'd', the functional micro-zones are further

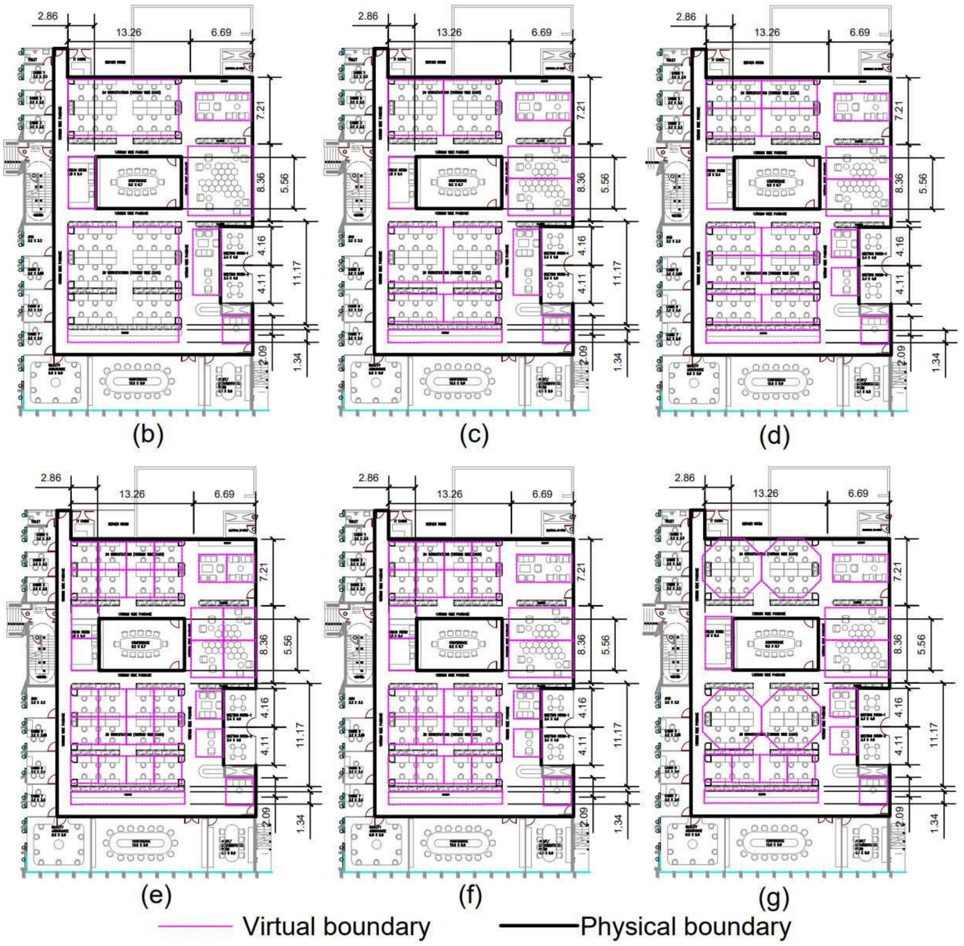

Figure 10: All cases of micro-zoning

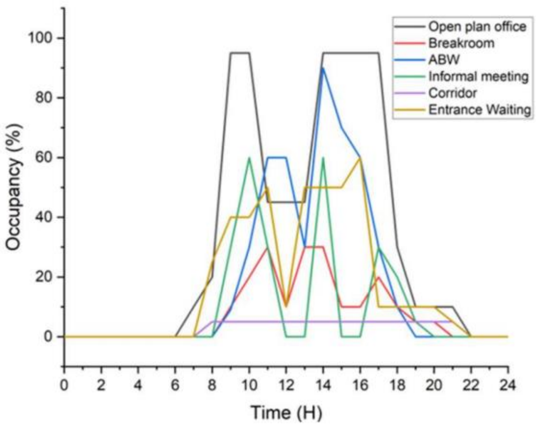

Figure 11: Occupancy pattern

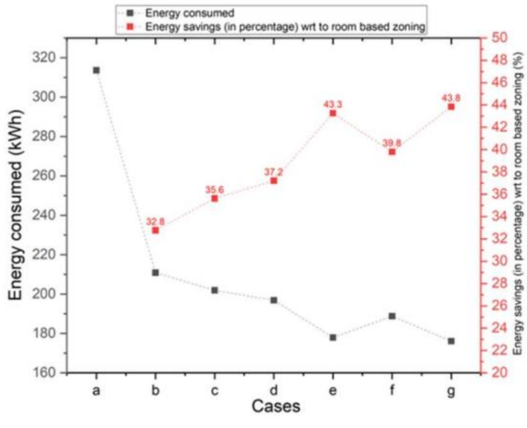

Figure 12: Energy consumption and savings under various micro-zoning

divided to form rectangular grids. Under this division, 2 square ceiling diffusers will be present in each microzone. In zoning type ‘e’, the micro-zones are further divided such that only one square ceiling diffuser is present in each micro-zone. Considering the area catered by a 4-way square ceiling diffuser of size 45x45cm, the micro-zone is sized 3x3m. Further division of micro-zone will lead to unwanted merging of air jets. But, under such division, in a few microzones (informal meeting spaces), the distance between supply diffusers and the wall is less than 1.5m. As discussed, this will lead to clinging of cool air to the walls. Hence, a larger rectangular grid is taken as shown in case ‘f’. Further, it is observed that the corners of the micro-zones containing workstations need not be conditioned. Hence, in zoning type ‘g’, the shape of micro-zone is altered to an octagon of side 3m. This makes the micro-zone more compact while serving larger occupancy. The total number of diffusers needed is also reduced. Thus, micro-zonal divisions ‘c’ to ‘g’ are planned considering the current understanding of micro-zoning, spatio-temporal characteristics of the office, and inter-micro-zonal interaction. Such analysis will give insights on how much more energy is saved through micro-zonal division compared to functionbased division. The energy consumption is computed as discussed in the method section, considering the occupancy schedule given in Figure 11. The results showing the energy consumption and percentage of energy saved in each micro-zonal division with respect to the single zone model are plotted in Figure 12. The results and calculations are uploaded as data [53].

It is observed that energy consumption drastically reduces from room-based zoning ('a') to function-based zoning ('b'). This is because, mostly, activity spaces such as informal meeting areas, activity-based work areas, etc., are unoccupied, and separate airflow control following the occupancy schedule reduces energy consumption. There is only a mild increase in energy savings from function-based zoning ('b') to zoning using large grids ('c') and rectangular grids ('d'). This is because the occupancy pattern does not vary much between these micro-zoning strategies. But, when the most granular square grid ('e') is applied, energy savings increases. This is because, under such granular division, there are several micro-zones that are unoccupied, and air-conditioning can be completely switched off. But, as discussed, such granular division is not feasible considering air jet movement. Micro-zoning 'f', where few micro-zones are merged to prevent clinging of cool air to surfaces, saves about 40% energy consumption and is a suitable micro-zonal division. The grid with a mix of octagonal divisions and granular square divisions ('g') saves 44% energy consumption and abides by all protocols regarding preventing the merging or clinging of air jets. Further, the increased size of micro-zones allows greater flexibility. Thus, improving the size and shape of micro-zones based on the current understanding of micro-zoning helps in reducing 16% more energy compared to function-based zoning. This micro-zonal division is, hence the best starting point to evaluate airflow strategies for MZOCC.

Conclusion

Creating micro-comfort zones around occupants to reduce energy wastage in open-plan offices has been of great interest to researchers. Several methods, such as personalised ventilation, personal comfort systems etc., which use additional 54igeria54g54ture to create micro-thermal environments and diffuser level micro-zonal control of standard HVAC systems, are used in this regard. The latter is preferred due to reduced investment and increased flexibility. Though few studies discuss the importance of planning micro-zones to avoid the merging of air jets to reduce draft and thermal gradients, there is no clarity on how micro-zones are to be planned. The parameters critical in micro-zoning have been identified in this study and are observed to be different from those of thermal zoning. There is a need to establish a link between micro-zoning and thermal zoning. Further, micro-zoning must also be linked to the spatial planning of open-plan offices. This study explored considerations in micro-zoning by performing a survey of existing Indian open-plan offices. It is observed that while Indian offices have characteristics similar to the ones observed in the literature, even standard thermal zoning methods are not employed, indicating huge energy wastage. The area required for each activity and the area catered by diffusers are analysed, and references for minimum micro-zonal grid sizes are outlined in the study. Protocols for micro-zoning are delineated, and an existing open-plan office with different activity spaces is micro-zoned using the protocols. Results indicate that planned micro-zoning reduces energy consumption by about 44% compared to zonal conditioning.

One limitation of this study is that the energy savings were estimated only using simulations, which are based on several assumptions. Field studies can be conducted to get a realistic understanding of the potential of MZOCC by choosing the best micro-zonal planning and strategizing airflow control. Future studies can look into planning airflow control considering micro-zonal divisions and further improve micro-zoning. Transient factors such as occupancy, activity schedule, location of occupants, occupant's thermal preferences, air movement, etc. will be critical in this regard. Based on these, choice of control strategies such as setback flow or setback temperature, whether these are to be employed in all micro-zones or only micro-zones adjacent to occupied micro-zones; and whether similar micro-zones must be combined into one micro-zone are to be decided. Thermal comfort within micro-zones is to be evaluated in the second stage. Thus, a linked bi-level framework with micro-zoning optimized in the first level and airflow control strategies optimised in the second must be framed. Thus, the protocols derived in this study give important contributions to the future development of a bi-level framework for optimised MZOCC.

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