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Analysis of thermal comfort in free-running and mixed-mode office buildings during summer season: A case study of Kathmandu Valley

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DECLARATION

I, ANJU RAI, affirm that the thesis titled "Evaluation of Thermal Comfort in Free-Running and Mixed-Mode Office Buildings during the Summer Season: A Case Study of Kathmandu Valley," is being submitted to the Department of Applied Science and Chemical Engineering at the Institute of Engineering, Tribhuvan University, as a partial fulfillment for the M.Sc. degree in Climate Change and Development. This research was conducted under the supervision of Prof. Dr. Sushil B. Bajracharya. I declare that the presented work is entirely my own, and it has not been previously submitted for a degree at any other academic institution.

………………………..

Anju Rai

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APPROVAL PAGE

We, the undersigned, confirm that we have thoroughly reviewed and endorse the acceptance of the thesis titled **"Analysis of Thermal Comfort in Free Running and Mixed-Mode Office Buildings: A Case Study of Kathmandu Valley."** This thesis has been submitted by Miss Anju Rai (078MSCCD002) as part of the requirements for the Master of Science degree in Climate Change and Development. We recommend its acceptance to the Institute of Engineering.

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ABSTRACT

Nepal is witnessing a more rapid temperature increase compared to the global average, heightening concerns about potential thermal discomfort and its impact on the workplace environment. Addressing this, there is a critical need to prioritize improvements in the indoor thermal conditions of office buildings to mitigate potential adverse effects on occupants. The indoor environmental quality, encompassing thermal comfort and indoor air quality, holds substantial sway over occupants' well-being and productivity in office settings. Therefore, fostering a comfortable and productive working environment is paramount for effective work outcomes. The scientific community, particularly in building analysis, has shown increased interest in issues related to thermal comfort and indoor air quality, evident in recent revisions to the Directive 2018/844/EU on the energy performance of buildings.

This study aims to report on the thermal environment conditions in free-running and mixed-mode office buildings and assess the thermal perception of office employees during the summer season. Through physical parameter monitoring and survey questionnaires conducted in Kathmandu Valley during June-July 2023, the study determined the comfort temperature using Griffiths' method. The results indicate comfort temperatures of 27.21 °C and 26.81 °C during the summer season in free-running and mixed-mode buildings, respectively. Throughout the field survey, indoor thermal comfort was observed within a range of 21 °C to 32.8 °C. The findings reveal that office employees found these temperature ranges tolerable, demonstrating their adaptability to CO_2 exposure, consistent with previous research.

Moreover, the study highlights that CO_2 concentrations in both free-running and mixed-mode buildings remained within limits set by ASHRAE 62 guidelines, suggesting good indoor air quality, ample ventilation, and occupant well-being. While these findings are promising, a more in-depth longitudinal study incorporating all relevant parameters is recommended for precise results regarding indoor thermal environments. Future research endeavors should continue exploring a comprehensive understanding of indoor environmental quality to further enhance our knowledge in this domain.

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CHAPTER-1: INTRODUCTION

1.1. Background

Currently, the operation of buildings accounts for a large portion of total primary energy consumption. Building only absorb 40% of energy when compare to other sector [1], with heating, ventilation and air-conditioning (HVAC) systems being the main energy consumers in buildings contributing to emission of GHG gases resulting climate change. While developed countries are predicted to consume more energy than developing countries by 2024, it is expected that emerging countries would consume more energy than developed countries [2]. Aligning the architectural design and thermal efficiency of a building with the specific characteristics of the local climate is a pivotal aspect of passive design strategies. This approach aims to minimize energy consumption while enhancing the overall thermal comfort for occupants [3]. However, one of the most significant tasks is to improve indoor thermal comfort and reduce energy consumption in buildings as to mitigate the climate change [1].

Thermal comfort have been considered an inevitable indicators for indoor quality defined by ASHRAE Standard 55 as a state of mind that is evaluated by subjective assessment and reflects satisfaction with the thermal environment. In addition to being the definition of a person's awareness of the thermal atmosphere, thermal comfort is also the state in which a person feels neutrally heated or cooled, without sweating [4]. The person's location, as well as the climatic conditions within and outside the enclosure, influence their thermal comfort standards .The largest impact on occupant comfort and productivity among all other criteria is thermal comfort [5]. The credibility of the adaptive comfort model has gained acknowledgment from contemporary comfort standards like ASHRAE Standard 55, EN 15251, and specific national guidelines such as China's GB/T 50785. This recognition is attributed to ongoing research efforts by various scholars, including Brager and de Dear, as well as Nicol and Humphreys [6].

Most adults dedicate approximately 90% of their time indoors, while children spend about 75% of their time in indoor environments [7]. The predominant reason for adults spending the majority of their time indoors is largely attributable to occupational demands. In the last five decades, a substantial shift from outdoor or factory work settings to indoor office environments has occurred, driven by extensive industrialization and urbanization trends. In offices, indoor environmental quality significantly influences occupants' comfort and productivity, hence for occupants to work effectively, a productive and comfortable working environment is a crucial and fundamental requirement [8]. A pleasant working atmosphere is essential for employees to concentrate and perform well. This will improve the quality of life at work as well as the performance of office workers, resulting in improved organizational performance.

In the context of the worldwide effort to curtail energy consumption in buildings, a frequently proposed strategy involves the integration of natural ventilation alongside HVAC systems. The adoption of mixed-mode operation in buildings, as opposed to relying solely on air conditioning, represents a climate adaptation advancement that typically leads to diminished energy usage [9]. Nonetheless, there is disagreement over comfort levels, and forecasting energy usage and demand in the context of global warming is challenging.

Nepal is a developing country where the urbanization process is very fast and located at with 28°N latitude and 84°E longitude. It has a very diverse and complicated climate that is influenced by the geography, regional weather systems, and uneven terrain [10]. In the last few decades, Kathmandu valley is the largest and fastest growing city where the office buildings are significantly located. The climate of Kathmandu can be classified as warm and cool temperate climate. This paper primarily focuses on inhabitants' perceptions of comfort and analyses room temperatures of free running and mixed –mode office buildings in Kathmandu Valley.

1.2. Need of Research

The urbanization trend in Nepal, is growing at 6.5% per year, particularly evident in the rapid growth of Kathmandu Valley [11] , highlights the need for focused research on the thermal comfort and indoor air quality in office buildings. [12]The population of Kathmandu Valley has surged, with estimates projecting a doubling by 2030, largely driven by rural-urban migration. This urban expansion is mirrored by a substantial increase in built-up areas, particularly in residential and mixed residential/commercial zones [13].

Considering that individuals typically spend a significant portion of their waking hours in offices, the conditions within these spaces are crucial. Furthermore, office buildings represent a substantial portion of non-residential constructions, making up 23% of conditioned areas, second only to wholesale and retail buildings [14]. Therefore, understanding and optimizing the thermal comfort and indoor air quality in office buildings is imperative for sustainable urban development.

Despite efforts to enhance energy efficiency without compromising comfort, there remains a significant gap in research, especially concerning office buildings. While studies have been conducted on residential, commercial, and school buildings, the specific requirements and challenges faced by office spaces have been relatively understudied [15]. Recognizing the unique dynamics of office environments, a comprehensive investigation is needed to establish thermal comfort standards that align with the specific conditions of Kathmandu Valley.

The climatic conditions of Kathmandu Valley further emphasize the necessity for context-specific standards. Generic comfort levels may not be suitable in all areas, making it imperative to develop climate-specific thermal comfort standards [16]. By conducting a detailed case study focusing on Kathmandu Valley, researchers can gain insights into the region's unique challenges and requirements regarding thermal comfort and indoor air quality in office buildings.

Ultimately, this research is not only academically valuable but also holds practical significance. Establishing context-specific standards will empower decision-makers to formulate and implement policies aimed at reducing energy consumption in office buildings effectively. This, in turn, contributes to sustainable urban development in Kathmandu Valley and serves as a model for similar metropolitan areas facing comparable challenges in South Asia.

1.3. Problem Statement

There is growing concern about the influence of climate change on internal summertime temperatures in buildings, as future summers are expected to be both warmer and drier, with an increase in the occurrence of high temperatures [17]. Elevated temperatures in office buildings, as it has direct impact on the indoor thermal comfort and indoor air quality that determines the productivity and wellbeing of the occupants and primarily influence the rate of energy consumptions [18].

In order to enable building designers create an indoor environment (thermal comfort and indoor air quality) that building occupants will find thermally comfortable, thermal comfort standards are necessary. More significantly, although mixed mode buildings are increasingly the norm, there are no national or international indoor environment (thermal comfort and indoor air quality) criteria.

The temperature in Nepal is rising more quickly than the average worldwide [19]. Indoor environment (thermal comfort and indoor air quality) must be prioritized in office building design. The Nepalese government published a building design code, however it does not address the issue of thermal comfort, making it the primary reason of inadequate indoor thermal comfort [20]. The goal is to create an adaptable indoor environment (thermal comfort and indoor air quality) that occupants like, improves their health, and makes them happy with the improved building design strategies.

1.4. Objectives

The general objective is to determine the comprehensive understanding of occupant's thermal perception in free running and mixed-mode office buildings.

Specific objectives

a) To predict the comfort temperature of Kathmandu valley.

b) To analyze the CO2 concentration with respect to mode of office building.

c) To study the impact of climate change with respect to thermal comfort

1.5. Importance of Research

The construction industry is increasingly facing a severe challenge with climate change as the effects of these changes are predicted to have a real influence on building thermal performance and HVAC systems over time. Over the past few decades, the building sector has seen a substantial growth in energy consumption, surpassing that of other major sectors such as transportation and industry. This increase can be attributed to a number of causes, including higher indoor temperature, increased demand for building services, and comfort levels. However, no thermal comfort research has been undertaken in office buildings in Kathmandu Valley. Hence this study will help to report the thermal environment conditions of office buildings and also will assist policymakers and designers in developing a paradigm for resilient office buildings construction in terms of energy performance and its impact on occupant's performance. Indoor comfort is of the utmost significance in offices. Energy efficiency, together with indoor climatic comfort, are critical characteristics of good practice for office worker performance in accordance with sustainable building principles. The rationale for the application of adaptive thermal comfort models in climate change impact assessments is supported by the significance of their implementation. Building designers can also employ adaptive thermal comfort to increase a building's resistance to change.

1.6. Limitations

Due to the three-month time limit, this research will solely focus on thermal comfort and indoor air quality inside the free-running and mixed-mode office buildings during June-July 2023. While many researcher advocate for the consideration of six factors in assessing thermal comfort, this study intentionally narrows its focus to air temperature and relative humidity due to time constraints. Similarly, the assessment of indoor air quality in this study centers on CO_2 concentration levels, with other parameters, such as volatile organic compounds, particulate matter, ventilation rates, and biological contaminants, excluded from the analysis. The decision to concentrate on these specific factors was driven by practical considerations, acknowledging the inherent limitations imposed by time constraints. A questionnaire survey will be used to gather data on the office employee's thermal perception using a 7-point ASHRAE scale. During the site visit, field measurements and temperature data are gathered. No conventional or Traditional typology of office buildings is included in the analysis. Additionally, no other types of buildings other than free - running and mixed-mode offices would be included in the investigation.

CHAPTER-2: LITERATURE REVIEW

2.1. Climate Change

As per the definition provided by the United Nations Framework Convention on Climate Change (UNFCCC), climate change is characterized as a discernible alteration in climate patterns exceeding natural variability over corresponding time spans. This change is ascribed directly or indirectly to human activities that modify the composition of the global atmosphere. Based on an ongoing temperature analysis conducted by scientists at NASA's Goddard Institute for Space Studies (GISS), the Earth's average global temperature has risen by a minimum of 1.1° Celsius (1.9° Fahrenheit) since 1880. The predominant portion of this warming has transpired since 1975, with an approximate rate of 0.15 to 0.20°C per decade.

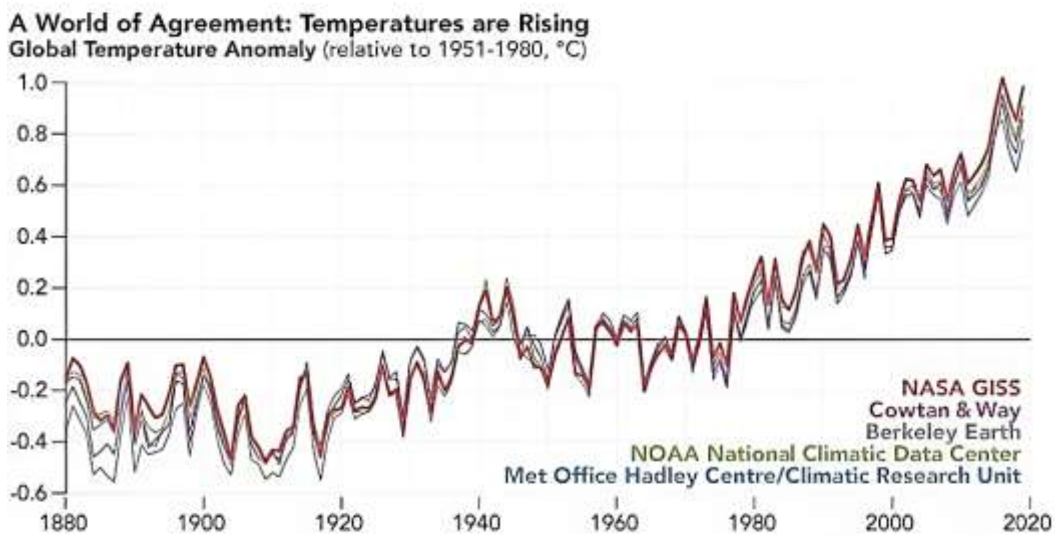


Figure 1: Global yearly temperature anomalies from 1880 to 2020*(Image: earthobservatory.nasa.gov)*

Because observations did not cover enough of the earth before to 1880, global temperature records begin about that time. The line figure above depicts yearly temperature anomalies recorded by NASA, NOAA, the Berkeley Earth research group, the Met Office Hadley Centre (United Kingdom), and the Cowtan and Way study from 1880 to 2020. Despite modest differences from year to year, all five datasets show peaks and dips that are in sync with one another. All show rapid warming over the last few decades, with the latest decade being the warmest.

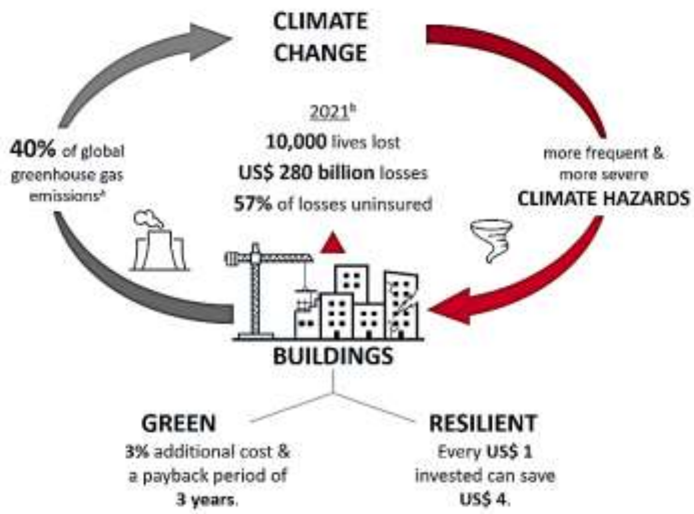


Figure 2: Building sector emissions and resilience cycle *(Image:Ommid Saberi, Naz Beykan, IFC; Data from IFC, MunichRE and National Institute of Building Science)*

Buildings consume around 40% of world energy, 25% of global water, 40% of global resources, and produce approximately 1/3 of global greenhouse gas emissions. Buildings, on the other hand, have the greatest potential for achieving large GHG emission reductions at the lowest cost in both developed and developing countries [21]. Furthermore, utilizing established and commercially accessible technology, energy consumption in buildings can be lowered by 30 to 80%.

2.2. Climate Change in Nepal

Climate change has now triggered a climate crisis in countries such as Nepal. Climate change impacts may be severe at high elevations and in complex topography such as Nepal, according to the global climate model. Based on various research [19], the average trend of temperature change in the country is 0.06°C per year. According to the Intergovernmental Panel on Climate Change (IPCC) research, Nepal would suffer the negative effects of climate change, notwithstanding its tiny contribution to greenhouse gas emissions. Nepal is identified as one of the ten countries most vulnerable to the impacts of global climate change, despite being among the least contributors to greenhouse gas (GHG) emissions. The nation's emissions account for merely 0.027% of the global share. [22].

Data spanning from 1975 to 2005 indicates an annual temperature increase of 0.06°C in Nepal, while the mean rainfall has notably decreased by an average of 3.7 mm (-3.2%) per month per decade. Projections suggest a further rise in mean annual temperatures by 1.3-3.8°C by the 2060s and 1.8-5.8°C by the 2090s under various climate change scenarios. Concurrently, annual precipitation is anticipated to decrease within a range of 10 to 20% across the country [22].

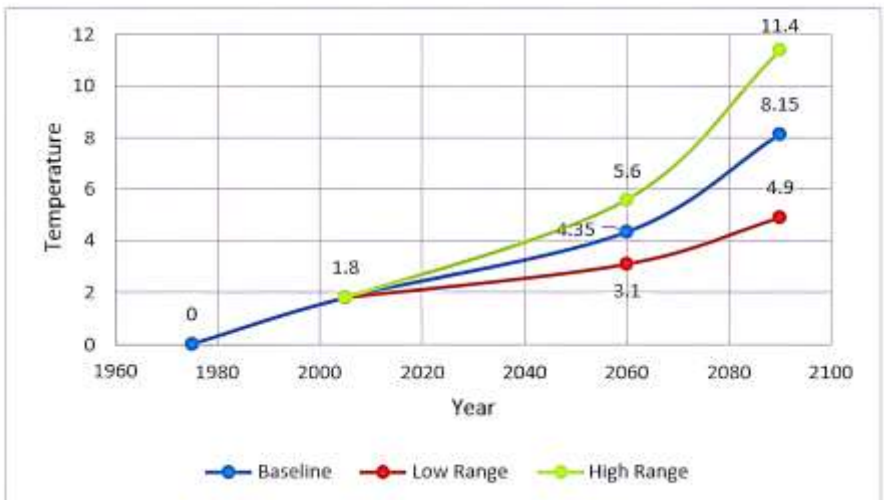


Figure 3: Raise in temperature pattern *[22]*

2.2.1. Climate change scenario of Kathmandu valley

Kathmandu Valley, a key urban center in Nepal, is centrally located with a watershed area of 656 km2, enclosed by the Mahabharata hills on all sides. The region experiences four distinct seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). The average annual rainfall in the valley, recorded from 1976 to 2005, is 1778 mm, with the majority occurring during the monsoon season (June-September). The valley's average maximum and minimum temperatures, based on data from 1980 to 2010, are 23.80°C and 11.4°C, respectively.

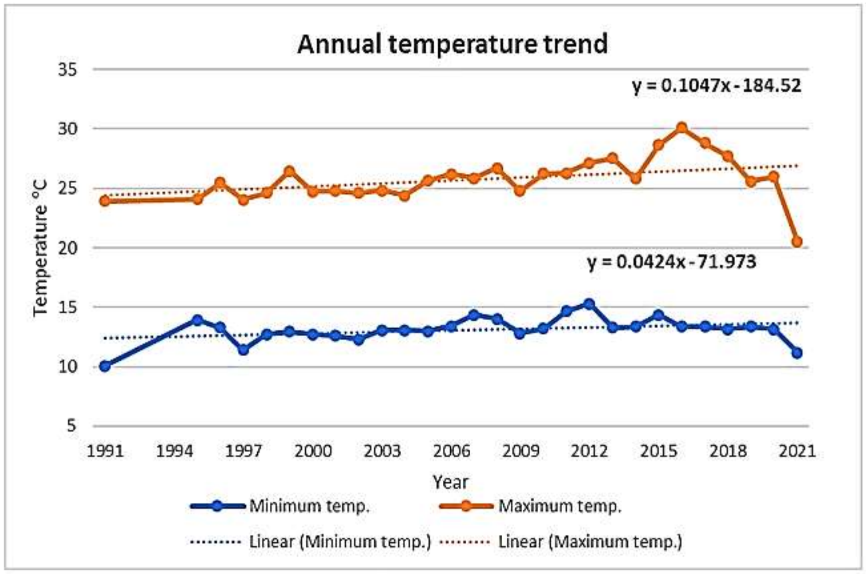


Figure 4: Trend of maximum and minimum temperature of KTM valley (1991-2021) [23]

*[23]*The graphic depicts the trend of maximum and minimum temperature, with the maximum temperature increasing by 0.1047 C every year. Similarly, the minimum temperature increased by 0.0424 C per year. It is similar to the National Adaptation Program of Action (NAPA), which reported a yearly, non-uniform increase in temperature of 0.04-0.06°C, with higher elevations warming quicker than the lower, southern lowlands.

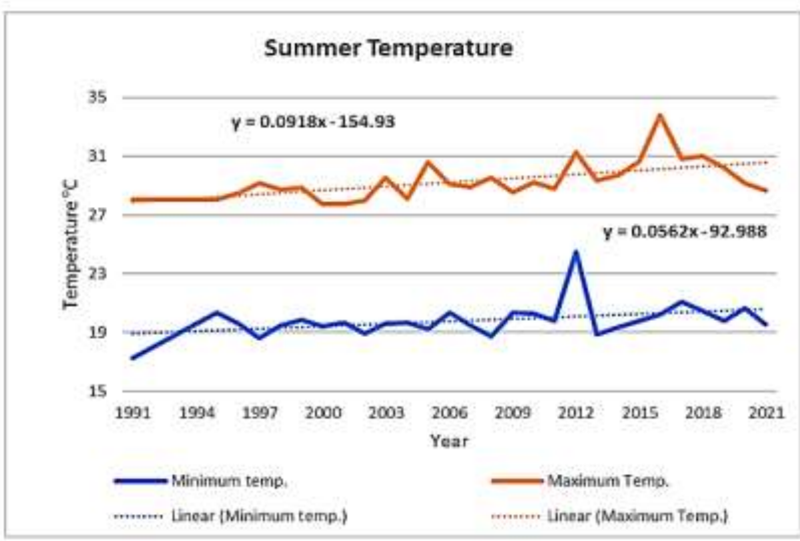


Figure 5: Average summer temperature of KTM valley (1991-2021) [23]

[23]The maximum summer temperature increased by 0.0918 degrees Celsius every year, whereas the minimum summer temperature increased by 0.0562 degrees Celsius per year.

Even if the change was slight at the moment, it might become more problematic soon. As a result, the Kathmandu Valley's climate is actually changing, which means that it needs to be taken seriously and that necessary adaptation, mitigation, and control measures need to be implemented in order to protect the ecosystem, infrastructure, resources, and human population from potential negative effects of warming.

2.3. Topographic and climatic description of Nepal

Nepal is a landlocked nation located in the northern hemisphere, having latitudes between 26° and 30° N and longitudes between 80° and 88° with a total lateral and vertical extent in the east-west and north-south directions. Nepal’s land area measures 147 516 km2. The elevation ranges from 80 meters above sea level to 8848 meters (Mount Everest). The upshot is that the climate varies greatly throughout space, from the tropics to the arctic. Political, topographical, climatic, and vegetation-based divides of Nepal's landscape are further classifications.

With respect to geography, Nepal is separated into the Terai, Hilly, and Mountain areas. Nepal features 8 distinct climatic zones, with heights ranging from 60 meters to 8848 meters above sea level, with climates ranging from Tropical Savannah to Polar Tundra. The climate zones and corresponding land coverage are shown in the figure below for various altitudinal belts.

Climatic Zones	Altitude (in meters)	% of land coverage	Areas occupied
Tropical	Below 1 000 m	36 %	All parts of outer and inner Terai and Sivalik hills region
Sub-Tropical	1 000 m - 2 000 m	22 %	Middle hills
Temperate	2 000 m – 3 000 m	12 %	High Hills and lower mountainous region
Sub-Alpine	3 000 m – 4 000 m	9 %	Mountainous and parts of Himalayan region
Alpine	4 000 m – 5 000 m	8 %	Himalayan region
Snow line	Above 5 000 m	13 %	Himalayan region

Figure 6: Climatic zones distribution with land coverage and altitude variations for Nepal *[20]*

2.4. Nepal National Building Code (NBC)

The NBC of Nepal, which is overseen by the DUDBC, Government of Nepal, sets the regulations for building construction. In 1994 AD, the first draft of the NBC was created to address the growing urbanization with the technical guidance of the United Nations Development Program (UNDP) and UNCHS. Following the GON's 2003 ratification of the NBC, new construction required to follow it. The VDCs were excluded from this law at the time. Due to a lack of frequent monitoring, a lack of resources, and individuals who did not comprehend the relevance of the code, the actual implementation was still plagued by significant issues. DUDBC advocated a variety of earthquake-resistant building designs following the 2015 earthquake, but no new NBC has been released. The NBC, on the other hand, makes no mention of thermal comfort or building energy efficiency [20].

2.5. Office buildings

According to the Nepal National Building Code, NBC 206:2015 defines "a public building as any government, non-government or private building used to provide services, facilities, products, and opportunities to the public."

NBC 206:2015 has categorized office building based on occupancy on group F with the definition as these shall include any building or part of building which is used for official or business use. Subgroup-A2: Residential with limited commercial use applies to residential normal rise buildings with a plinth area of less than 150 square meters and a portion of the building utilized for offices.

Free running mode buildings (FR)

Rather than being a particular kind of building, free running is a way of functioning. When a building is not using energy for cooling or heating, it is free operating. A free-running building does not have mechanical cooling, so according to CIBSE's (Chartered Institution of Building Services Engineers) AM10 (Application Manual), the occupancy rate should be 10 m2 per person and the total internal heat gains should not exceed 40 W/m2 in order to create a comfortable environment.

Mixed mode buildings (MM)

It's a structure with windows that can be opened by residents, and it's planned using efficient passive climate control techniques. For most of the year, the passively designed building is used to create suitable conditions, and a mechanical system is added either “as and when required" or on a seasonal basis” [24].

Passive inlet vents or operable windows are used in a hybrid space conditioning strategy called MM to allow for natural ventilation (either automatically or manually controlled). When necessary, air conditioning mode is switched to maintain a comfortable temperature while using the least amount of energy. MM buildings are neither pure AC buildings nor pure NV buildings because they use both air cooling (AC) and naturally ventilated (NV) modes [25].

The use of mixed-mode ventilation (MM) techniques is growing in popularity as a more energy-efficient substitute for conventional HVAC systems. By combining mechanical cooling and natural ventilation, mixed-mode (or hybrid) building operation reduces dependency on energy-intensive HVAC systems and creates comfortable interior environments [26].

[27]MM building, which is categorized as "zoned" (natural ventilation and HVAC occur in different building zones), "concurrent" (natural ventilation and HVAC occur simultaneously), and "change-over" (natural ventilation and HVAC occur in the same area at different times).

2.6. Thermal comfort

"Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE 55:2017).

The ASHRAE definition of thermal comfort specifies that in order to be thermally comfortable, a variety of climate or environmental factors as well as human elements must be considered. Jones defined thermal comfort [28] as the achievement of a balance between metabolic heat development and heat loss due to thermal environmental conditions, which include human properties such as the rate of activity and insulation of the garment.

Six elements were identified by Macpherson in 1962 as influencing thermal perception: two personal variables (activity level, or metabolic rate) and four physical variables (air temperature, air velocity, relative humidity, and mean radiant temperature) [29]. Both physiological and non-physiological factors can affect thermal comfort. The thermal perception range in semi-outdoor and outdoor settings may be wider since it is widely known that it might be difficult to change the temperature conditions in these regions to ones that are as comfortable as indoors, even though doing so may be helpful.

Thermal comfort requirements are crucial for building sustainability since they dictate how much energy is used by a building's environmental systems [30]. This energy frequently includes the combustion of fossil fuels, which contributes to CO2 emissions and climate change [31]. Thermal comfort is also an important factor in maintaining a healthy and productive workplace [32].

The PMV model is used by thermal comfort standards to suggest appropriate thermal comfort levels. The recommendations made by ASHRAE Standard 55 are shown in Table 1 [33]. The specified conditions considered in this context involve a relative humidity of 50%, a mean relative velocity below 0.15 m/s, a mean radiant temperature equating to the air temperature, and a metabolic rate set at 1.2 met. Furthermore, the definition of clothing insulation was established at 0.5 clo during the summer and 0.9 clo in the winter.

Table 1: ASHRAE -55 Standard recommendations [33]

S.N.		**Operative temperature**	**Acceptable range**
1.	Summer	22ºC	20-23ºC
2.	Winter	24.5ºC	23-26ºC

2.7. Adaptive thermal comfort

Nicol defines the 'adaptive comfort temperature' as the temperature deemed comfortable by individuals in a specific environment. The fundamental premise of the adaptive approach is encapsulated in the adaptive principle. This perspective on thermal comfort acknowledges the influence of human behavior in response to their thermal surroundings [6], [34].

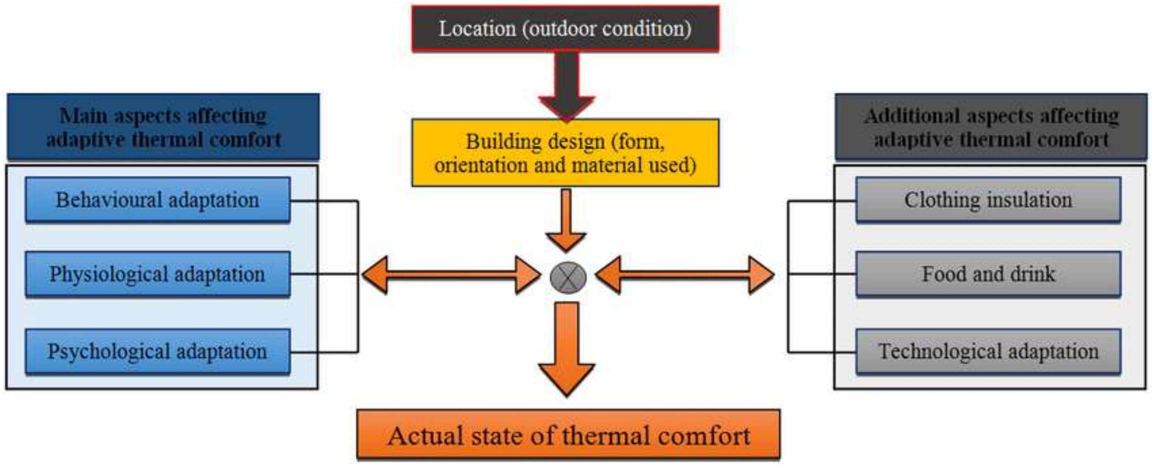


Figure 7: Aspects effecting thermal comfort and other additional common aspects that leading to the actual state of thermal comfort *[35]*

The adaptive approach is grounded in field studies designed to assess the genuine acceptability of the thermal environment. This methodology recognizes the significant influence of context, occupant behavior, and their expectations on the perceived comfort in the given setting [4]. The adjustments have been summarized by De Dear [36] in three categories: behavior adaptation, physiological adaptation and psychological adaptation. Researchers conduct field surveys to collect information about the thermal environment and the simultaneous thermal response of individuals going about their daily lives. Subjects' thermal responses are typically measured by asking them for a 'comfort vote' on a descriptive scale such as the ASHRAE or Bedford scale [37](Table 2).

Table 2: Thermal scale by ASHRAE-55 and Bedford

ASHRAE descriptor	**Numerical equivalent**	**Bedford descriptor**
Hot	3	Much too hot
Warm	2	Too hot
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cool
Cool	-2	Too cool
Cold	-3	Much too cool

The 'rational' approach to thermal comfort seeks to explain people's responses to thermal environment in terms of physics and physiology. An 'index' of thermal comfort is devised that reflects the thermal state of the human body in terms of the thermal environment, taking into account temperature, humidity, air movement, clothing, and activity. Current standards, such as ISO 7730 [38] and ASHRAE 55, are based on this method [37].

The implementation of an Adaptive Thermal Comfort standard holds significant potential for mitigating energy consumption and reducing greenhouse gas emissions. This approach aims to achieve these environmental goals while simultaneously preserving the comfort, productivity, and overall well-being of occupants [39]. The adaptive indoor temperature in Kathmandu considering the studies of Rijal and Nicol comfort temperature (Tc) is shown in table 3 below [27].

Table 3: Adaptive indoor temperature in Kathmandu considering the studies of Rijal and Nicol comfort temperature *[15]*

S.N	Thermal Sensation	Thermal Scale	Nicol Tc(°C)		Rijal Tc(°C)		Comfort Category	Remarks
			Summer	**Winter**	**Summer**	**Winter**		
1	Hot	3	32	*	32	*	Very uncomfortable	
2	**Warm**	2	30	*	30	*	Uncomfortable	
3	**Slightly warm**	1	28	*	28	*	Comfortable	Comfort zone
4	**Neutral**	0	26	19	26	15	Very comfortable	
5	**Slightly cool**	-1	*	17	*	13	comfortable	
6	**Cool**	-2	*	15	*	11	Uncomfortable	
7	Cold	-3	*	13	*	9	Very uncomfortable	

2.8. Comfort Temperature from Various Field Studies

Comfort is reported to be achievable at temperatures ranging from as low as 17.6 ◦C to as high as 31.2 ◦C, a finding consistent with Humphreys' 1978 study where the comfort range was identified as 17 to 30 ◦C. In a naturally ventilated or free-running building mode, the comfort temperature spans from 17.6 to 31.2 ◦C, while in air-conditioned buildings, the range narrows to 20.3 to 27.5 ◦C [27].

2.9. Thermal comfort in office buildings

The application of the adaptive comfort model is restricted to pure NV spaces, where occupants are free to adjust themselves to indoor or outdoor thermal conditions through adaptive opportunities such moveable windows and clothing, in accordance with the most recent revisions of ASHRAE Standard 55.Furthermore, these two standards specify that the adaptive model is not applicable to structures with mechanical cooling systems, hence MM buildings are not included in the adaptive model's application domain. Therefore, MM buildings, which may actually run primarily in a passive natural ventilation mode and only utilize supplemental cooling/heating during peak periods, are not eligible for the potential flexibility provided by these standards.

According to the study [40], Studies on mixed-mode (MM) ventilation reveal the broadest indoor thermal comfort temperature range, spanning from 15.0 to 30.0 °C. Comparatively, the highest indoor thermal comfort temperature is reported in natural ventilation (NV) mode, ranging from 20.0 to 33.8 °C. Ventilation studies focused on air-conditioning (AC) show the narrowest range of indoor thermal comfort temperature, falling between 22.0 and 28.4 °C. For studies involving the combination of NV and AC modes, the reported indoor thermal comfort temperature ranges from 16.0 to 30.0 °C.

These ranges suggest that different ventilation modes have varying effects on indoor thermal comfort. MM ventilation has the widest range, while NV mode has the highest upper limit of comfort temperature. On the other hand, AC ventilation has the narrowest range and is associated with more controlled temperatures. The combination of NV and AC falls within an intermediate range. These findings can be valuable for designing indoor environments that prioritize thermal comfort based on the chosen ventilation mode.

Location	References	Climate	Building	Modes	Equation	R^2	S.E.
Japan	Rijal et al. [39]	Subtropical	Offices	FR CL and HT	$T_c = 0.206T_{rm} + 20.8$ $T_c = 0.065T_{rm} + 23.9$	0.42 0.10	0.012 0.003
Southeast Asia	Nguyen et al. [85]	Humid	Mostly Offices	NV	$T_c = 0.341T_o + 18.83$	0.52	-
India	Toe et al. [40]	Hot-humid Hot-dry Moderate	ASHARE-based	NV NV NV	$T_c = 0.57T_o + 13.8$ $T_c = 0.58T_o + 13.7$ $T_c = 0.22T_o + 18.6$	0.64 0.59 0.09	- - -
	Indrganti et al. [17]	Dry	Offices	NV CL	$T_c = 0.26T_{rm} + 21.4$ $T_c = 0.15T_{rm} + 22.1$	0.058 0.026	0.028 0.014
	Dhaka and Mathur [59]	Composite	Offices	CL	$T_c = 0.078T_o + 23.3$	0.03	-
	Dhaka et al. [56]	Composite	Offices and Dwellings	NV	$T_c = 0.75T_o + 5.37$	-	-
	Tewari et al. [61]	Composite	Offices	EC	$T_c = 0.22T_{rm} + 21.45$	0.06	0.02
	Thapa et al. [63]	Cold and cloudy	Offices	NV	$T_c = 0.639T_o + 9.02$	0.67	0.001
	Manu et al. [66]	All climates	Offices	NV MM	$T_c = 0.54T_o + 12.83$ $T_c = 0.28T_o + 17.87$	0.81 0.72	0.001 0.001
Southern Brazil	Rupp et al. [21]	Temperate	Offices	NV HT	$T_c = 0.56T_o + 12.74$ $T_c = 0.09T_o + 22.32$	0.89 0.02	- -
China	Wu et al. [24]	Temperate-humid	Offices	MM	$T_c = 0.01T_{rm} + 26.9$	-	-
	Guo and Wang [71]	Hot-dry	Offices	EC	$T_c = 0.06T_{pma} + 26.17$	0.368	-
	Yang et al. [97]	Temperate-humid	Offices	NV	$T_c = 0.56T_{rm} + 12.6$	0.893	-
Spain	Martin et al. [20]	Mediterranean	Offices	MM	$T_c = 0.2427T_{rm} + 19.28$	0.410	-
Chile	Trebilcock et al. [82]	Temperate	Offices	MM	$T_c = 0.28T_{rm} + 18.5$	0.427	-

NV: Naturally Ventilated, CL: Cooling, HT: Heating, MM: Mixed mode, T_c: Comfort temperature (°C), T_{rm}: Running mean outdoor temperature (°C), T_o: Outdoor temperature (°C), T_{outdm}: Dailly mean outdoor temperature, T_{pma}: Prevailing mean outdoor temperature, R^2: Coefficient of determination, S.E.: Standard error

Figure 8: Regression equation of comfort and indoor temperature from different field studies

2.10. Impact of thermal comfort in human life

One of the main factors in the design of the interior environment is thermal comfort, which has a big effect on health and safety. Some studies revealed a significant link between the environment's temperature and the root cause of some morbidities. The lag time between a hot and cold temperature was shorter for a high temperature, and it will also be socio-demographic and environmental factors have an impact.

2.11. Factors affecting thermal comfort

The human thermal environment is made up of environmental or climatic variables as well as personal characteristics [41]. The six most significant components or variables that influence the thermal environment, according to Fanger are:

a. Average radiation temperature
b. Air velocity
c. Radiant
d. Air humidity
e. Metabolic rate or degree of activity
f. Insulation of clothing.

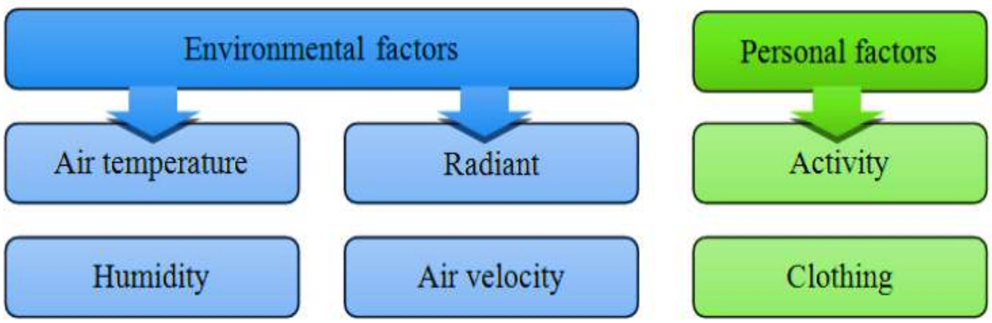


Figure 9: The most important environmental factors affecting thermal comfort *[35]*

The six Fanger-suggested parameters are divided into two groups, as illustrated in Figure-8 environmental and human variables (humidity, air temperature, mean radiant temperature) (activity level). It refers to a scenario in which a person is neither "too hot" nor "too chilly." It is mostly a subjective emotion or state of mind in which a person displays pleasure in his surroundings [42]. In Gadi's (2010) classification, factors influencing thermal comfort are categorized into two groups. The first group encompasses metabolic rate, mean radiant temperature, air velocity, clothing thermal resistance, air temperature, and vapor pressure. Meanwhile, the second group comprises sweat rate, skin wetness, clothing fit, skin temperature, clothing wittedness, and clothing surface.

Air Temperature

Air temperature, which can be measured in degrees Celsius or Fahrenheit, is the temperature surrounding the body, according to the Health and Safety Executive (HSE).

When discussing air temperature, it is meant that it has the greatest impact on all other environmental parameters. The reason for this is that people are extremely sensitive to temperature. This is made abundantly clear when individuals want to take a quick break. For example, while considering the weather in that location, the first thing people think about is the "temperature".

Radiant Temperature

Radiant heat, emanating from heated objects in the environment, can exert a significant impact, sometimes surpassing the influence of air temperature itself. The sun stands out as a primary source of radiated heat, yet other examples include cookers, dryers, hot surfaces, and ovens. The strategic incorporation of radiant heat control measures during the initial design phases of a building can render the use of radiation natural and environmentally friendly. A study by Memon et al. (2008) has demonstrated that with thoughtful design considerations for solar radiation control, it is feasible to achieve thermal comfort for a significant portion of the year.

Air Velocity

Described as "The speed of air moving across the worker and may help cool the worker if it is cooler than the environment," air velocity holds considerable significance due to its sensitivity to human perception. Its impact extends to both cooling and heating the space, depending on indoor conditions such as temperature and relative humidity. The critical aspect of air velocity lies in its influence on convective heat exchange between individuals and their surroundings, thereby affecting overall heat loss (ISO-7730, 2005).

This correlation is contingent upon the temperature and relative humidity of the surrounding environment. While ASHRAE 44 notes that the relationship between air speed and improved comfort is not firmly established, practical experience suggests that indoor air speeds exceeding 0.2 m/s could cause discomfort, even in high indoor temperatures, emphasizing the essential nature of convective interaction between the skin and the environment (ASHRAE-55, 2004).

Clothing Insulation: In ancient times, individuals utilized animal furs for protection against the cold (Caril et al., 2007). Both clothing and skin serve as the body's insulation, offering protection from the surrounding environment. Oliveira et al. (2011) emphasized the significance of assessing the thermal insulation of clothing in the study of human thermal comfort. Clothing insulation functions as a barrier, regulating heat transfer between the body and the external environment, thereby maintaining a comfortable thermal state in diverse climates. Clothing serves multifaceted purposes, with 'fashion' being a notable aspect, as highlighted by Sakka et al. (2012). Caril et al. (2007) further supported this notion, recognizing clothing as a means of self-expression within the community. Additionally, Lee and Choi (2004) pointed out that, in cold climates, energy consumption tends to be higher with lighter clothing compared to heavier garments.

Activity

Activity stands as a crucial determinant in thermal comfort, with various buildings catering to different functions and activity levels. The diverse nature of activities in spaces like offices and schools introduces significant fluctuations in thermal perception among individuals. Mustapa et al. (2016) highlight that the heat generated within our bodies during physical activity is a key factor influencing thermal comfort. As physical activity increases, so does the heat production, necessitating the release of additional heat to prevent discomfort. According to ISO-7730 (2005), a mere 0.1 met difference in activity may result in a thermal sensation equivalent to a 1°C change in air temperature, while a 0.4 met difference could lead to a substantial 2.5 to 3°C shift in air temperature. This underscores the importance of accommodating a range of indoor activities to mitigate overheating or cooling issues based on the prevailing circumstances.

2.12. Thermal Effects of Building Materials

According to Givoni (1976), a building's envelope serves as both a barrier against the outside environment and a safeguard against the direct effects of weather on the structure. This envelop can be constructed using three different types of building materials: opaque, transparent, and translucent.

In instances where indoor thermal conditions lack mechanical control, building materials play a pivotal role in influencing both indoor air and surface temperatures, thereby significantly impacting occupant comfort. Even when mechanical control measures such as heating or air conditioning are implemented, the thermophysical properties of materials continue to influence the amount of heating or cooling provided, along with the internal surface temperature (radiant temperature). Consequently, the choice of materials continues to bear on passenger comfort and the economic efficiency of control systems, as emphasized by Givoni (1976, pp. 120).

2.13. Thermo physical Properties of Building Materials

Heat transfer in buildings occurs through conduction, convection, radiation, and evaporation/condensation. As highlighted by Givoni (1976), the mechanism of heat transport can undergo changes during the process of heat entry into a building. Key material properties influencing the rate of heat transfer, subsequently impacting indoor thermal conduction and occupant comfort, include thermal conductivity, resistance, and transmittance; surface characteristics; surface convective coefficient; heat capacity; and transparency to radiation of different wavelengths (Givoni, 1976, pp. 103).

Conduction

Conduction is the process of transferring heat from a hot surface to a cold surface through a material's wall thickness. Different materials have different thermal conductivities. For instance, compared to an insulating substance like cork, concrete and steel have high conductivities. Under steady-state conditions, the rate of heat conduction (Qcond.) through any element such as a roof, wall, or floor can be written as:

$Q\ cond = A x U x \Delta T$

Where, A - surface area [m2]

U - Thermal transmittance [W/ m2 K]

ΔT - temperature difference between inside and outside air [K]

U is given by: U= 1/RT Where RT is the total thermal resistance

Convection

Convection, a heat transfer process, occurs when ambient air near a wall moves from a hot zone to a cold zone, carrying thermal energy away. This movement is facilitated by air molecules with lower temperature and density replacing those that have been heated. The entire process is recognized as convection, and the presence of air movement serves to enhance the rate of heat transfer.

Radiation

Radiant heat transfer, unlike other forms, doesn't depend on a medium and can occur through a vacuum, as seen in the sun's heat reaching the Earth. In this process, heat moves from a warmer source to cooler areas. Reflective surfaces, like metal foils, play a role in this by reflecting thermal radiation and minimizing heat absorption by walls. Building materials, as highlighted by Rosenlund (2001), possess thermal capacity and resistance, influencing their response to radiant heat.

Envelope Thermal Properties

Density (ρ, kg/m3), specific heat (cp, Wh/kgK), and conductivity (λ, W/mK) are three critical factors influencing the thermal properties of a building envelope. The material's density is a key consideration, as lighter materials tend to provide better insulation, while heavier ones have greater heat storage capacity. Specific heat, on the other hand, determines the material's ability to store heat, with lower specific heat indicating a lower heat storage capacity. Conductivity measures a material's heat conduction capability, with insulating materials exhibiting low conductivity, translating to a reduced rate of heat transfer between surfaces. These thermal properties significantly impact time lag and attenuation concerning temperature dynamics within a building (Mohammad & Shea, 2013).

R-value

One of the most crucial variables in determining a building's energy efficiency is its thermal resistance (R-value). The relationship between thickness and conductivity (d/) determines the thermal resistance for a single material layer under steady-state circumstances. A building element's overall thermal resistance can be estimated by adding up the R-values for all of its layers, including the film resistance of the air layers next to the element's surface. For non-reflective materials, the inner film resistance ranges from 0.11 m2K/W to 0.16 m2K/W depending on locations and heat flow directions, whereas the outside film resistance ranges from 0.03 m2K/W to 0.04 m2K/W depending on the wind.

Thermal conductivity

When heat is carried through insulation, it mostly does so by conduction, which is measured by a material's thermal conductivity. The phrase "thermal conductivity" (also known as the "lambda" or "k") is frequently used, and the lower the number, the better the performance. This estimated number serves as a gauge for how well a material can transfer heat through its mass. The quantity of heat or energy (expressed in kcal, Btu, or J) that can pass through a material with a unit area and unit thickness in a unit time is known as thermal conductivity.

***U*-value**

In the realm of heat flow calculations, the thermal transmittance (U-value) plays a central role. Representing the amount of heat transferring through a unit area of the structure per unit of time when there's a one Kelvin difference in air temperature on each side of the building, the U-value is a key metric in assessing thermal performance.

The U-value of a window measures how quickly heat moves through it as a result of conduction, convection, and radiation when there is a temperature differential between the inside and the outside. In the winter, heat is transported (lost) via windows more through windows with higher U-factors. The heat flow (q) of a building element is therefore:

$q = U \cdot (Ti - To)$ W/m2 ………………………….(1)

The manually calculated heat transfer is made using the equation (Sandin 2011):

$Q = U \cdot A \cdot (T1 - T2)$ W/m2 …………………..(2)

2.14. Types of International Comfort Standard

2.14.1. ISO 7730

ISO 7730: MODERATE THERMAL ENVIRONMENTS - DETERMINATION OF THE PMV AND PPD INDICES AND SPECIFICATION OF THE CONDITIONS FOR THERMAL COMFORT, (EN ISO 7730)

The objective of this standard is to establish acceptable thermal conditions for comfort while providing a framework for predicting the thermal sensation and level of discomfort *(thermal dissatisfaction) experienced by individuals exposed to moderate thermal environments.*

The standard is applied to individuals in good health who are exposed to interior surroundings with the goal of achieving thermal comfort or when there are only slight variations from thermal comfort. It can be applied to both the evaluation of current surroundings and their design. Although the standard was created for work situations, it can be used in any type of setting.

The norm is in good agreement with recent research of Japanese people exposed to mild heat settings, however it was originally based on studies of North American and European subjects. While most of the world is predicted to apply the norm rather well, there may be ethnic and national-geographic variations that call for additional research.

By projecting the proportion of people who are anticipated to feel excessively hot or cold in a particular setting, the PPD (predicted percentage of dissatisfied) index offers data on thermal discomfort, also known as thermal dissatisfaction. As stated in Article 4, the PPD is available from the PMV. Clause 5 explains how the draught model, which includes data on air temperature, air velocity, and turbulence intensity at ankle, waist, and neck levels, can be used to forecast the percentage of people who are unhappy because of draught. The requirements for appropriate thermal environmental conditions for comfort are covered in Clause 6.

The educational Annex A outlines the suggested thermal comfort standards based on the opinions of no more than 10% of unsatisfied individuals ($-0.5 \leqslant \text{PMV} \leqslant 0.5$). The corresponding comfort limits for winter and summer conditions are provided for the following factors: air humidity, floor temperature, mean air velocity, vertical air temperature difference (between 110 cm and 10 cm above the floor), and radiant temperature asymmetry from warm ceilings and cold vertical surfaces.

The normative Annex B lists the metabolic rates associated with various activities.

For the purpose of evaluating the thermal insulation of individual garments as well as clothing ensembles, Annex C provides informative tables.

The computer program's BASIC source code for calculating PMV and PPD for a given set of input variables is provided in Annex D, which is normative.

The informational table in Annex E shows data for calculating PMV at 50% relative humidity based on air velocity, operating temperature, and thermal insulation of clothing.

2.14.2. ASHRAE 55: THERMAL ENVIRONMENTAL CONDITIONS FOR HUMAN OCCUPANCY

The standard's objective is to outline the combinations of human characteristics and indoor space environments that will result in thermal environment conditions that are acceptable to at least 80% of a space's occupants.

The scope of the standard is as follows:

- The variables that affect the environment are temperature, thermal radiation, humidity, and air speed; the variables that affect the individual are clothing and activity.
- Given the complexity of the space environment and how all the aspects it addresses interact to determine comfort, it is intended that all of the standard's criteria be applied collectively.
- In indoor spaces intended for human occupation, the standard specifies appropriate thermal environment conditions for healthy individuals at atmospheric pressure comparable to altitudes up to 3000 m for durations of at least 15 minutes.
- Non-thermal environmental elements including air quality, acoustics, and lighting, as well as other physical, chemical, or biological space pollutants that could have an impact on comfort or health, are not covered by the standard.

The standard defines terms, classifies characteristics, and offers details on what constitutes a suitable temperature environment. The allowable thermal environment conditions are specified by the standard using the operative and effective temperatures. These are the conditions for individuals wearing standard indoor attire and engaged in light, mostly sedentary exercise (see 5.1). The permissible thermal environment requirements for individuals with varying degrees of activity are listed in 5.2.

Section-by-section detailed bibliography is provided in Appendix A. It is noteworthy to notice that ISO 7726 is followed in the development of Section 6 "Instruments" of the standard. The risk of drafts is covered in Appendix B, which also offers a method for predicting the PD index, or proportion feeling drought (in ISO 7730 DR = draught rating). A method and examples for calculating the radiant temperature at any given space location using measured zone surface temperatures and the associated angle factors are given to the user in Appendix C.

2.14.3. European standard EN15251

The indoor air quality, thermal climate, lighting, and acoustics input factors for building design and energy efficiency assessment are outlined in EN15251. The Comite Europeen de Normalisation (CEN) created Standard EN15251 in response to requests from the European Union for standards to support the Energy Performance of Buildings Directive (EPBD).The standard takes into account additional environmental factors that affect a building's energy consumption, such as indoor air quality, lighting, and acoustics. The definition of the thermal environment is the standard's main focus, with the other sections mainly consisting of references to other standards.

The standard adheres to the general guidelines of the ASHRAE standard and includes an adaptive standard called PMV for evaluating mechanically cooled buildings when they are operating in the free-running mode. Even if EN15251 assigns categories to buildings, the category descriptions remain the same. Similar to ASHRAE 55, the adaptive standard in EN15251 uses data from the European SCATs project, which gathered data from five European nations, rather of the ASHRAE RP884 database. While there are fewer sets of comfort data in the SCATs database, they were all gathered using a common set of instruments over the same time period.

2.15. Method for determining acceptable thermal conditions in occupied spaces

Graphic Comfort Zone Method for Typical Indoor Environments

When individuals are dressed in clothing with thermal insulation ranging from 0.5 to 1.0 clo and engaging in activities to sustain metabolic rates between 1.0 and 1.3 met, they can apply the methodology described in this section.

The adaptive approach

Humphreys and Nicol invented the adaptive approach methodology. The thermal adaptive model was developed in light of the adaptable nature of human behavior. The adaptive approach is also acknowledged in the ASHRAE-55 Standard in addition to the PMV-PPD method (ASHRAE, 2017). In contrast to Fanger's model, the adaptive approach model establishes the comfort zone, which is also tied to thermal experiences changes in clothes and activities. Age, gender, and physical limitations will all have an impact on thermal comfort in this model. There are three categories of thermal adaptation. They are psychological, which derives from the mental state brought on by prior experiences, physiological, which relates to the body's response to a change in temperature, and behavioral adaptation (Berge, 2009).PMV and PPD are the two factors used by ISO 7730 to evaluate the indoor climate. ASHRAE Standard 55 specifies the formula for determining the ideal comfort temperature (Tcomf).

$T_{comf} = 0.31 \times T_{out} + 17.8$ (Desired room temperature is about 20˚ C, ±2 ˚ C, i.e. 18 ˚ C, to 22˚C)

Predicted Mean Vote (PMV)

The PMV index serves as a tool for predicting the average thermal sensation votes of a group of occupants, utilizing a seven-point thermal sensation scale. Achieving thermal equilibrium occurs when the internally generated heat matches the heat lost by an individual. Factors such as the thermal environment, clothing insulation, and physical activity levels contribute to the degree of bodily heat balance.

For instance, residents' control over interior temperature through natural ventilation, like opening or closing windows, is often associated with improved thermal sensation. This practice can reduce occupants' elevated thermal expectations on mechanical ventilation systems. The ASHRAE thermal sensation scale, designed to gauge people's heat experiences, plays a crucial role in this context.

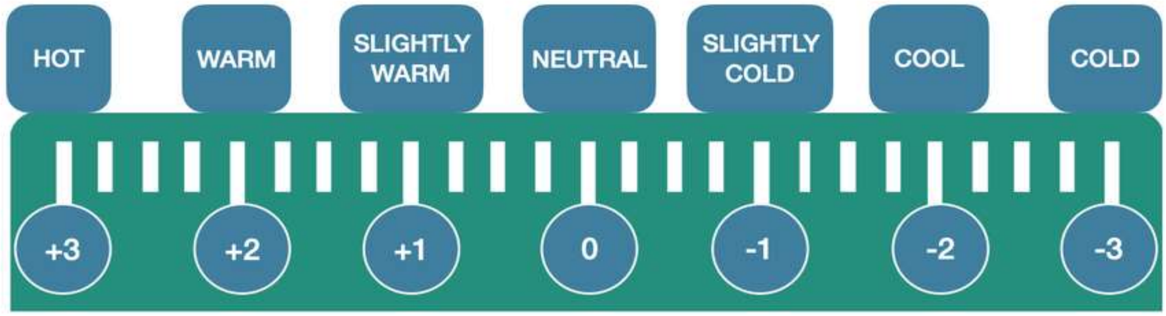


Figure 10: Graphical representation of ASHRAE thermal sensation scale

Using the ideas of heat balance, the predicted mean vote (PMV) model connects the six significant thermal factors. There are six important factors that need to be considered when setting the requirements for thermal comfort. In certain cases, comfort is influenced by several other, secondary factors.

Predicted Percentage Dissatisfied (PPD)

While PMV is a valuable tool for predicting the thermal perception of a population, it doesn't provide a complete assessment. To obtain a more comprehensive understanding of whether and how thermal comfort is achieved, it is essential to consider the satisfaction level of individuals using the space. Recognizing this, Fanger introduced an alternative formula that correlates PMV with the Predicted Percentage of Dissatisfied (PPD). PPD essentially represents the proportion of individuals likely to experience local discomfort. This metric reflects the percentage of people who perceive the indoor temperature as excessively hot, warm, cool, or cold, or are expected to feel uncomfortable.

2.16. Estimation of comfort temperature

Comfort temperature by polynomial regression analysis

Comfortable temperature levels are determined by the interplay between thermal sensation and indoor globe temperature across various aspects. Student responses are classified into two binary groups, with "Uncomfortable" encompassing cold, very cold, hot, or very hot, while the "Comfortable" responses include mildly warm, neutral, and slightly chilly. ASHRAE-55 guidelines suggest deeming the central zone (slightly chilly, neutral, and slightly hot) as comfortable if 80% of responses fall within this range. This approach provides a comprehensive framework for evaluating thermal comfort based on student feedback. The quadratic regression equation for each of the three districts' ratio of agreeable to indoor globe temperature is defined as follows:

$$P_{comfortable} = -0.009T_g^2 + 0.521T_g - 6.436$$
$$\begin{pmatrix} N = 2454, R_2 = 0.02, S.E._1 = 0.001, \\ S.E._2 = 0.077, p < 0.001 \end{pmatrix}$$

The comfort temperature equation by Nicol formula

Tcomf = 0.53 Tom + 13.8……………………………….(1)

The Adaptive thermal comfort from monthly mean maximum (Tmax), monthly mean outside temperature (Tom), and monthly comfort temperature over a 12-month period can be computed using the above formula for the Nichol adoptive thermal comfort model.

Comfort temperature by Griffiths method

The responsive adjustments made by office employees throughout their workday can result in an overestimation of regression coefficients within regression analyses, potentially skewing the determination of the optimal comfort temperature. This distortion may lead to the generation of unnecessary comfort temperature values. The Griffiths equation (a) is commonly applied for the precise calculation of comfortable temperatures, taking into account the intricate dynamics of individual behavior in office settings.

Tc is equal to Tg + (4- TSV/a)…………………….(a)

where a is the Griffiths constant, Tc is the comfort temperature (°C), Tg is the indoor globe temperature (°C), and TSV is the thermal sensation vote.

2.17. Indoor Air quality

According to research, there is frequently a mismatch between the modelled and perceived thermal comfort sensation. One of the causes could be because additional parameters are involved that are not currently accounted for in the models. [43] Elevated CO2 levels stimulate the human respiratory system, increasing metabolic rate and heat exchange with the environment. This is one feasible hypothesis and causal mechanism. It is hypothesized that an increase in indoor CO2 concentration may make people feel warmer. [44] Has demonstrated a connection between occupants' feelings of stuffiness and discomfort and indoor CO2 concentrations between 600 ppm and 1000 ppm or higher.

While there may not always be a direct specification of the link between carbon dioxide and indoor air quality, carbon dioxide concentrations are often referenced as an indicator of indoor air quality. The implications of elevated carbon dioxide levels extend to health effects, occupant perceptions of the indoor environment, correlations with other indoor contaminants, and the association with outdoor air circulation rates. Notably, ASHRAE Standard 62-1989 and the common citation of carbon dioxide values at 1,800 mg/m3 (1,000 ppm(v)) contribute to discussions surrounding indoor air quality and carbon dioxide dynamics.

2.18.1. Carbon Dioxide level and· ASHRAE Standard 62-1989

There are guidelines for indoor carbon dioxide concentrations of 1,800 mg/m3 (1000 ppm) in the indoor air quality protocol. Investigating Indoor Air Quality and building ventilation can benefit from continuous monitoring of indoor carbon dioxide concentrations using a data recorder device. The ASHRAE rules only propose a concentration of 1000 parts per million for CO_2. A minimum of two ach level of air change rate should be maintained in case 5. Health problems can arise when CO_2 concentrations are higher than 2500 ppm, and keeping the equilibrium CO_2 level below 2500 ppm can be achieved by maintaining at least 0.5 to 0.75 ach.

2.19. Previous studies related to thermal comfort in office buildings

[45]**Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century**

This study addresses the dual challenge of constructing energy-efficient buildings while ensuring thermal comfort in the face of rising summer temperatures attributed to human-induced climate change—a crucial consideration for contemporary building designers. The primary focus is on buildings designed to operate without extensive energy inputs during certain periods of the summer, relying on natural ventilation or a mixed-mode approach (employing mechanical cooling only when necessary). Given the variable conditions in such structures, it is essential to understand how occupants respond and adapt to their environment. The review encompasses current developments in this field and outlines the climate data necessary for assessing building performance. The temperatures within free-running buildings are intricately linked to external conditions. Anticipated changes in the environment and projected increases in summer temperatures pose challenges for future sustainable building design, particularly in achieving fully passive or low-energy comfort cooling. Case study buildings are examined to forecast their performance amidst climate change, highlighting the complexities that sustainable designers may encounter. These examples underscore key principles associated with low-energy, climate-sensitive design.

[18]**Impact of climate change on comfort and energy performance in offices**

This study investigates the interplay between building design, occupant behavior, and their impact on comfort and energy efficiency in office spaces across diverse climate change scenarios. Focused on a standard cellular office in Athens, Greece, the research employs EnergyPlus, a building simulation program, to conduct parametric analyses. The IPCC's A2 climate change scenario for 2020, 2050, and 2080 is coupled with two occupant scenarios, standard meteorological data, and three building design variations. The study evaluates adaptive thermal comfort in naturally ventilated buildings following ASHRAE Standard 55 and EN 15251 guidelines. In a mixed-mode setting, emphasis is placed on its influence on greenhouse gas emissions, peak heating and cooling demands, and the percentage of unoccupied working hours. Results highlight the significant impact of climate change scenarios on adaptive thermal comfort, revealing differences in assessment standards between ASHRAE Standard 55 and EN 15251. The comparison of climate change, building design, and occupant scenarios underscores the potential for occupant behavior to reduce energy consumption and emissions, emphasizing the crucial role of building design in optimizing thermal comfort.

[46]**INVESTIGATION OF THE THERMAL COMFORT AND PRODUCTIVITY IN JAPANESE MIXED-MODE OFFICE BUILDINGS**

This study aims to assess the overall comfort and productivity of Japanese office workers in mixed-mode office buildings. A two-year thermal comfort survey was conducted in Tokyo, Yokohama, and Odawara, focusing on the following key findings:

- The standard deviation of the indoor globe temperature is maintained at 24.8 ± 2.0 °C in mixed-mode (MM), resulting in minimal fluctuations in indoor globe temperature.
- Occupants in the office buildings reported high levels of comfort and productivity in the indoor thermal environment.
- Optimal temperature ranges for maximum comfort were identified as 22–26 °C for MM mode and 23–25 °C for full-range (FR) mode.
- The globe temperature range of 20–27 °C for FR mode and 21–27 °C for MM mode plays a crucial role in determining the productivity range for workers. These findings underscore the importance of considering these variables in the design of new office buildings.

[25] **Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate**

This study unveils findings from a longitudinal field survey in a subtropical office building, exploring occupant responses to thermal comfort in mixed-mode (MM) buildings. Key observations include:

- Thermal perception and acceptance shifted as the MM building transitioned from air-conditioning (AC) to natural ventilation (NV) mode. Occupants were more likely to report a neutral thermal experience, showing increased tolerance for a broader indoor temperature range during the NV period.
- Some current comfort standards, like ASHRAE Standard 55 and GB/T 50785, restrict the adaptive comfort model to pure NV environments, categorizing MM buildings as AC structures. This classification not only confines MM building temperatures to more limited indoor settings but also overlooks energy-saving opportunities inherent in the "hybrid" concept defining these structures.

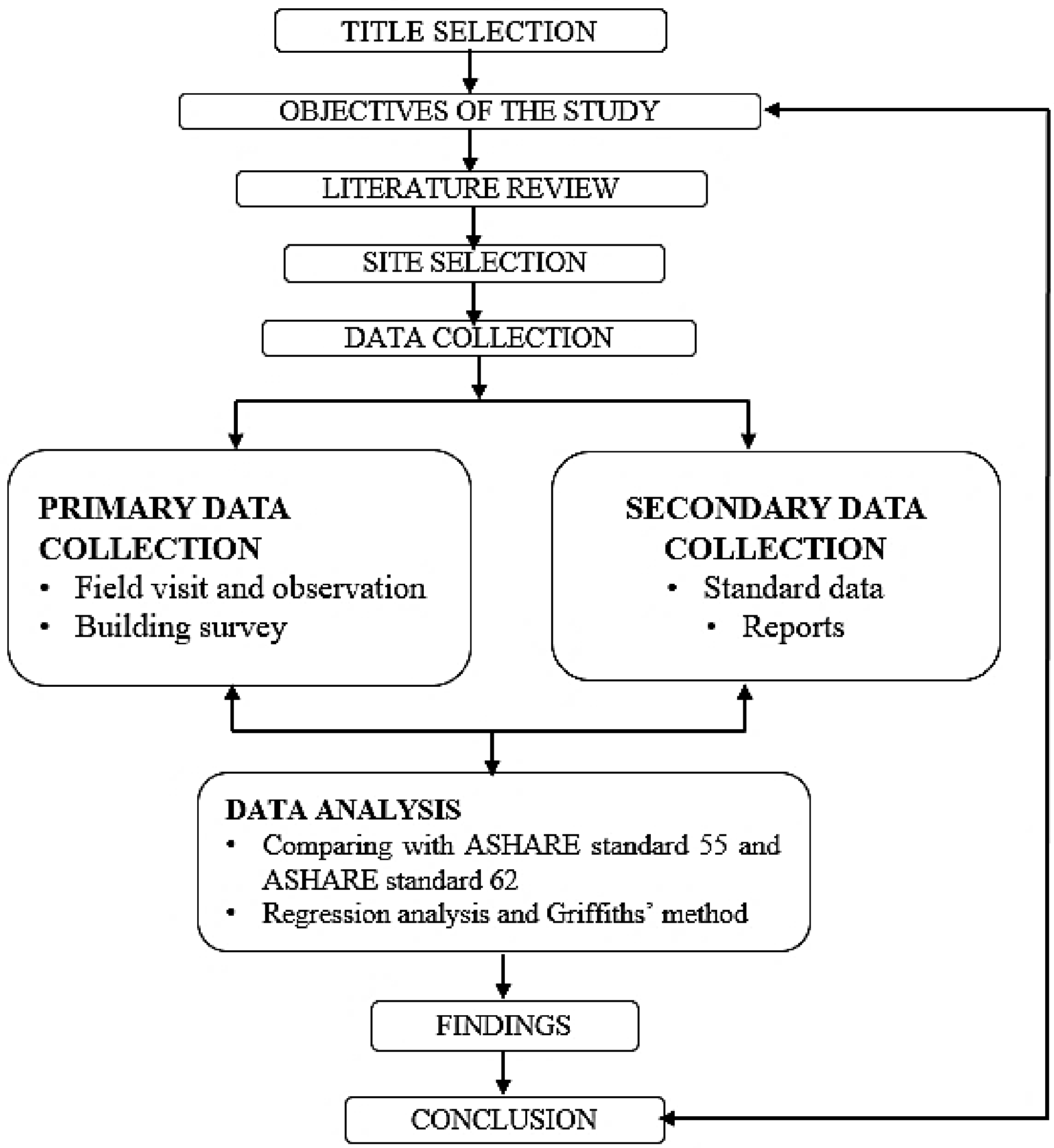
[47]**The role of adaptive thermal comfort in the prediction of the thermal performance of a modern mixed-mode office building in the UK under climate change**

This article explores the impact of climate change on the thermal performance of a United Kingdom office building and highlights the advantages of employing an adaptive thermal comfort strategy over a static one. The study anticipates outcomes related to energy consumption and overheating risks. Notably, the risks of overheating projected by static and adaptive thermal comfort methods differ significantly. By 2020, following a static strategy would result in a tenfold increase in overheating risk, whereas the adaptive approach would lead to less than a twofold increase. Both strategies foresee a reduction in heating energy usage, but applying the adaptive comfort strategy could yield an additional 10% savings compared to the static strategy for the base case building. The impact on cooling energy is noteworthy, with static thermal comfort predicting a 500% increase in cooling energy by 2080, while the adaptive approach foresees roughly half that amount.

[48]**Indoor Thermal Comfort and Carbon Dioxide Concentration: A comparative study of air conditioned and naturally ventilated houses in Sri Lanka.**

Carbon Dioxide (CO_2) serves as a practical and easily measurable indicator of indoor air quality and ventilation. While lower concentrations and shorter exposure durations pose minimal health risks, elevated levels can signal inadequate ventilation or potential pollution from other contaminants. This study compared bedrooms with natural ventilation to those with air conditioning concerning thermal comfort and CO_2 concentration. Bedrooms with natural ventilation exhibited higher temperatures and humidity levels than air-conditioned ones. Notably, all air-conditioned homes, including those with larger volumes, exceeded recommended CO_2 concentration levels. CO_2 levels in air-conditioned homes varied based on factors like room size, occupancy, and ventilation. Examined air-conditioned dwellings lacked mechanical fresh air intake, contributing to increased CO_2 concentrations, particularly in smaller spaces due to enhanced air tightness. Balancing improved energy efficiency with acceptable indoor air quality remains a challenge for air-conditioned homes. Maintaining an air change rate of 0.5 air changes per hour (ach) is suggested to mitigate health risks associated with CO_2 emissions.

CHAPTER-3: RESEARCH METHODOLOGY



Research Framework

The study site and six office buildings, featuring both free-running and mixed-mode designs, were identified for investigation. A quantitative method was employed, utilizing field questionnaires with the ASHRAE 7-point scale and air quality preference. Digital instruments (TR-76i, Thermo Recorder-(TR-52i)) were used for thermal measurements (air temperature, relative humidity), and indoor air quality (CO_2 concentration) was assessed. Two methods, Griffiths' approach and regression, were employed to determine comfort temperature. The regression method substituted the linear equation of thermal feeling and indoor air temperature with "4 neutral" for estimating comfort temperature. Meanwhile, Griffiths' approach was employed for examining adaptive comfort temperature, as the regression method's temperature predictions might not align well with field survey conditions.

3.1. Description of digital instrument used for field survey

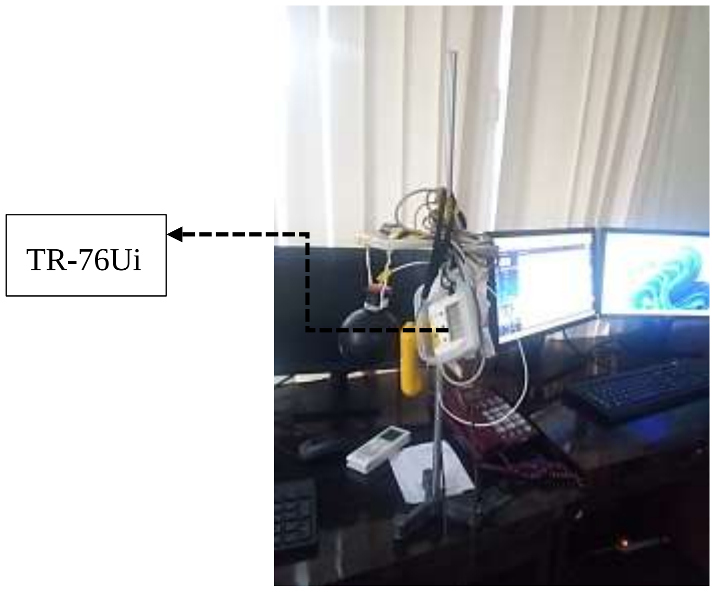


Figure 11: Digital Instrument Setup

Digital instruments were employed for the measurement of various physical parameters, encompassing air temperature, relative humidity, globe temperature, surface temperature, air movement, and CO_2 concentration (Figure 11). Table 4 provides details about the specific digital devices utilized in the field investigation to monitor ambient conditions. Measurements were taken at approximately 1.1m above the floor level, recorded three times with intervals of 15-20 minutes during office hours.

Table 4: Properties of digital instrument used for field survey

Parameter measured	Sensors	Range	Accuracy	Name of instruments
Air temperature	Thermistor	0-55ºC	±0.5ºC	**TR-74Ui**
Relative humidity	Polymer membrane	10-95%	±5% RH	**TR-74Ui**

Carbondioxide	**Non dispersive infrared analyzer**	**0 to 9,999 ppm**	**±50 ppm**	**` TR-76Ui**

3.1.1. Temperature, humidity and CO2 data logger with built-in sensors- TR-76Ui

Figure 12: Instrument TR-76Ui

The "CO_2 Recorder TR-76Ui" is a three-channel data recorder that measures and records CO_2 concentration, temperature, and humidity all at the same time. Setting the ambient pressure for the measuring site ensures more steady and precise CO_2 measurements. The included software allows the user to download data captured by the TR-76Ui to a PC via USB connection, allowing data from all three channels to be examined in graph or tabular form at the same time.

3.2. Questionnaires and Thermal comfort scale

Appendix-1 and 2 includes questions and scaled responses, comprising two questionnaire sections. The first section captures demographic data (age, gender), room location, and orientations to categorize AC and free-running modes. The second segment addresses thermal comfort aspects, encompassing the subject's thermal sensation vote (TSV), thermal preference (TP), thermal acceptance (TA), humidity feeling (HF), and indoor air quality satisfaction vote (ASV). Table 5 outlines the scale used for the thermal comfort survey. Staff members were instructed to wait at least fifteen minutes after arriving and settling in the office before responding to the questionnaire. A total of one hundred office workers, representing both genders with an average age of twenty-eight, participated in the survey. Notably, a majority of participants did not adaptively adjust their temperature.

Table 5: The questionnaire's response options and scales for the thermal comfort section

Scale	Thermal Sensation Vote (TSV)	Thermal Preference (TP)	Air quality satisfaction vote (ASV)	Humidity Feeling (HF)
1	Very Cold	Much Warmer	Very bad	Much too humid
2	Cold	A bit warmer	Bad	Too humid
3	Slightly cold	No Change	Slightly Bad	Slightly humid
4	Neutral	A bit cooler	Slightly good	Just right
5	Slightly hot	Much cooler	Good	Slightly dry
6	Hot		Very good	Too dry
7	Very Hot		Very high	Much too dry

CHAPTER-4: CASE STUDY

4.1. INVESTIGATED AREA AND BUILDINGS

The research is conducted in the Kathmandu Valley, which stands as Nepal's primary metropolis and serves as the capital of the nation within province three. Kathmandu Valley experiences a warm temperate climate, characterized by an average winter temperature of around 10ºC and a typical summer day temperature of approximately 30ºC.

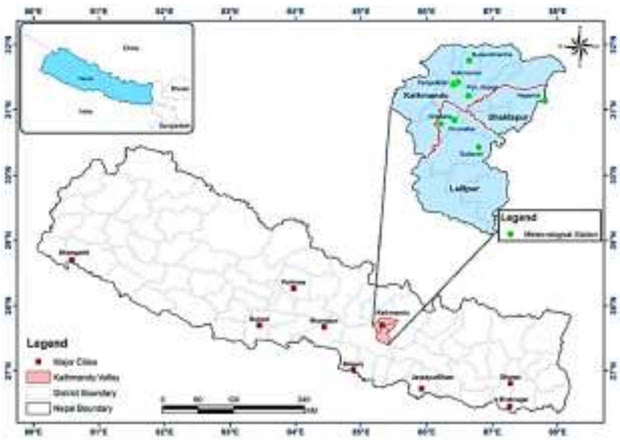


Figure 13: Location of investigated area

The field survey encompassed six diverse office buildings situated in the Kathmandu Valley, conducted between June and July 2023. Table 6 provides a description of the investigated buildings. Monitoring focused solely on occupational hours. The study presents a comparative analysis of CO_2 concentrations and comfort parameters, including indoor temperature and relative humidity, in relation to established guidelines and relevant standards. The dataset and ensuing analysis contribute valuable insights into the correlation between ventilation systems, indoor air quality (IAQ), and thermal comfort within buildings.

The thermal comfort survey targeted office employees occupying the ground, first, second, and fourth floors of six different buildings within the study areas. The surveyed office buildings include Nepal Telecom (NT), Expert Education and Visa Services (EVS), AKG Associates Chartered Accountants (AKG), HECAF 360 (HECAF), Informative Solutions (IS), and Civil Informatics and Solutions (CIS). Notably, Nepal Telecom (NT) and AKG Associates Chartered Accountants (AKG) operate on a mixed-mode, while Health

Environment and Climate Action Foundation (HECAF 360), Informative Solutions (IS), and Civil Informatics and Solutions (CIS) adopt a free-running mode.

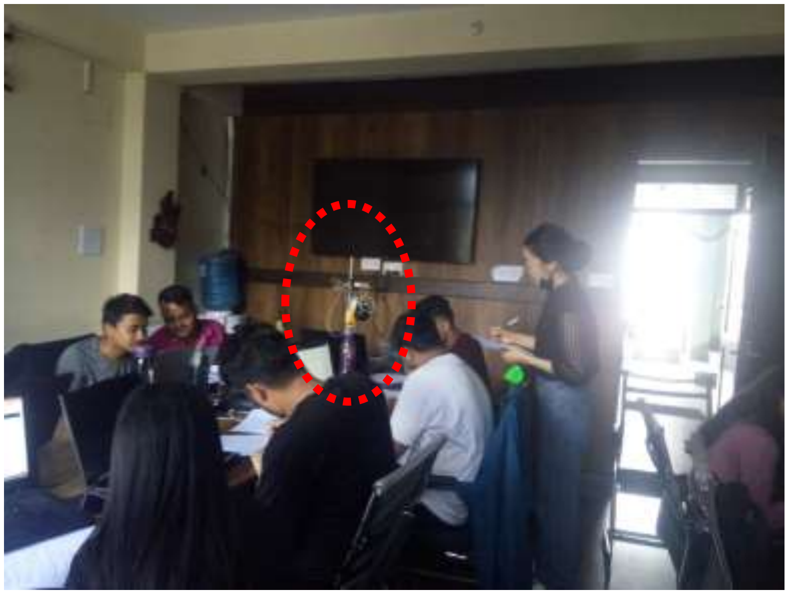


Figure 14: Field study and questionnaire survey

Table 6: Description of the investigated office buildings

S.N	Office Name	Office building Code	Orientation of the building	Mode of ventilation	Location	Nos of employee	Investigated floors
1.	Nepal Telecom	NT	North	Mixed-mode	Babarmahal	23	Fourth
2.	Expert Education and Visa Services	EVS	North-East	Mixed-mode	Seto pul	22	GF and FF
3.	AKG Associates Chartered Accountants	AKG	West	Free running	Kupondole	18	FF and SF
4.	HECAF 360	HCAF	South	Free running	Maharajgunj	10	GF
5.	Informative Solutions	IS	East	Free running	Pulchowk	12	GF
6.	Civil Informatics and Solutions (CIS)	CIS	East	Free running	Patan Dhoka	15	GF and FF

4.1.1. Case-1: Nepal Doorsanchar Company Limited (Nepal Telecom), Babarmahal

Figure 15: Office building-1 (Nepal Telecom located at Babarmahal)

Twenty three (23) office employees of fourth floor are surveyed from Nepal Telecom (NT) in June 13,2023 on Change-over mixed-mode of ventilation : "change-over" in the context of natural ventilation and HVAC (Heating, Ventilation, and Air Conditioning) taking place in the same location at various times.

Table 7: Description of surveyed office building-1 (Nepal Telecom)

Element	**Description**	**Details**
External wall	Insulation: no Wall thickness=9”	Glass facade
Floor	No Insulation	Marble flooring
Window		Aluminum frame
Roof	Concrete slab of thickness 125mm	
Room Height	14ft	

The digital instrument was set up at table of height 1.1 meter from ground level in 10 rooms which are partitioned with aluminum frame. Below figure 16 shows the investigated area and the position of the digital instrument during survey period (11:50am to 1:40pm). The total area investigated is 3749.9 ft².Questionnaire survey and the reading of the recorded data were done simultaneously.

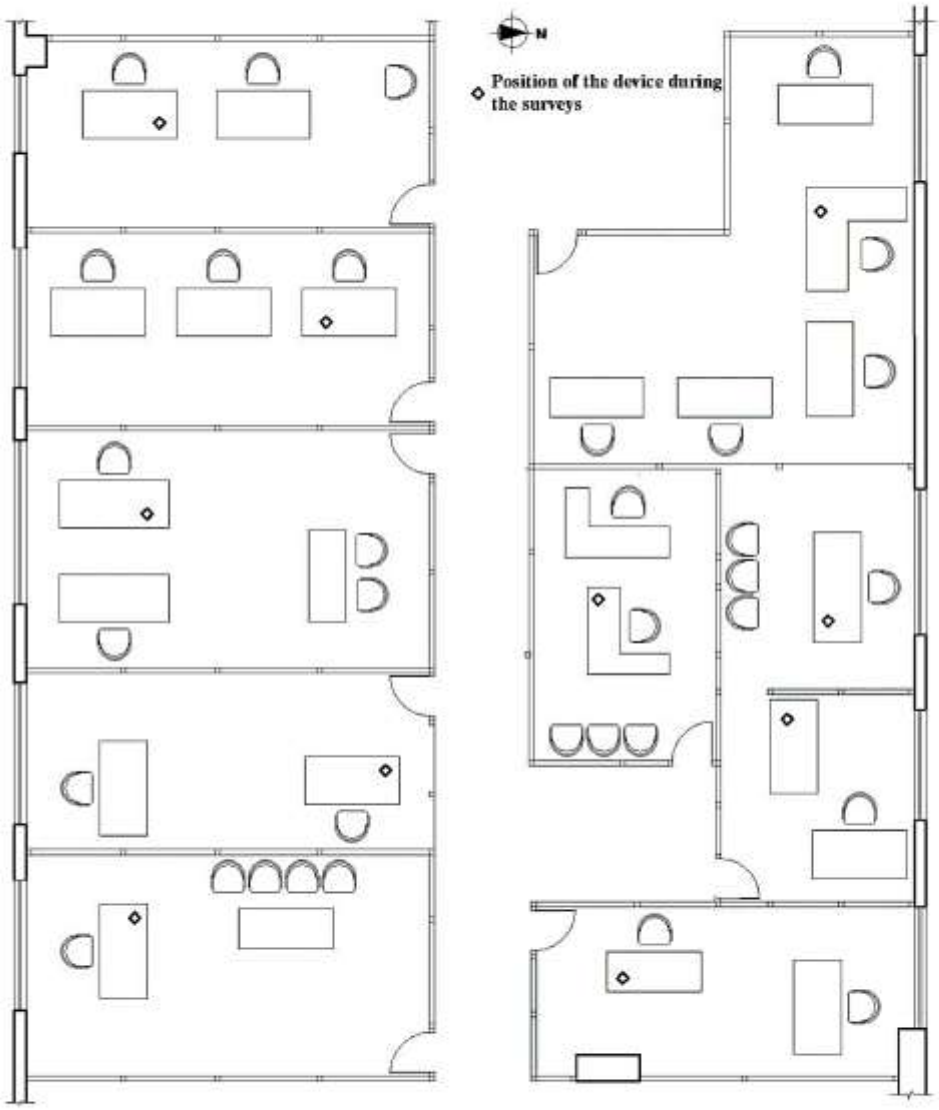


Figure 16: Investigated fourth floor plan of Nepal Telecom

Analysis of recorded data during surveyed period

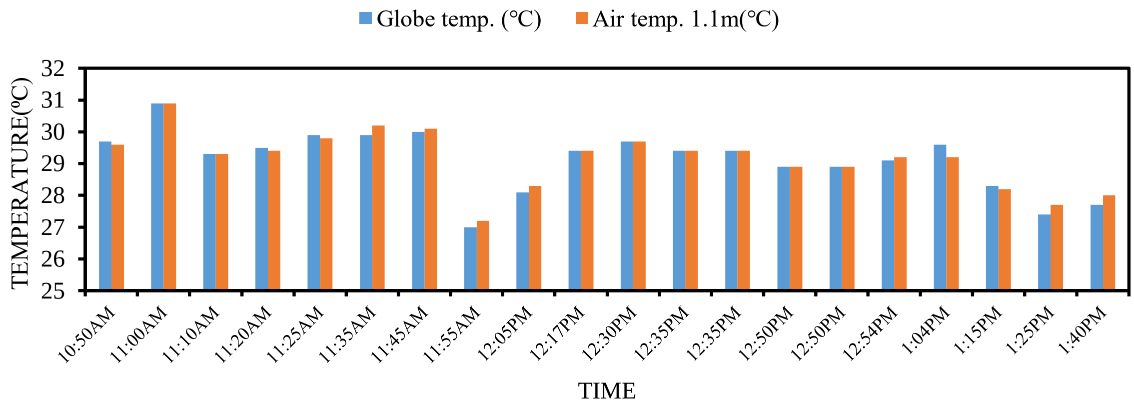


Figure 17: Globe temperature and outdoor air temperature of Nepal Telecom during survey period

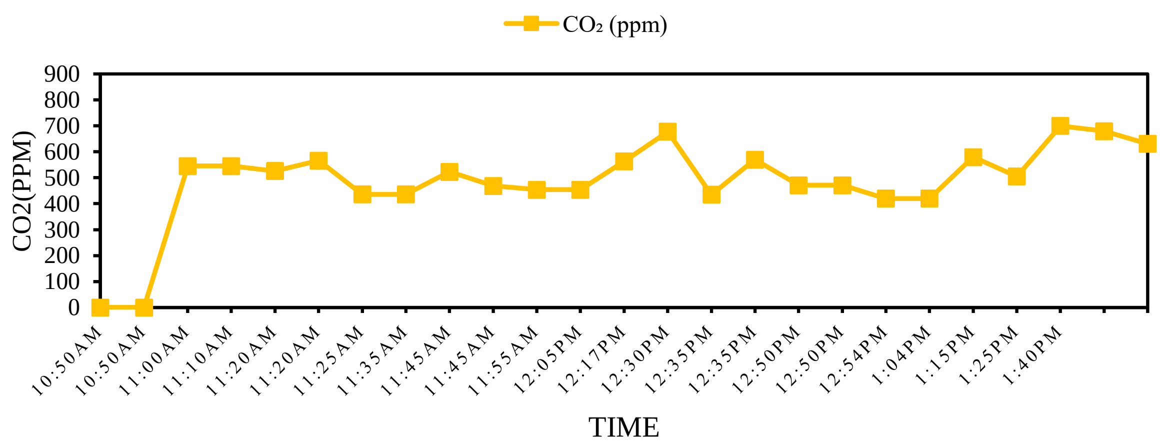


Figure 18: CO_2 concentration of Nepal Telecom during survey period

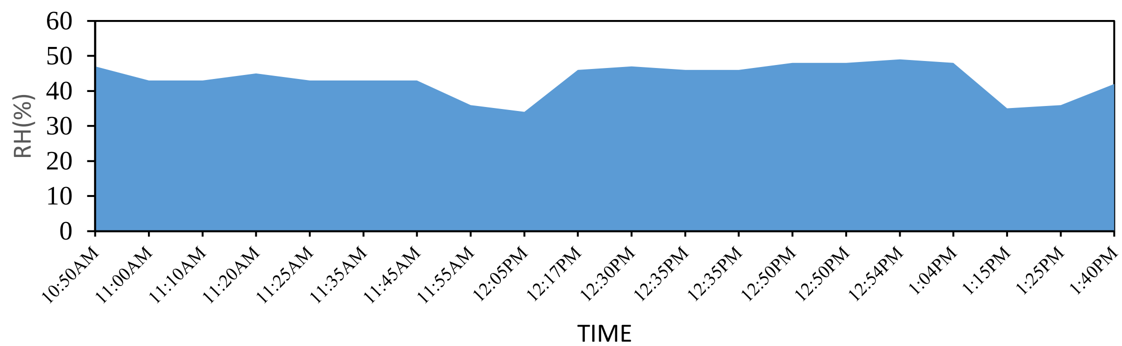


Figure 19: Relative Humidity of Nepal Telecom during survey period

Figure 17 depicts the globe temperature and air temperature measured at 1.1 meter ftom ground level. The average global temperature for the voting period was 29.8 °C, indicating that temperature fluctuations are significant. One possible explanation is that workers employed cooling during the summer to keep the working thermal environment in mixed mode (MM). Figures 18 and 19 indicate the CO_2 concentration and relative humidity for the survey period, with a mean CO_2 concentration of 525 ppm and a mean relative humidity of 44%, both of which are within the ASHARE comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

The Nepal Telecom office's field survey included the measurement of office employees' subjective thermal perception using the standard ASHRAE thermal comfort scale vote. The gathered data from the survey underwent analysis and tabulation in Excel to enhance comprehension and facilitate a more organized presentation of the findings..

The thermal sensation voteS from 23 office employees at this office reveals that 31% of them feel neutral, indicating satisfaction with their current thermal environment. Meanwhile, 43% feel slightly hot, 13% feel hot, 9% feel very hot, and the remaining respondents feel slightly cold. This outcome suggests that employees situated in the south wing of the building, near windows, experienced elevated temperatures due to continuous direct solar radiation.

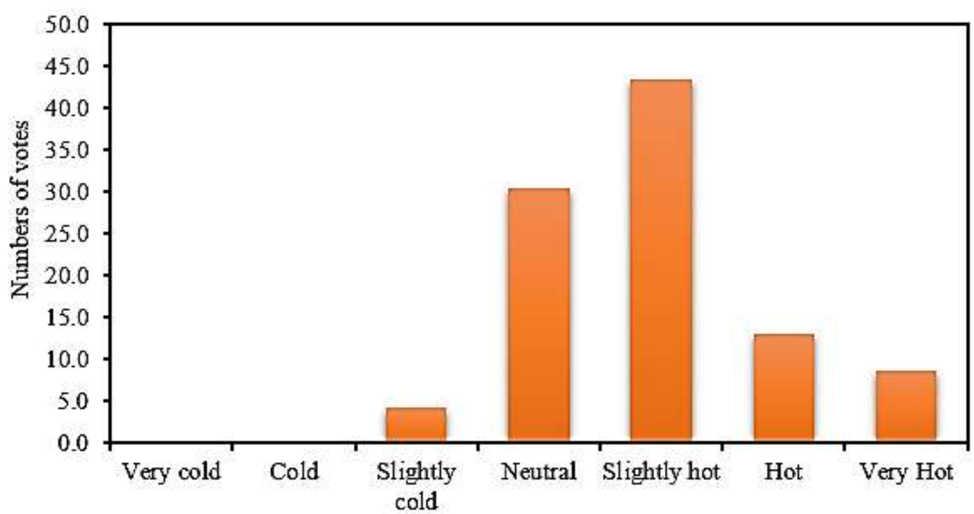


Figure 20: Distribution of Thermal Sensation Vote by employee of Nepal Telecom (NT)

Thermal perception

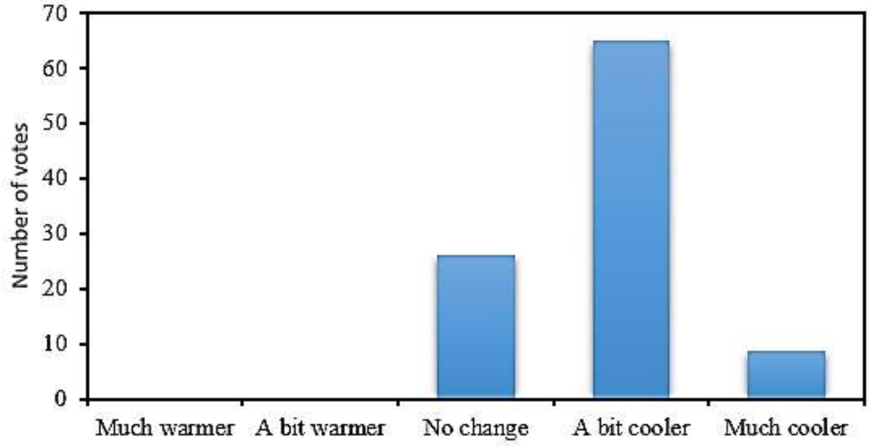


Figure 21: Distribution of Thermal perception vote by employee of Nepal Telecom (NT)

Similarly, the thermal preference of employees was assessed through 5-point thermal preference vote scales. This method facilitated the analysis of respondents' thermal preferences within their current thermal environment. The results indicated that 65% of respondents favored a slightly cooler setting, 9% preferred a significantly cooler environment, while 26% expressed a preference for no change.

Overall comfort

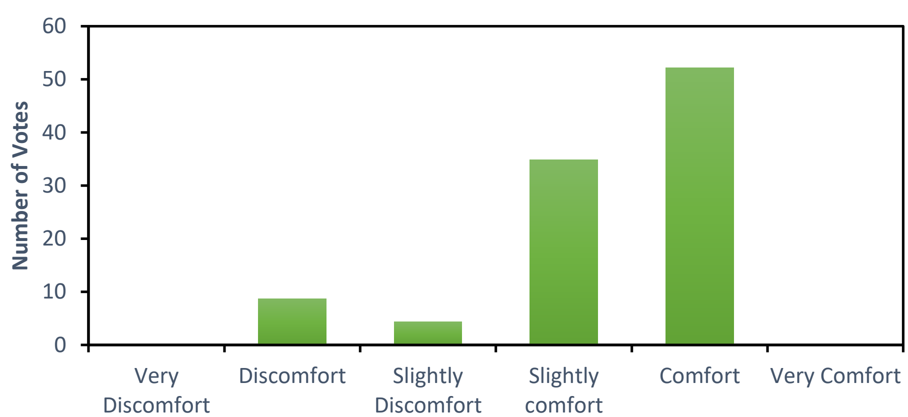


Figure 22: Distribution of Overall comfort vote by employee of Nepal Telecom (NT)

Similarly, overall thermal comfort of the employee is surveyed and resulted that 52% of the employee voted comfort,35% of the employee voted slightly comfort while 4% and 9% voted slightly discomfort and discomfort respectively.

Humidity Feeling

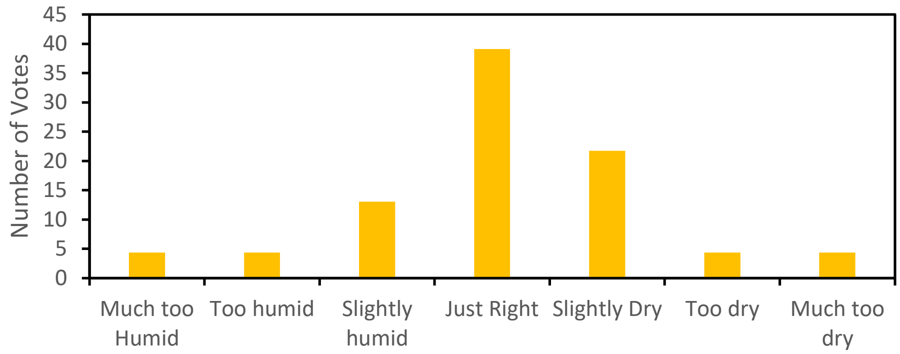


Figure 23: Distribution of Humidity Feeling by employee of Nepal Telecom (NT)

As depicted in Figure 24, the majority of employees, accounting for 40%, reported feeling just right in terms of humidity. On the other hand, smaller percentages expressed varying levels of humidity perception, with 4% each feeling much too humid, too humid, slightly humid, slightly dry, too dry, and much too dry, respectively.

Figure 24: Reading the data from installed instrument while office employee are filling questionnaire at Nepal Telecom

4.1.2. Case-2: Expert Education and Visa Services, Setopol

Figure 25: Office building-2 Expert Education and Visa Services (EVS)

A survey was conducted on June 10, 2023, involving twenty-two (22) office employees from the ground and first floors of Expert Education and Visa Services (EVS). The study focused on the "change-over" mixed-mode of ventilation, where natural ventilation and HVAC alternately occur in the same location at various times.

Table 8: Description of office building-2 (Expert Education and Visa Services)

Element	Description	Details
External wall	Insulation: no Wall thickness=14”	Brick facade
Floor	No Insulation	Marble flooring
Window		Wooden frame
Roof	Concrete slab of thickness 125mm	
Room Height	9ft	

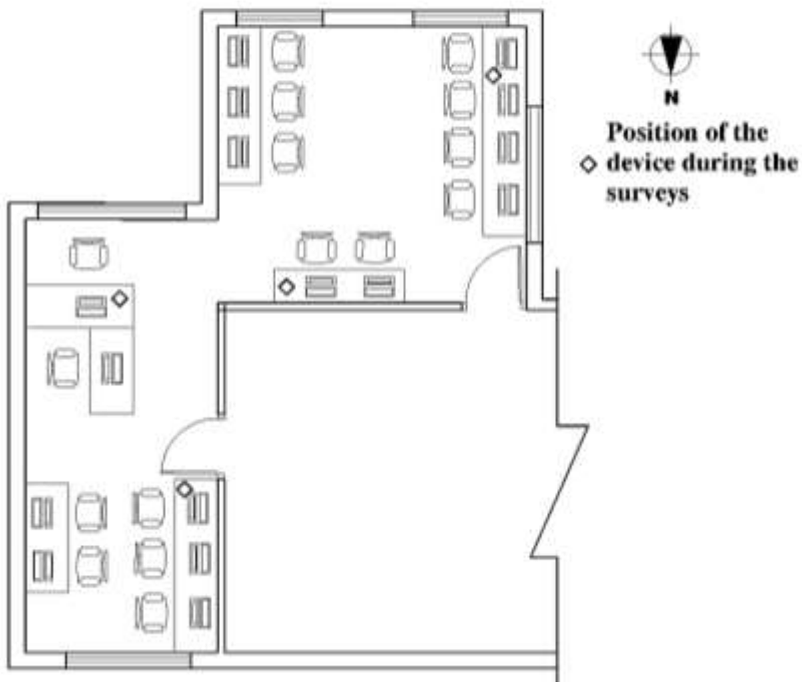


Figure 26: Ground floor plan of EVS

The digital instrument was set up at table of height 1.1 meter above floor in 2 rooms of ground floor and one room of first floor. Above figure 26 shows the investigated area and the position of the digital instrument during survey period (11:30am to 2:00pm). The total area investigated is 358.6 ft2 of ground floor and 105.1 ft2.Questionnaire survey and the reading of the recorded data were done simultaneously.

Analysis of the recorded data during surveyed period

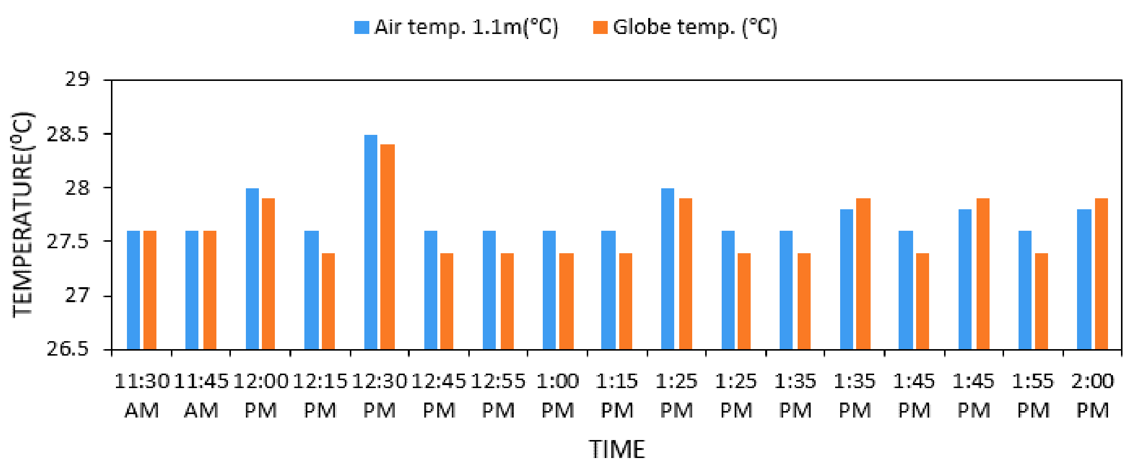


Figure 27: Globe temperature and outdoor air temperature of EVS during survey period

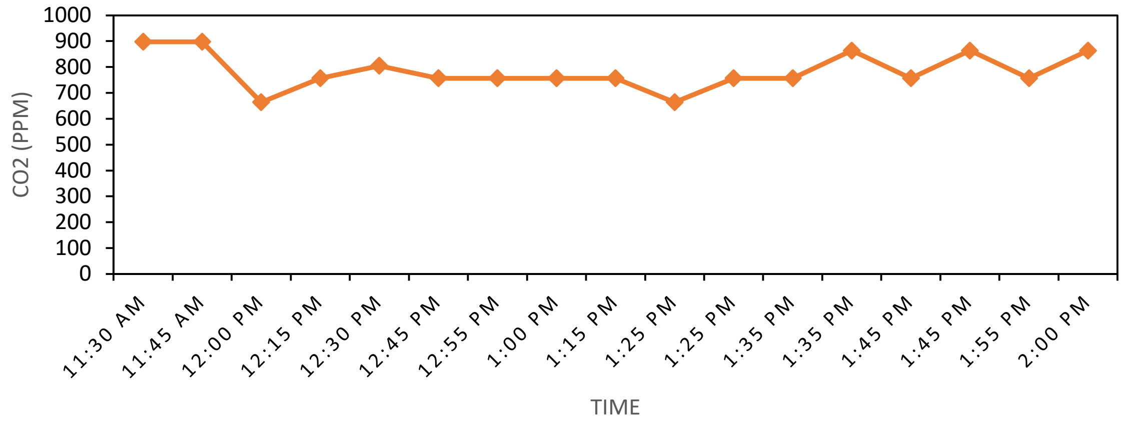


Figure 28: CO_2 concentration of EVS during surveyed period

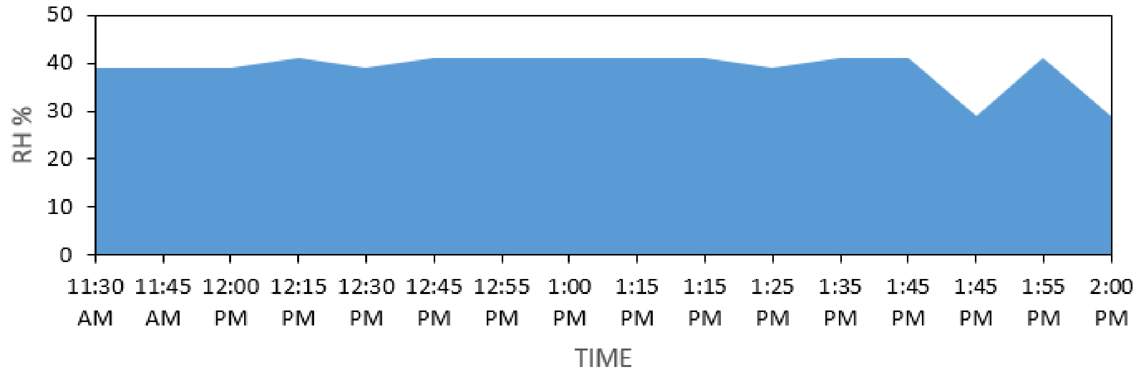


Figure 29: Relative Humidity of EVS during surveyed period

Figure 27 displays the recorded globe temperature and air temperature at a height of 1.1 meters from the floor level. Throughout the voting period, the mean globe temperature stood at 27.6 °C, with minimal changes in the globe's temperature. Figures 28 and 29 illustrate the CO_2 concentration and relative humidity during the surveyed period, indicating a mean CO_2 concentration of 780 ppm and humidity level of 39%. According to ASHRAE-55 standards, these values fall within the comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

The EVS office's field survey involved measuring the subjective thermal perception of office employees using the standard ASHRAE thermal comfort scale vote. The collected data from the survey underwent analysis and tabulation in Excel for better comprehension. The thermal sensation vote from the 22 office employees indicates that 10% of them feel neutral, expressing satisfaction with their current thermal environment. Furthermore, 41% feel slightly hot, 45% feel hot, 4% feel very hot, and the remaining respondents feel slightly cold. This suggests that employees adopt strategies such as keeping windows closed, using blinds to shade from direct sunlight, and relying on the opening of doors as the primary source of airflow. Additionally, some employees use the air conditioning system to maintain thermal comfort.

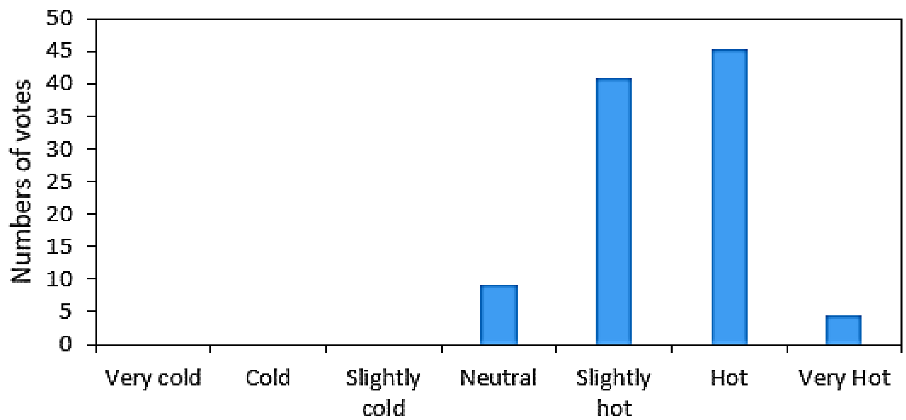


Figure 30: Distribution of Thermal Sensation Vote by employee of EVS

Thermal perception

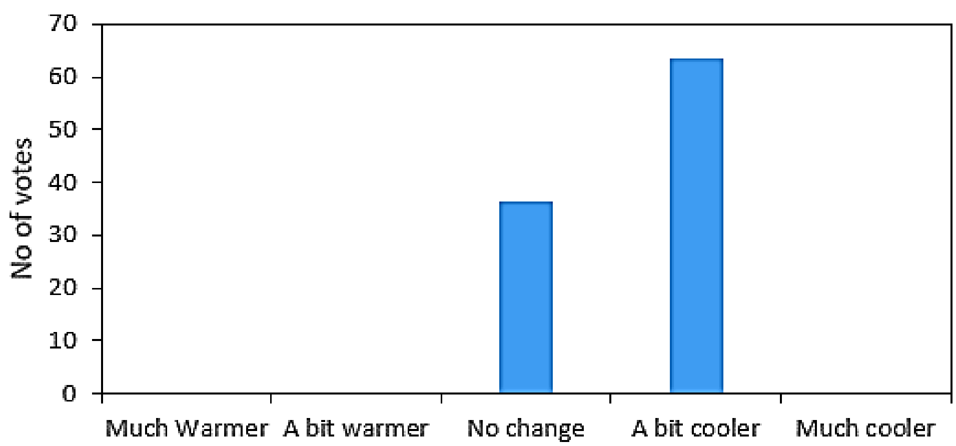


Figure 31: Distribution of Thermal perception votes by employee of EVS

Likewise,thermal preference of the employee were obtained by using 5-point thermal preference vote scales.This helps to analyze the thermal preference of the respondent in their present thermal environment .The vote shows that 63% students preferred a bitcooler , 0% prefered much cooler while 37% prefered no change.

Overall Comfort

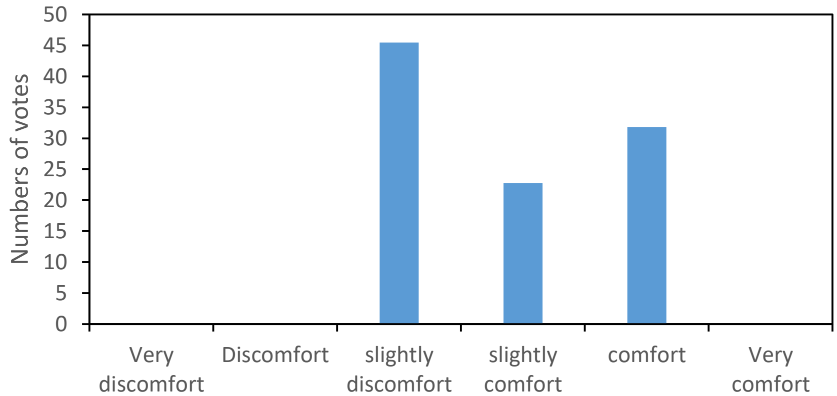


Figure 32: Distribution of overall comfort votes by employee of EVS

Similarly, overall thermal comfort of the employee is surveyed and resulted that 32% of the employee voted comfort,23% of the employee voted slightly comfort while 45% and 0% voted slightly discomfort and discomfort respectively.

4.1.3. Case-3: AKG Associates Chartered Accountants,Kupondole

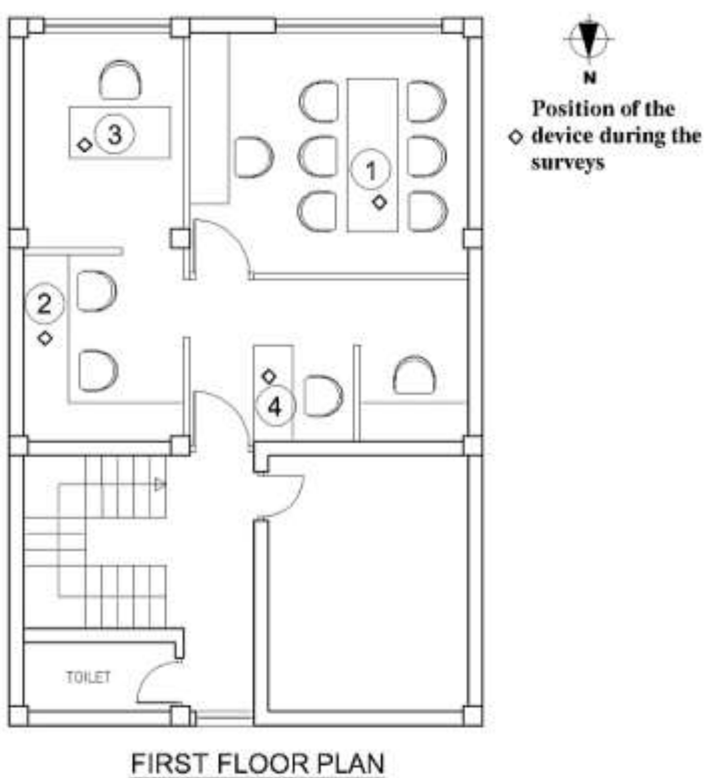
Figure 33: Office building-3 (AKG Associates Chartered Accountants)

On June 10, 2023, a survey was conducted with eighteen (18) office employees from the ground and first floors of AKG Associates Chartered Accountants (AKG). The study focused on the free-running mode, indicating that the building is either naturally ventilated or equipped with an HVAC system. Notably, during the study period, either the heating (HT) or cooling (CL) systems were turned off.

Table 9: Description of office building AKG

Element	Description	Details
External wall	Insulation: no Wall thickness=9”	Front :Glass façade Back: Brick facade
Floor	No Insulation	Marble flooring
Window		Aluminium frame
Roof	Concrete slab of thickness 125mm	
Room Height	10ft	

First and second floor plan of AKG office building



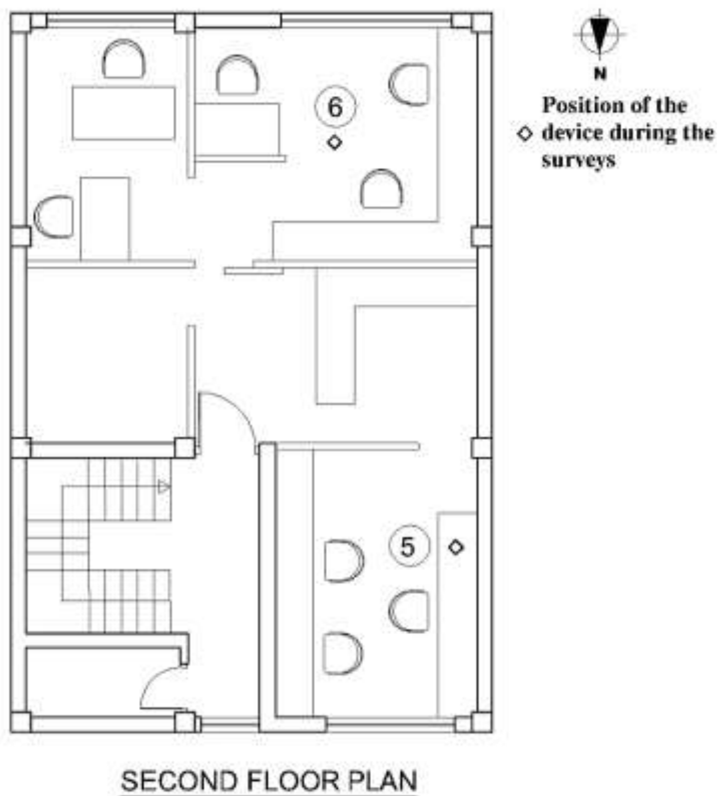


Figure 34: First floor and second floor plan of AKG

Analysis of data during surveyed period of AKG

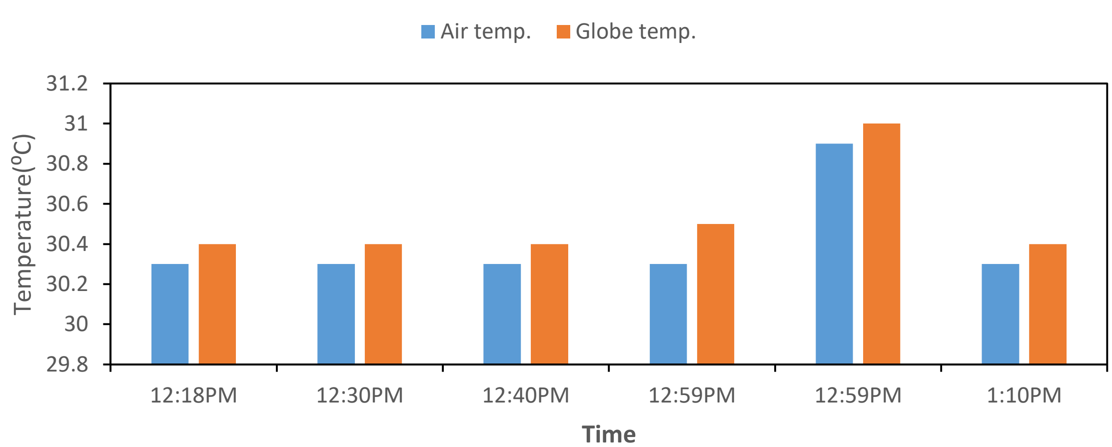


Figure 35: Globe temperature and outdoor air temperature of AKG during survey period

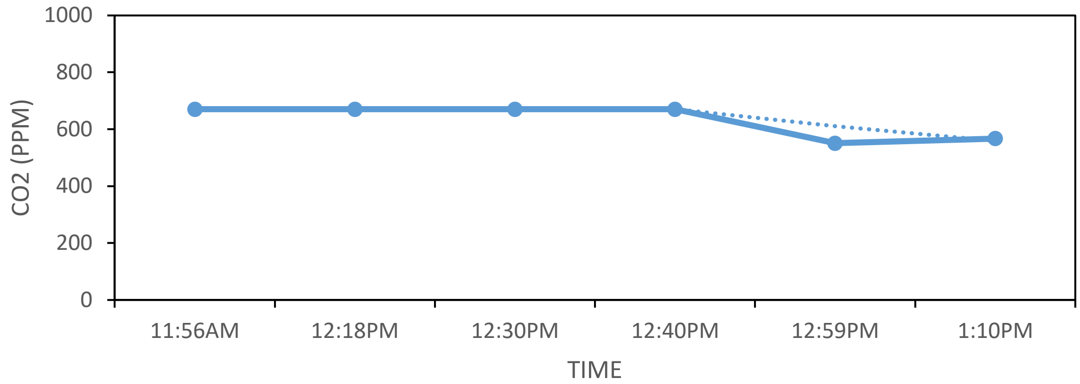


Figure 36:CO2 concentration of AKG during surveyed period

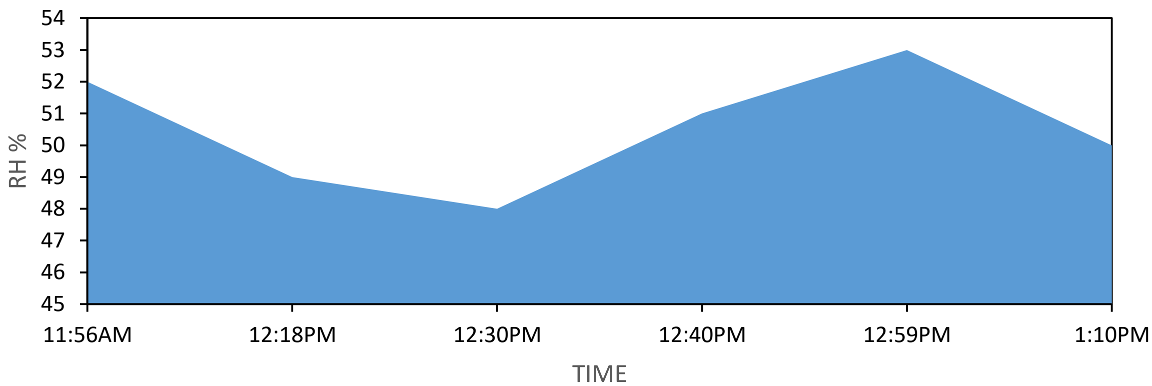


Figure 37: Relative Humidity of AKG during surveyed period

As depicted in Figure 35, the recorded globe temperature and air temperature at a height of 1.1 meters from the floor level reveal a mean globe temperature of 30.2 °C during the voting period, with minimal fluctuations. Figures 36 and 37 illustrate the CO_2 concentration and relative humidity throughout the surveyed period, indicating a mean CO_2 concentration of 593 ppm and humidity level of 51%. In accordance with ASHRAE-55 standards, these values are deemed to fall within the comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

From the field survey of the AKG office ,the subjective thermal perception of the office employees was measured by using the standard ASHRAE thermal comfort scale vote.The data obtained from the survey is analyzed and tabulated in excel for better understanding.

The thermal sensation vote of the 18 office employee of this office shows 17% office employee feel neutral i.e. they are satisfied with their present thermal environment , 55% feel slightly hot,16% feel hot,5% very hot and remaining feel slightly cold.This result shows that employee gets heat from direct sunlight as this building is south facing and also at office hours it recevies direct sunlight from glass façade since there is no insulation.

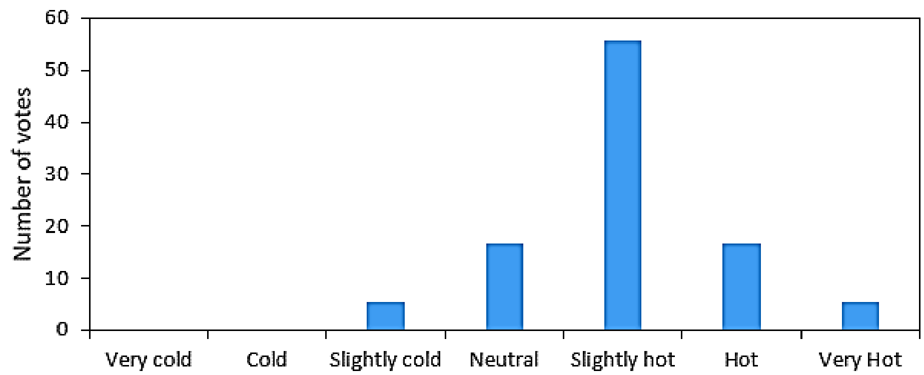


Figure 38: Distribution of Thermal Sensation vote by employees of AKG

Thermal Perception

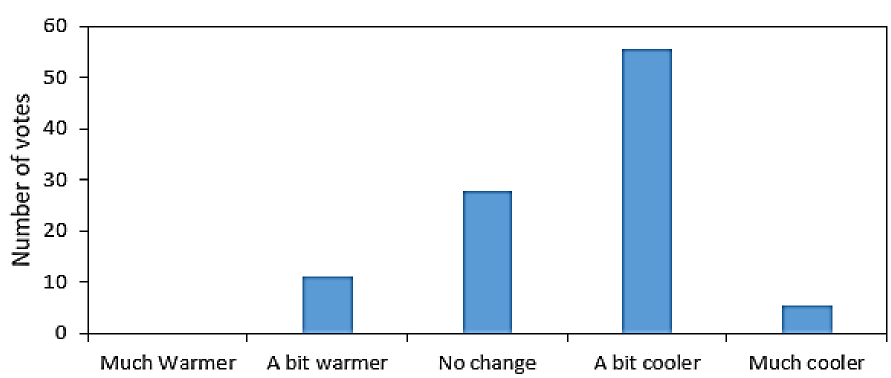
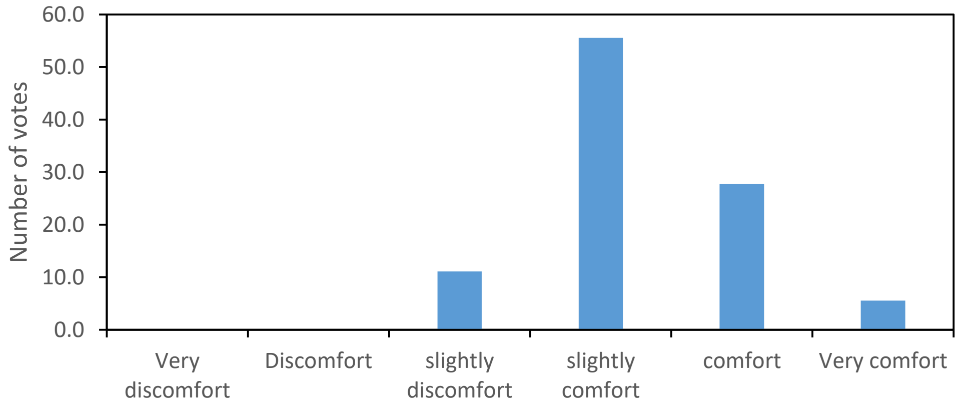


Figure 39: Distribution of thermal perception by employees of AKG

Likewise,thermal preference of the employee were obtained by using 5-point thermal preference vote scales.This helps to analyze the thermal preference of the respondent in their present thermal environment .The vote shows that 56% students preferred a bitcooler , 5% prefered much cooler while 28% prefered no change and 11% preferred a bit warmer.

Overall comfort



Similarly, overall thermal comfort of the employee is surveyed and resulted that 5.6% of the employee voted comfort,56% of the employee voted slightly comfort while 0% and 11% voted slightly discomfort and discomfort respectively.

4.1.4. Case-4: Health Environment and Climate Action Foundation (HECAF 360)

Figure 40: Investigated office building-4 (HECAF-360)

As depicted in Figure 35, the recorded globe temperature and air temperature at a height of 1.1 meters from the floor level reveal a mean globe temperature of 30.2 °C during the voting period, with minimal fluctuations. Figures 36 and 37 illustrate the CO_2 concentration and relative humidity throughout the surveyed period, indicating a mean CO_2 concentration of 593 ppm and humidity level of 51%. In accordance with ASHRAE-55 standards, these values are deemed to fall within the comfort zone.

Table 10: Description of office building-4 (HECAF 360)

Element	**Description**	**Details**
External wall	Insulation: no Wall thickness=14”	Brick façade with 12mm thick cement plaster
Floor	No Insulation	Marble flooring
Window		Wooden frame
Roof	Concrete slab of thickness 125mm	
Room Height	9.5ft	

The structure of HECAF is load bearing and has 14 inch thick brick wall. Below figure 41 depicts the studied area of the building and the position of the digital instrument that was set up at height of 1.1meter from ground level.

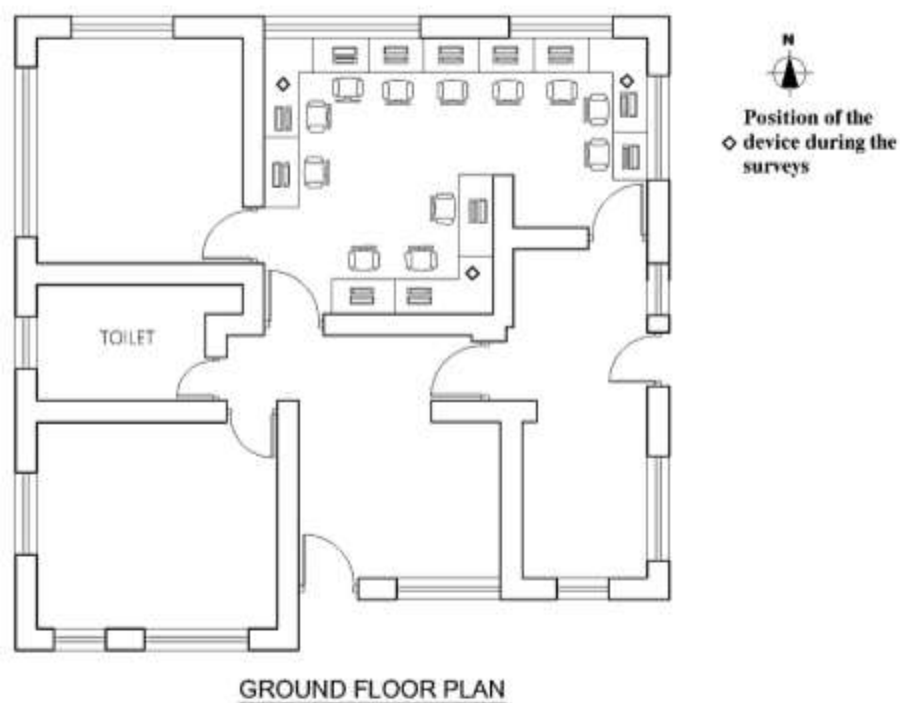


Figure 41: Ground floor plan of HECAF

Analysis of recorded data during surveyed period in HECAF

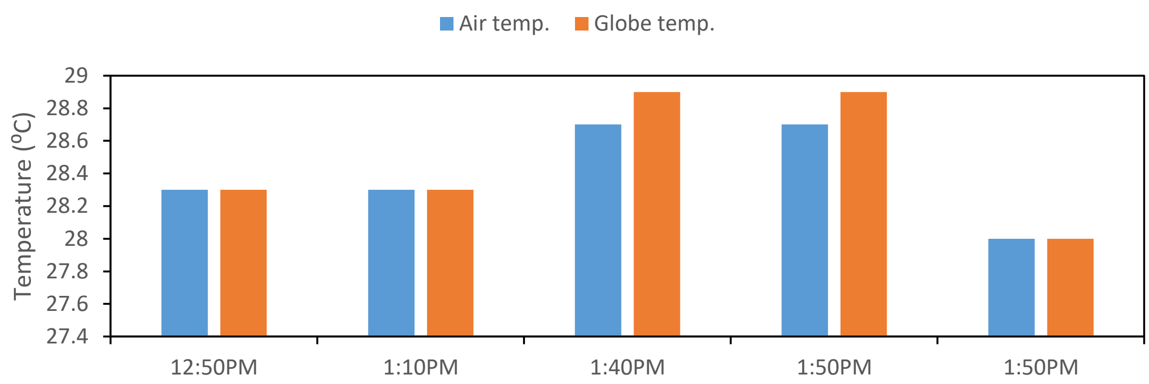


Figure 42: Globe temperature and outdoor air temperature of HECAF during survey period

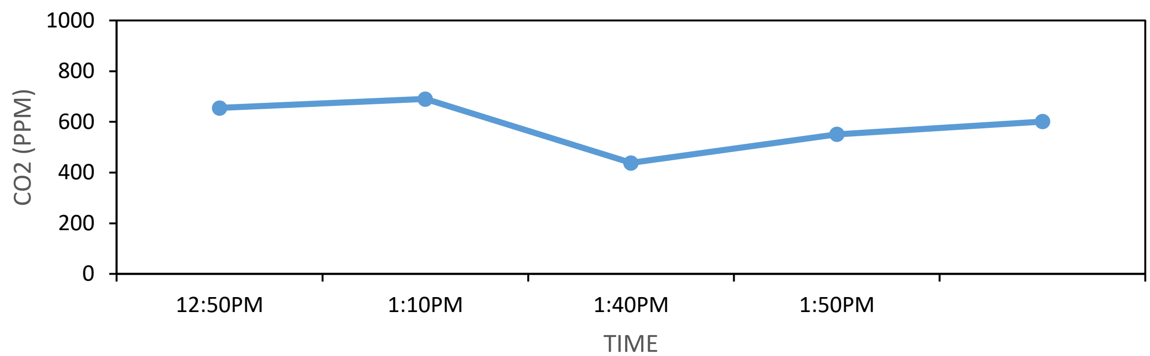


Figure 43: Co2 concentration of HECAF during surveyed period

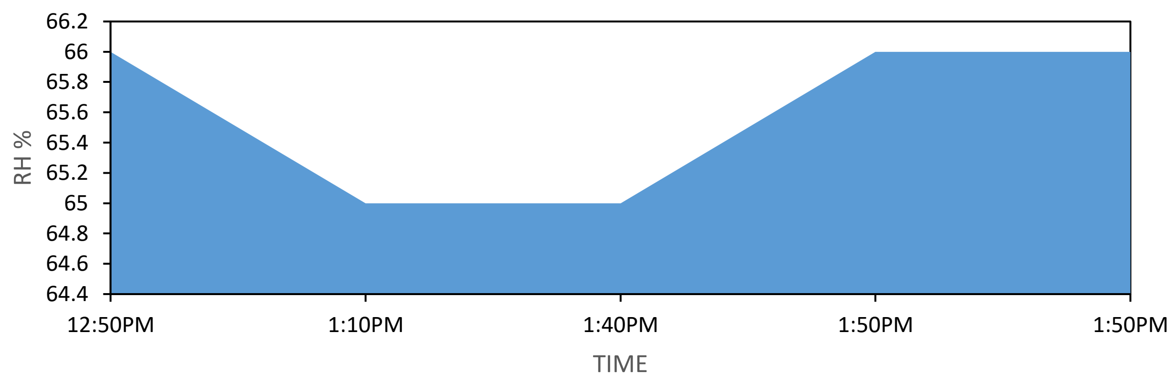


Figure 44: Relative Humidity of HECAF during surveyed period

As illustrated in the above figure, the recorded globe temperature and air temperature at a height of 1.1 meters from the floor level show a mean globe temperature of 28.3 °C during the voting period, with minimal fluctuations. Figures 43 and 44 depict the CO_2 concentration and relative humidity throughout the surveyed period, indicating a mean CO_2 concentration of 601.3 ppm and humidity level of 66.3%. According to ASHRAE-55 standards, these values are deemed to fall within the comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

From the field survey of the HECAF office ,the subjective thermal perception of the office employees was measured by using the standard ASHRAE thermal comfort scale vote.The data obtained from the survey is analyzed and tabulated in excel for better understanding.

The thermal sensation vote of the 10 office employee of this office shows 70% office employee feel neutral i.e. they are satisfied with their present thermal environment , 10% feel slightly hot,20% feel hot,0% very hot and remaining feel slightly cold.

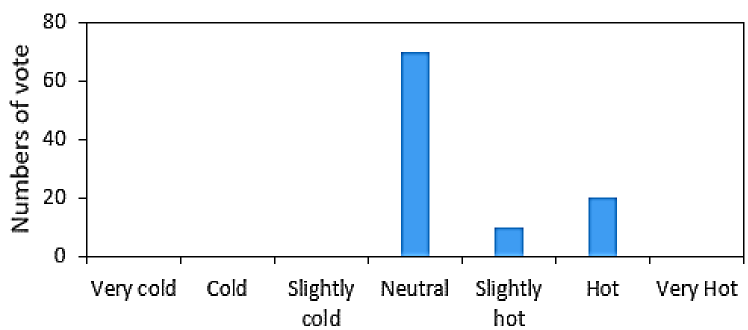


Figure 45: Distribution of Thermal sensation vote by employee of HECAF

Thermal Perception

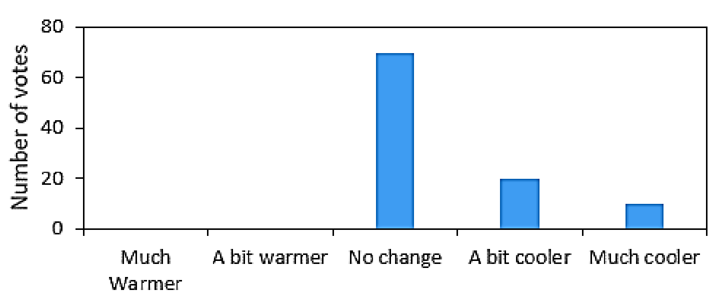


Figure 46: Distribution of Thermal Perception vote by employee of HECAF

Likewise,thermal preference of the employee were obtained by using 5-point thermal preference vote scales.This helps to analyze the thermal preference of the respondent in their present thermal environment .The vote shows that 20% students preferred a bitcooler , 10% prefered much cooler while 70% prefered no change and 0% preferred a bit warmer.

Overall comfort

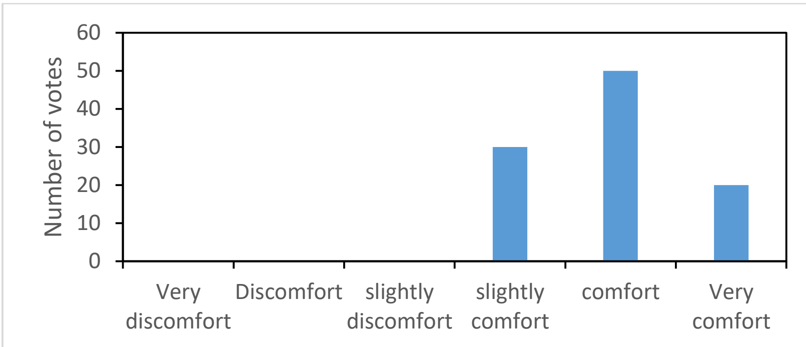


Figure 47: Distribution of Overall thermal comfort vote by employee of HECAF

Similarly, overall thermal comfort of the employee is surveyed and resulted that 50% of the employee voted comfort,30% of the employee voted slightly comfort ,20% voted for very comfort while 0% and 0% voted slightly discomfort and discomfort respectively.

4.1.5. Case-5: Informative Solutions Pvt. Ltd, Patan Dhoka

Figure 48-Investigated office building-5 (Informative solutions)

On July 2, 2023, a survey was conducted with twelve (12) office employees from the ground floor of Informative Solutions (IS). The investigation focused on the free-running mode, indicating that the building is either naturally ventilated or equipped with an HVAC system. Notably, during the study period, either the heating (HT) or cooling (CL) systems were turned off.

Table 11: Description of office building-5 (Informative Solutions)

Element	Description	Details
External wall	Insulation: no Wall thickness=14”	Brick façade with 12mm thick cement plaster
Floor	No Insulation	Marble flooring
Window		Wooden frame
Roof	Concrete slab of thickness 125mm	
Room Height	9.5ft	

The structure of office building -5 (IS) is load bearing and has 14 inch thick brick wall. Below figure 49 depicts the studied area of the building and the position of the digital instrument that was set up at height of 1.1meter from ground level.

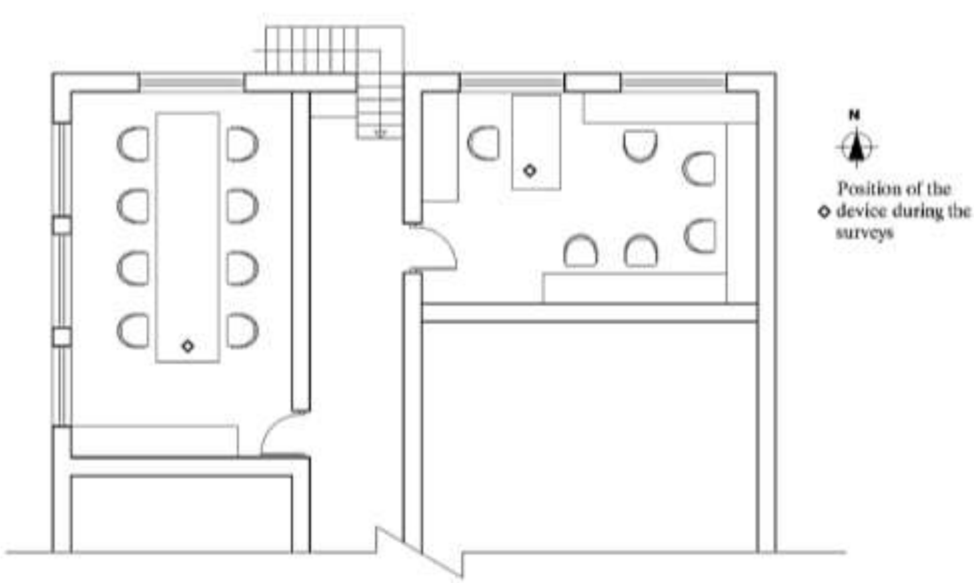


Figure 49: Ground floor plan of office building-5 (IS)

Figure 50: Questionnaire survey and reading of the recorded data at Informative Solutions (IS)

Analysis of the recorded data during survey period

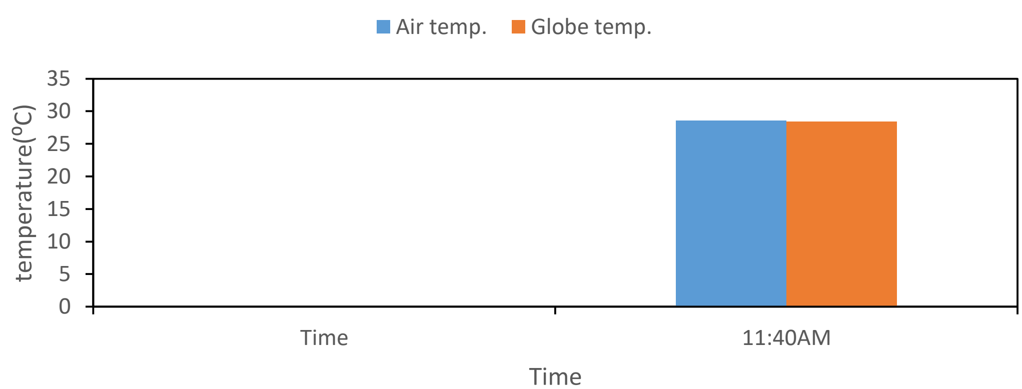


Figure 51: Globe temperature and outdoor air temperature of IS during survey period

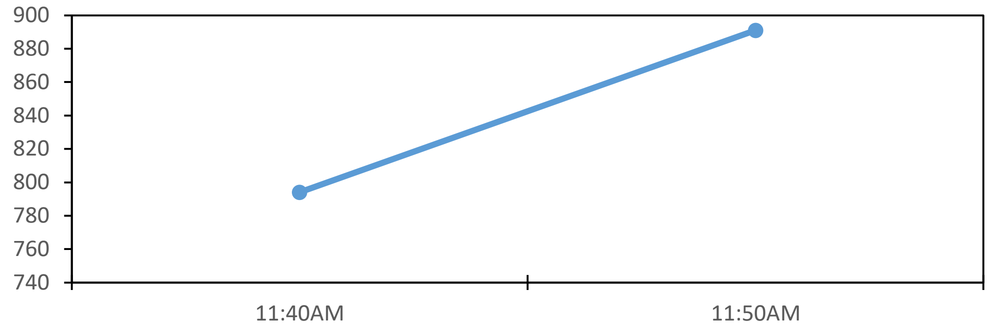


Figure 52: CO2 concentration of IS during survey period

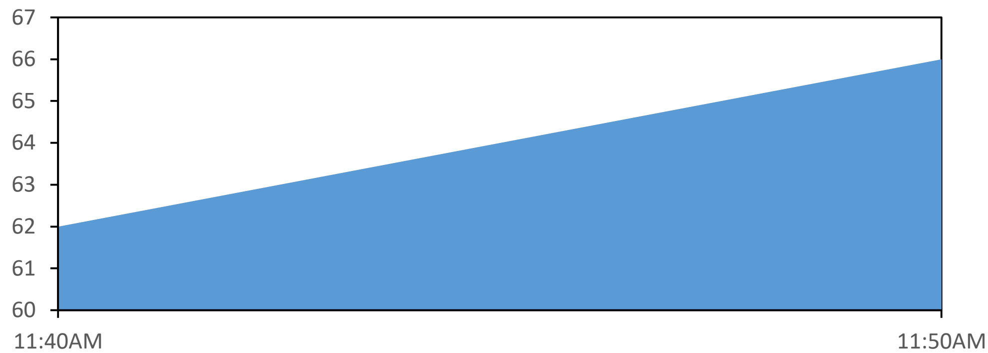


Figure 53: Relative Humidity of IS during survey period

As depicted in the above figure (Figure 51), the recorded globe temperature and air temperature at a height of 1.1 meters from the ground level reveal a mean globe temperature of 28.3 °C during the voting period, with minimal fluctuations. Figures 52 and 53 illustrate the CO_2 concentration and relative humidity throughout the surveyed period, indicating a mean CO_2 concentration of 601.3 ppm and humidity level of 66.3%. According to ASHRAE-55 standards, these values are considered to fall within the comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

From the field survey of the IS office ,the subjective thermal perception of the office employees was measured by using the standard ASHRAE thermal comfort scale vote.The data obtained from the survey is analyzed and tabulated in excel for better understanding.

The thermal sensation vote of the 12 office employee of this office shows 67% office employee feel neutral i.e. they are satisfied with their present thermal environment , 25% feel slightly hot,8% feel hot,0% very hot and 0% feel slightly cold.

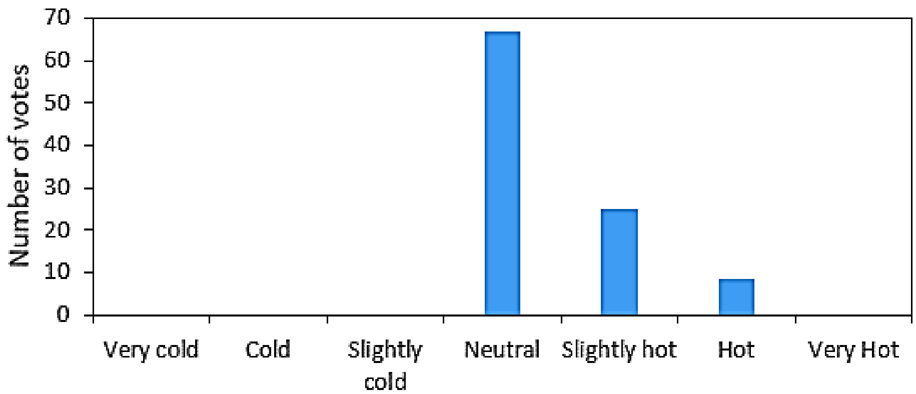


Figure 54: Distribution of Thermal Sensation vote by employee of IS

Thermal perception

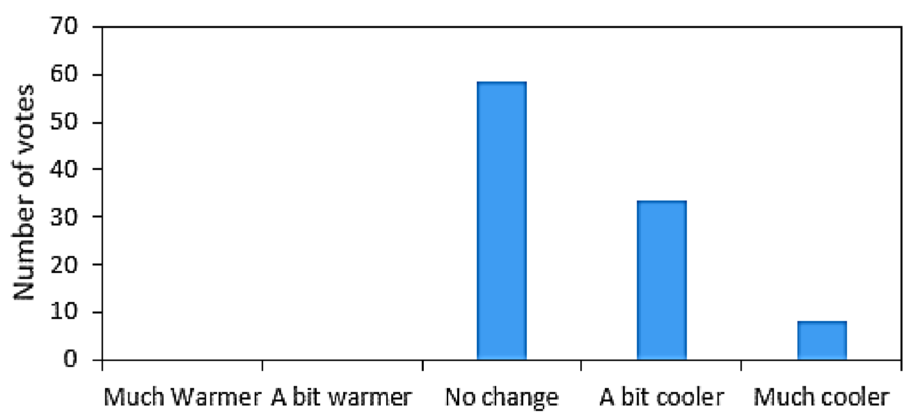


Figure 55: Distribution of Thermal Perception vote by employees of IS

Likewise,thermal preference of the employee were obtained by using 5-point thermal preference vote scales.This helps to analyze the thermal preference of the respondent in their present thermal environment .The vote shows that 34% students preferred a bitcooler , 8% prefered much cooler while 58% prefered no change and 0% preferred a bit warmer.

Overall comfort

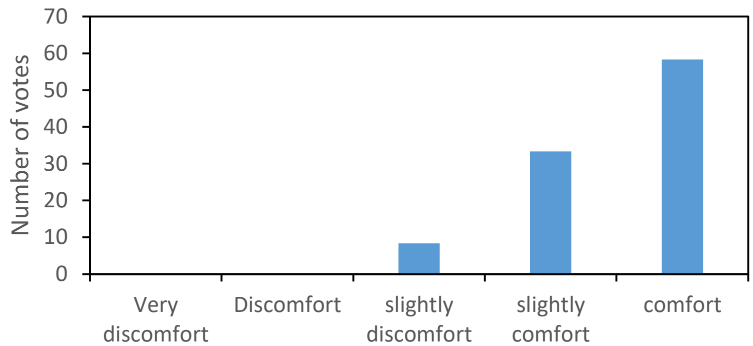


Figure 56: Distribution of Overall thermal comfort vote by employee of IS

Similarly, overall thermal comfort of the employee is surveyed and resulted that 58% of the employee voted comfort,33% of the employee voted slightly comfort ,20% voted for very comfort while 0% and 0% voted slightly discomfort and discomfort respectively.

4.2.6. Case-6: Civil Informatics and Solutions, Pulchowk

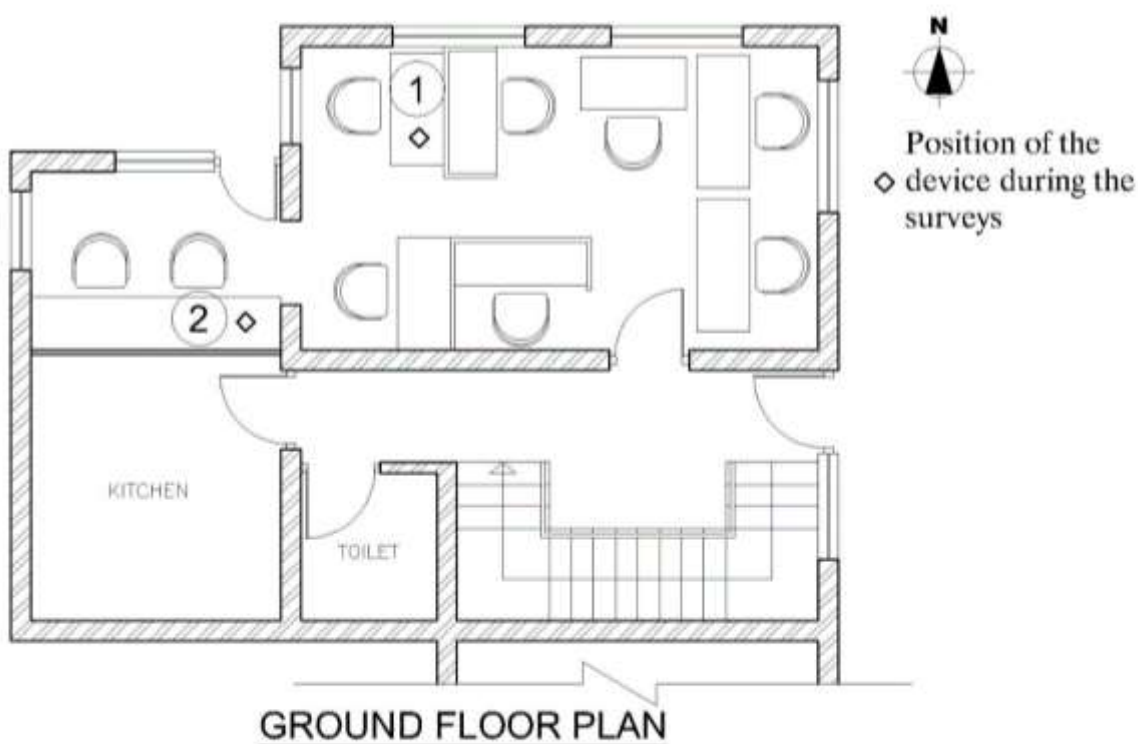
Figure 57: Investigated office building-6 (Civil Informatics and Solutions)

n July 6, 2023, a survey was conducted involving fifteen (15) office employees from the ground floor of Civil Informatics and Solutions (CIS). The study focused on the free-running mode, indicating that the building is either naturally ventilated or equipped with an HVAC system. Importantly, during the study period, either the heating (HT) or cooling (CL) systems were turned off.

Table 12: Description of office building-6 (CIS)

Element	**Description**	**Details**
External wall	Insulation: no Wall thickness=9”	Brick façade with 12mm thick cement plaster
Floor	No Insulation	Marble flooring
Window		Wooden frame
Roof	Concrete slab of thickness 125mm	
Room Height	10ft	

GROUND FLOOR PLAN OF CIS



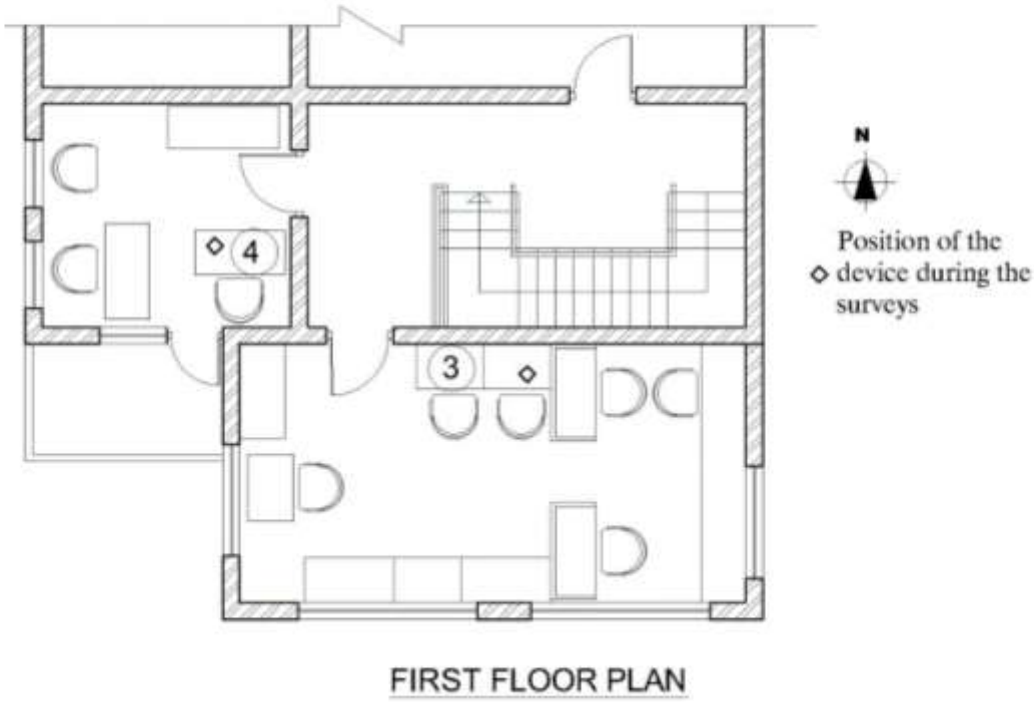


Figure 58: Ground and first floor plan of CIS

Figure 58 shows the position of the digital instrument that was set up at height of 1.1meter from floor level.

Figure 59: Questionnaire Survey at CIS

Analysis of recorded data during surveyed period

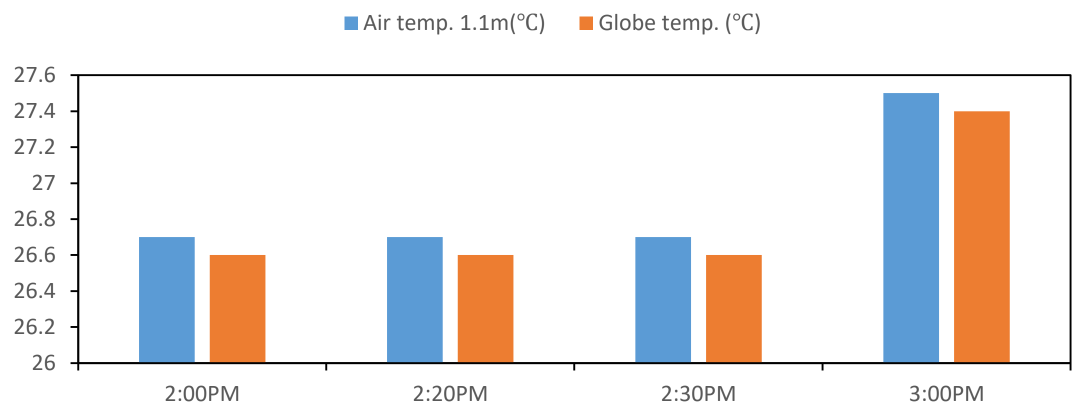


Figure 60: Globe temperature and outdoor air temperature of CIS during survey period

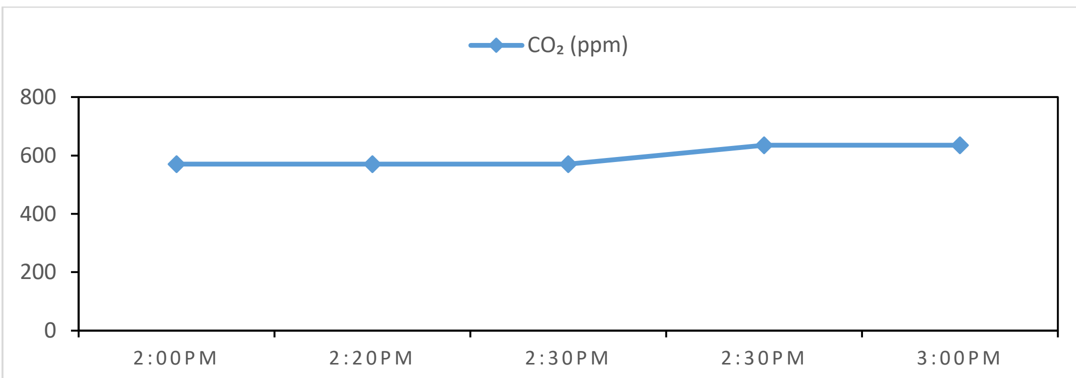


Figure 61: CO_2 concentration of CIS during surveyed period

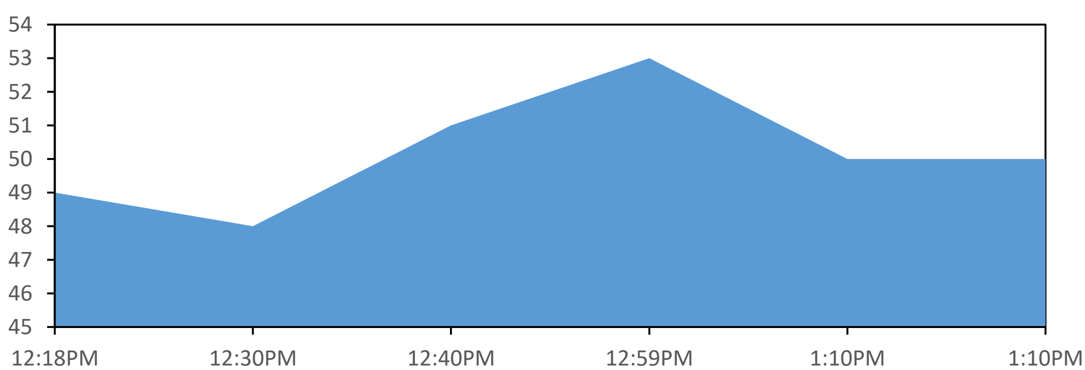


Figure 62: Relative Humidity of CIS during surveyed period

As depicted in Figure 60, the recorded globe temperature and air temperature at a height of 1.1 meters from the floor level reveal a mean globe temperature of 28.3 °C during the voting period, with minimal fluctuations. Figures 61 and 62 illustrate the CO_2 concentration and relative humidity throughout the surveyed period, indicating a mean CO_2 concentration of 601.3 ppm and humidity level of 66.3%. According to both ASHRAE-62 and ASHRAE-55 standards, these values are considered to fall within the comfort zone.

Study of Thermal sensation,thermal perference and overall comfort

From the field survey of the office- Civil Informatics and Solutions(CIS) ,the subjective thermal perception of the office employees was measured by using the standard ASHRAE thermal comfort scale vote.The data obtained from the survey is analyzed and tabulated in excel for better understanding.

The thermal sensation vote of the 15 office employee of this office shows 53% office employee feel neutral i.e. they are satisfied with their present thermal environment , 33% feel slightly hot,13% feel hot,0% very hot and 0% feel slightly cold.

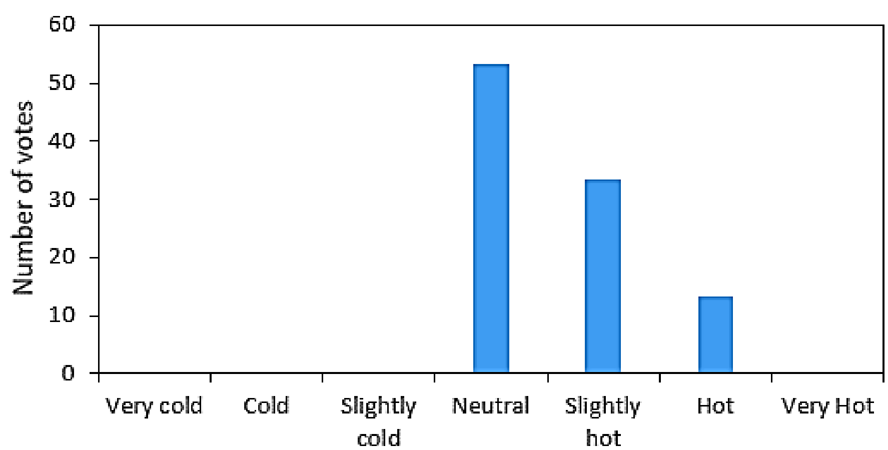


Figure 63: Distribution of Thermal Sensation Vote by employees of CIS

Thermal Perception

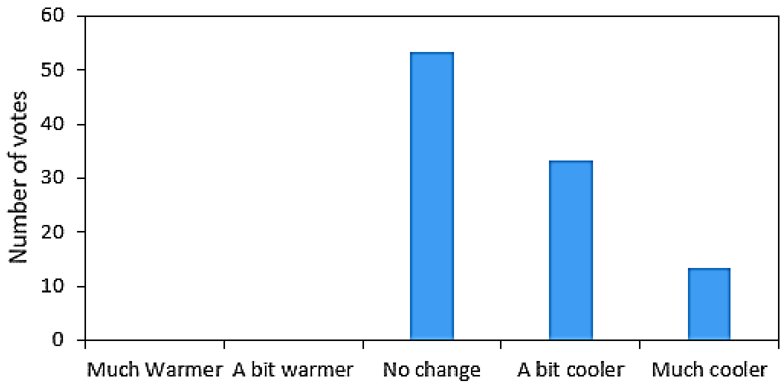


Figure 64: Distribution of Thermal Perception vote by employees of CIS

Likewise,thermal preference of the employee were obtained by using 5-point thermal preference vote scales.This helps to analyze the thermal preference of the respondent in their present thermal environment .The vote shows that 34% students preferred a bitcooler , 8% prefered much cooler while 58% prefered no change and 0% preferred a bit warmer.

Overall comfort

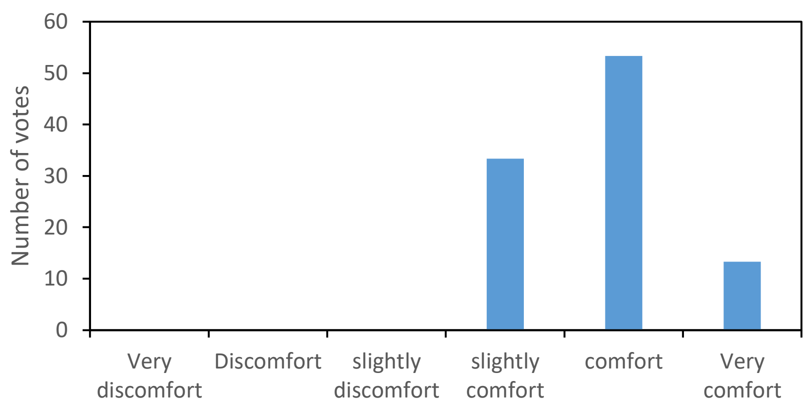


Figure 65: Distribution of Overall comfort vote by employees of CIS

Similarly, overall thermal comfort of the employee is surveyed and resulted that 53% of the employee voted comfort,33% of the employee voted slightly comfort ,20% voted for very comfort while 0% and 0% voted slightly discomfort and discomfort respectively.

CHAPTER-5: DATA ANALYSIS AND FINDINGS

5.1. Thermal Sensation Votes and Thermal Preference

The field survey data was employed to analyze the thermal sensation votes (TSV) and thermal preference (TP). Total 100 employees were surveyed where 45 were in free-running office buildings and 55 were in mixed-mode office buildings as shown in table 13.

Table 13: Numbers of employees in FR and MM office buildings

Mode of office buildings	Nos of employees
Free-running (FR)	45
Mixed-mode (MM)	55

Figure 65 depicts the results of the thermal sensation votes (TSV). In terms of free-running, 44% of respondents chose slightly warm, 31% chose neutral, 9% chose slightly chilly, 15% chose warm, and 2% chose hot, as shown in figure 65. The comfort zone is indicated by three central options (3 to 5) on the ASHRAE seven-point sensory scale [33]. In the free running mode office building, 84% of respondents were inside their comfort zone, whereas 16% were outside of their comfort zone.

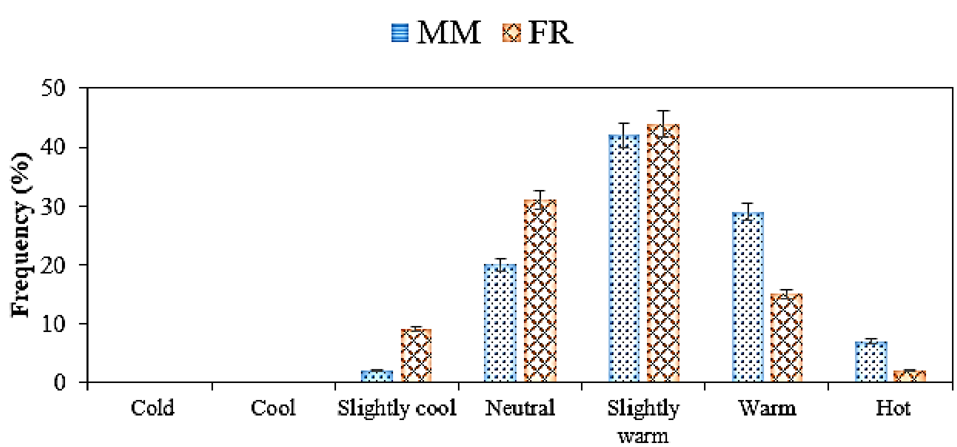


Figure 66: Distribution of Thermal Sensation Votes (TSV) for FR and MM office buildings

In reference to mixed-mode office buildings, as figure 65 illustrated, 42% of respondents voted for slightly warm, while 20% voted for neutral, 2% for slightly cool, 29% voted for warm and 0% voted for hot. The comfort is indicated by three central alternatives (3 to 5) on the ASHRAE seven-point sensory scale comfort [33] .Based on this, 64% of respondents in the free-running mode office building were in their comfort zone, while 36% were not.

Table 14: Percentage of thermal sensation in FR and MM office buildings

	Scale	**TSV on MM**		**TSV on FR**	
		N	P (%)	N	P (%)
Cold	1	0	0	0	0
Cool	2	0	0	0	0
Slightly cool	3	1	2	5	9
Neutral	4	9	20	17	31
Slightly warm	5	19	42	24	44
Warm	6	13	29	8	15
Hot	7	3	7	1	2
		45	100	55	100

The majority of respondents felt a slightly warm or neutral thermal sensation during the summer season, with a notable proportion expressing a warmer conditions.

Thermal Preference (TP)

In the same specific thermal environment, regarding free-running office buildings, 55% of respondents prefer a bit cooler, while 39% said they would prefer no change and remaining 6% voted for much cooler. Furthermore, in case of mixed-mode office buildings 64% of respondents prefer a bit cooler, 31% prefer no change while 4% of respondents said they'd prefer to have much cooler.

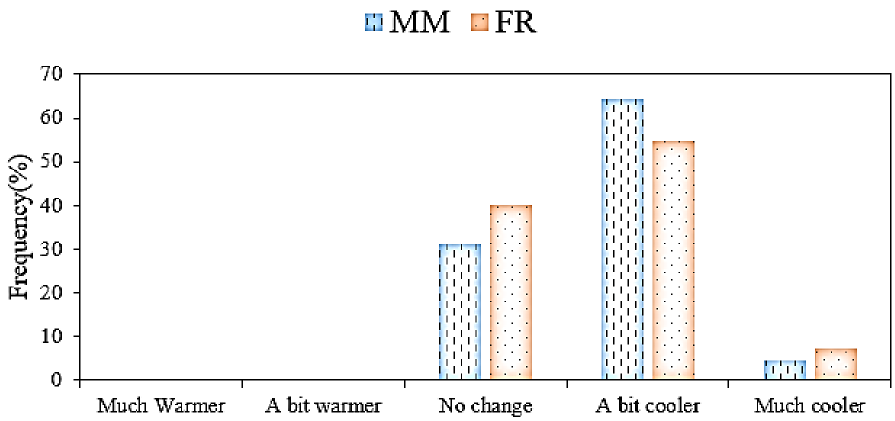


Figure 67: Distribution of thermal preference in FR and MM office buildings

Table 15: Percentage distribution of thermal preference in MM and FR office buildings

	Scale	**TP on MM**		**TP on FR**	
		N	P (%)	N	P (%)
Much Warmer	1	0	0	0	0
A bit warmer	2	0	0	0	0
No change	3	14	31	21	39
A bit cooler	4	29	64	30	55
Much cooler	5	2	4	4	6
		45	100	55	100

Conclusions from analysis of votes on thermal sensation votes and thermal preference from office employees:

- In both free-running and mixed-mode office buildings, the majority of respondents prefer a bit cooler, indicating a common preference for a cooler thermal environment.
- The thermal sensation votes and comfort zone analysis suggest that a significant portion of respondents in both office building types are within their comfort zone. This aligns with the thermal preferences, as a preference for a bit cooler is generally in line with being within the comfort zone.
- Interestingly, even though a significant percentage of respondents prefer a bit cooler, some still experience thermal sensations outside their comfort zone. This could be influenced by factors such as individual differences in thermal sensitivity, clothing choices, or the actual temperature conditions in the buildings.

- The absence of votes for a hot thermal sensation in the mixed-mode office building aligns with the 0% preference for a much cooler environment, suggesting a consistent trend toward cooler preferences.

Table 16: Comfort temperature for the autumn season in naturally ventilated office buildings observed in various studies.

Country/City	**References**	**Mode**	**Period**	**Variable for *Tc***	***To* (℃)**	***Tg,Ta* (℃)**	***Tc* (℃)**
This study	-	FR	Summer	*Ta*	26.2	28.0	27.21
	-	MM	Summer	*Ta*	25.6	27.51	26.81
Japan /Yokohama, Tokyo	Rijal et al. [49]	FR	Autumn	*Tg*	17.9	24.8	24.9
India/ Chennai, Hyderabad	Indragant et al. [50]	NV	Autumn	*Tg*	31.3	29.0	27.0
India/ Tezpur, Shillong	Singh et al. [51]	NV	Autumn	*Tg*	20.9	27.9	27.3

FR: Free Running, MM: Mixed Mode, NV: Naturally ventilated, Tg: Globe temperature, Top: Operative temperature, Ta: Indoor air temperature

5.2. Prediction of thermal comfort temperature

The study of thermal comfort field survey data yielded a major result: comfort temperature. In free-running and mixed-mode office buildings, the assessment of comfort temperature is based on a linear relationship between thermal sensation votes (TSV) and indoor air temperature, as shown in Figures 67 and 68, respectively. Additionally, the sensitivity of the subjects is assessed through the use of regression analysis and the regression coefficient obtained from that analysis.

For free-running office buildings, equation for linear regression that we have obtained is as follows:

$$TSV = 0.138Ti + 0.7039 \ (N=55, R^2=0.05) \ldots\ldots (1)$$

Where TSV: Thermal sensation vote, Ti: Indoor air temperature (°C), N=Number of votes, R^2= Coefficient of determination

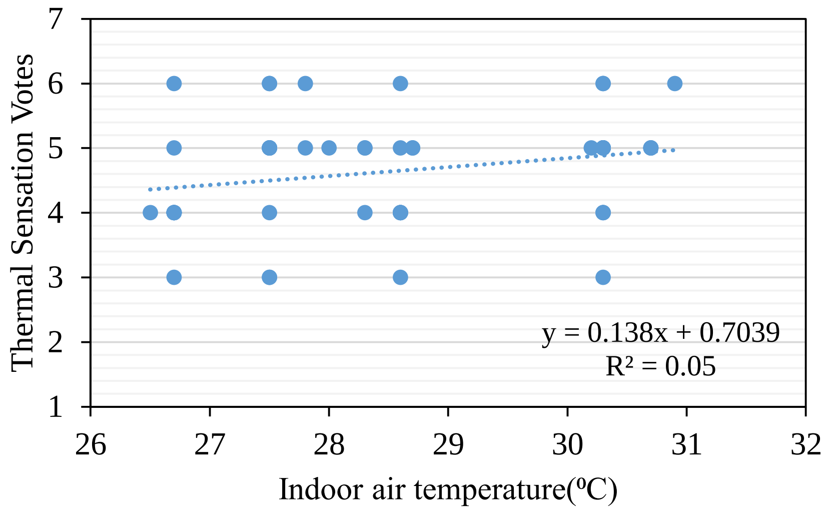


Figure 68: Relationship between Thermal Sensation Votes and Indoor air temperature (FR office buildings)

By substituting "4. Neutral" into equation (1), the calculated comfort temperature is 23.88ºC. The equation's regression coefficient, determined as 0.13 from equation (1), indicates that a shift of 7.6ºC (1/0.13) is necessary to alter one thermal sensation vote. This implies that, according to the regression model, a change of 7.6ºC in environmental conditions would result in a perceptual shift in thermal sensation by one unit. However, the practicality of requiring a shift of more than 5ºC to change one thermal sensation vote is questioned. This observation suggests that, based on the provided regression coefficient, the model would demand a substantial and potentially impractical alteration in environmental conditions to bring about a noticeable change in thermal sensation. [52]. As a result, Griffiths' approach is utilized to exclude superfluous values from the regression analysis.

Griffiths' method is especially beneficial when there is little volatility in the temperature throughout the field survey and there is a probability that the little number of data will not offer a strong regression to predict the comfort temperature. Griffiths' comfort temperature (Tc) is calculated using the equation;

Tc = Ti + (4-TSV)/a…………………………………………… (2)

Where, Tc: Comfort temperature, a: Griffiths' constant, Ti: Indoor air temperature, TSV: Thermal sensation votes, a: regression coefficient (0.50).

The regression coefficient of 0.5 was used here, as was done by many other researchers [16]. For each comfort vote, we approximated the Griffiths' comfort temperature and obtained mean comfort temperature was 27.21ºC.

Similarly with regard to mixed-mode office buildings equation for linear regression that we have obtained is as follows:

TSV=0.22 Ti -1.53 (N=45, R^2 = 0.1162)………………………………… (3)

Where TSV: Thermal sensation vote, Ti: Indoor air temperature (°C), N=Number of votes, R^2=Coefficient of determination)

Upon substituting "4. Neutral" into equation (3), the resulting comfort temperature is determined to be 25.13ºC. The regression coefficient from equation (3), calculated as 0.22, indicates that a shift of 4.5ºC (1/0.22) is required to alter one thermal sensation vote. In accordance with the regression model, this suggests that a change of 4.5ºC in environmental conditions would induce a perceptual shift in thermal sensation by one unit.

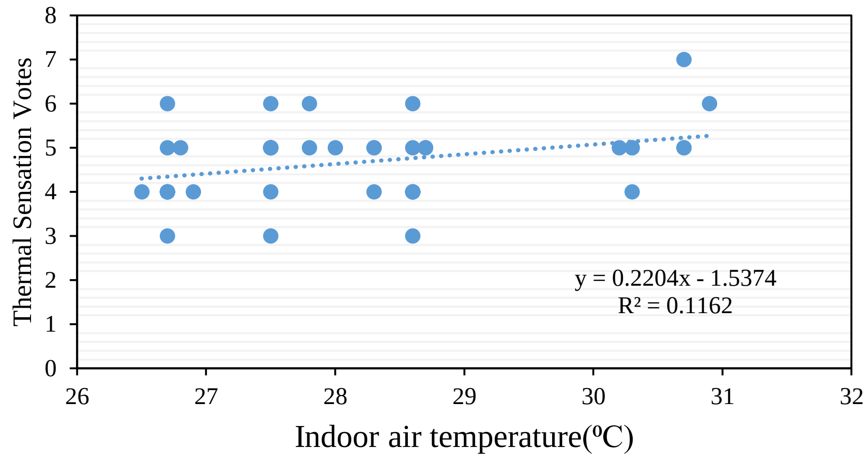


Figure 69: Relationship between Thermal Sensation Votes and Indoor air temperature (MM office buildings)

Griffiths' comfort temperature (Tc) is estimated for all the comfort votes, using the equation (2). We obtained a mean comfort temperature of 26.81°C.

Here, through Griffiths' method the comfort temperature in free-running and mixed-mode office building are 27.21°C and 26.81°C respectively on summer season, which is found to be very similar to the study on [50], [51] as presented in table 15.However, there is significant difference with Japan, this implies that the ideal comfort temperature in office buildings vary depending on the climate of the region. This emphasizes the importance of conducting further studies to better understand and establish comfort temperature standards for office buildings, taking into account regional climatic variations. This is a valid point, as climate plays a crucial role in determining the thermal comfort preferences of individuals.

Conducting additional research can help refine and expand the existing knowledge on comfort temperatures, considering specific climatic conditions. This might involve studying various regions and their unique climates to develop more accurate and region-specific guidelines for maintaining thermal comfort in office buildings.

5.3. Indoor CO_2 concentration, air temperature and relative humidity

Figure 70 shows the indoor CO_2 concentration level of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) investigated office buildings that is recorded from 1st July to 7th July 2023 during office hours (10:08am to 5:08pm). Seven days at interval of 1 hour were recorded by using digital instrument named TR-76Ui.The average CO_2 concentration of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) were found to be 453ppm, 460ppm, and 414ppm respectively. The current version of ASHRAE Standard 62.1 sets the maximum allowable continuous CO_2 concentration at 700 ppm above outdoor levels. The average CO_2 concentrations for NT, AKG, and CIS fall well below the ASHRAE guideline of 700 ppm. This is generally considered favorable, as lower CO_2 concentrations are associated with better indoor air quality and can contribute to a healthier and more comfortable indoor environment.

In line with ASHRAE Standard 62.1, which emphasizes ventilation for maintaining acceptable indoor air quality, the recommended range for indoor relative humidity typically falls between 30% and 60%. The observed indoor relative humidity levels in the surveyed office buildings are consistent with the guidelines outlined in ASHRAE Standard 62.1. This alignment indicates that the ventilation and humidity control systems within these buildings are functioning within acceptable parameters, thereby fostering a conducive indoor air quality environment.

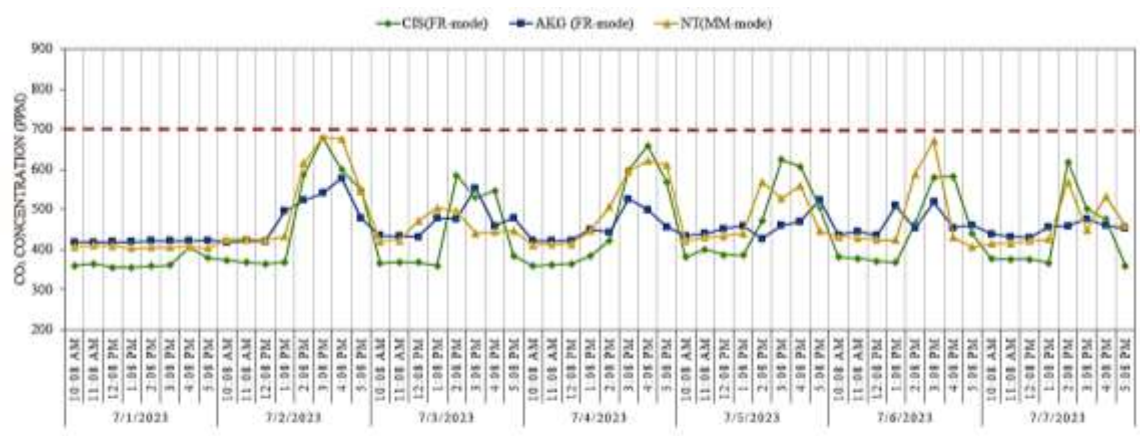


Figure 70: Comparison of Indoor CO_2 concentration recorded from 1st to 7th July-2023 in MM and FR office buildings

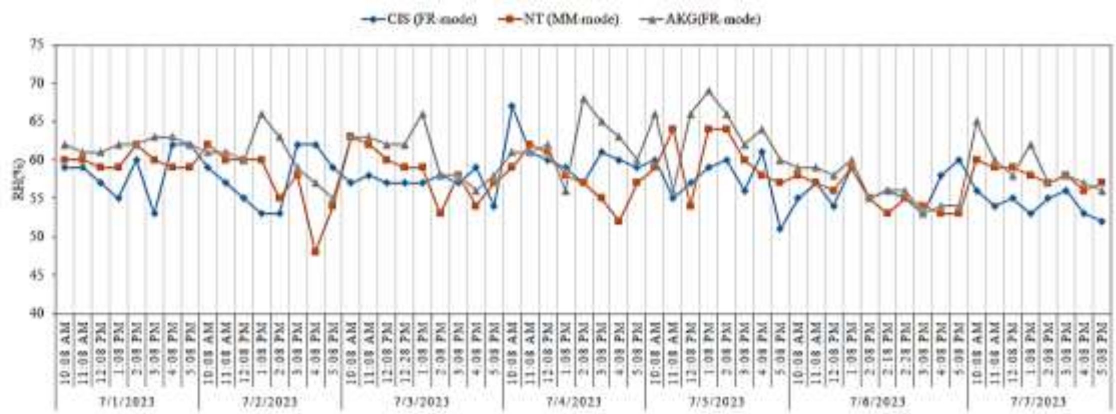


Figure 71: Comparison of indoor relative humidity recorded from 1st to 7th July-2023 in MM and FR office buildings

Figure 71 shows the indoor relative humidity of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) investigated office buildings that is recorded from 1st July to 7th July 2023 during office hours (10:08am to 5:08pm). Seven days at interval of 1 hour were recorded by using digital instrument named TR-76Ui. The average relative humidity of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) were found to be 58.08%, 58.21%, and 59.8% respectively.

ASHRAE-55 standard typically recommends indoor relative humidity levels to be maintained between 30% and 60% for comfort and health. In this case, the recorded average relative humidity values for NT (MM-mode), AKG (FR-mode), and CIS (FR-mode) fall within this range, suggesting that, from a humidity perspective, the indoor environments in these office buildings are generally in line with ASHRAE-55 recommendations.

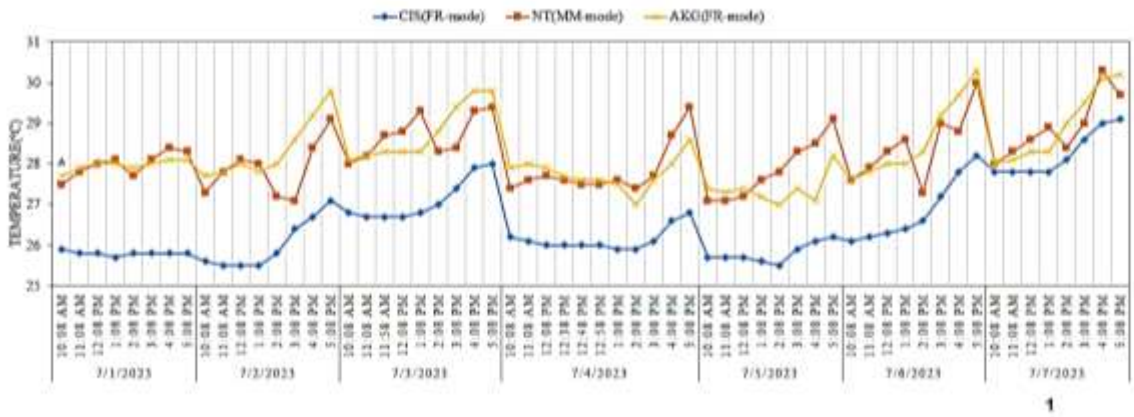


Figure 72: Comparison Indoor air temperature recorded from 1st to 7th July-2023 in MM and FR office buildings

Figure 72 illustrates the indoor air temperature of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) investigated office buildings that is recorded from 1st July to 7th July 2023 during office hours (10:08am to 5:08pm). Seven days at interval of 1 hour were recorded by using digital instrument named TR-76Ui. The average air temperature of NT (MM-mode), AKG (FR-mode) and CIS (FR-mode) were found to be 28.05°C, 27.17°C and 28.69°C respectively. The recorded temperatures, particularly for NT (MM-mode) and CIS (FR-mode), may fall slightly outside the ASHRAE Standard 55 -recommended thermal comfort range of 23.5ºC to 26.1ºC for office spaces. This suggests in need of further investigation into factors such as air velocity, and clothing levels could provide insights into occupant comfort.

Table 17: Average value of air temperature.CO_2 and Relative Humility recorded for 7 days in MM and FR office buildings during office hours

S.N.	Office Building	Mode of building	Indoor Air temperature(ºC)	CO_2 (ppm)	Relative Humidity (%)
1.	NT	MM	28.05 ºC	452.54	58.08
2.	CIS	FR	27.17ºC	414.34	58.21

3.	AKG	FR	28.69ºC	459.31	59.8

FR: Free-running, MM: Mixed-mode

5.4. Study the impact of climate change with respect to thermal comfort

The Nicol graph serves as a tool for assessing adaptive thermal comfort within a building concerning the outside mean temperature. Aligned with adaptive principles, the Nicol graph acknowledges that the perceived comfort indoors is contingent on the outdoor temperature, reinforcing the idea that individuals find different indoor conditions comfortable based on the prevailing outdoor temperatures. Analysis of recent data [53] suggests the equation Tcomf = 0.53 Tom + 13.8………………… (4), where thermal comfort from yearly mean (Tcomf), monthly mean outside temperature (Tom).Using this equation comfort temperature can be calculated for each year.

Here to study the impact of climate change with respect to thermal comfort, yearly maximum and minimum temperature (1981 to 2021) were collected from Department of Hydrology and Meteorology (DHM) and calculated the comfort temperature by using equation (4) as presented in table 17.

Table 18: Calculation of yearly comfort temperature from 1981 to 2021 by Nicol formula

YEAR	Tmax	Tmin	Tom	Tcomf
1981	34.18	17.7	25.9	27.5
1982	33.95	19.52	26.7	28.0
1983	37.23	18.85	28.0	28.7
1984	34.69	19.87	27.3	28.3
1985	35.08	19.69	27.4	28.3
1986	34.84	17.05	25.9	27.6
1987	36.64	19.57	28.1	28.7
1988	33.98	18.57	26.3	27.7
1989	33.92	19.19	26.6	27.9
1990	35.83	20.34	28.1	28.7
1991	33.71	19.01	26.4	27.8
1992	35.32	18.91	27.1	28.2
1993	33.44	18.74	26.1	27.6
1994	36.13	20.08	28.1	28.7

1995	34.43	19.65	27.0	28.1
1996	33.41	17.4	25.4	27.3
1997	35.7	18.83	27.3	28.3
1998	37.3	20.48	28.9	29.1
1999	34.21	17.78	26.0	27.6
2000	33.28	18.48	25.9	27.5
2001	33.62	19.35	26.5	27.8
2002	32.49	19.3	25.9	27.5
2003	33.8	19.5	26.7	27.9
2004	29.33	17.87	23.6	26.3
2005	35.58	18.68	27.1	28.2
2006	31.73	18.12	24.9	27.0
2007	32.96	19.24	26.1	27.6
2008	29.78	18.72	24.3	26.7
2009	34.15	17.31	25.7	27.4
2010	34.73	19.56	27.1	28.2
2011	32.06	17.86	25.0	27.0
2012	35.66	20.84	28.3	28.8
2013	30.89	17.65	24.3	26.7
2014	33	19.86	26.4	27.8
2015	34.95	19.92	27.4	28.3
2016	31.95	19.4	25.7	27.4
2017	34.04	20.48	27.3	28.2
2018	30.58	19.28	24.9	27.0
2019	34.58	19.01	26.8	28.0
2020	29.97	16.94	23.5	26.2
2021	33.18	19.88	26.5	27.9

Obtained yearly (1981 to 2021) comfort temperature from table 17 were plotted in a graph , resulted as shown in figure 72 that illustrates that the comfort temperature is very proportional with the maximum and minimum temperature . As outdoor temperatures increase, the comfort temperature also shows an increasing trend. This implies that to maintain thermal comfort in buildings, adjustments need to be made in response to rising temperatures. The observed correlation between comfort temperature and outdoor temperatures suggests a potential impact of climate change on thermal comfort.

With increasing temperatures, there may be a need for enhanced heating or cooling measures to maintain comfort levels inside buildings. The study demonstrates the importance of considering climate change effects on thermal comfort. It provides valuable insights into how building design and passive building design systems need to adapt to changing outdoor conditions to ensure occupants' comfort.

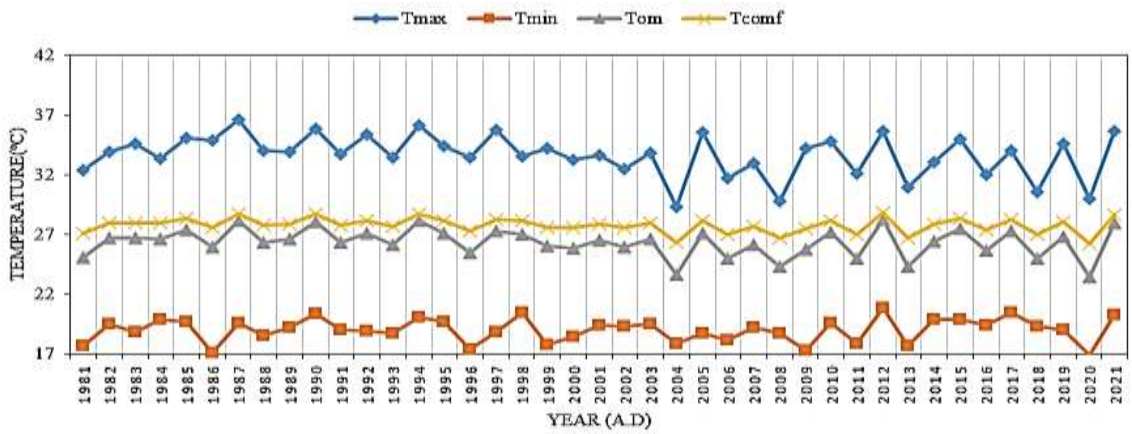


Figure 73: Trend of comfort temperature with the yearly DHM data

CHAPTER-6: CONCLUSION AND RECOMMENDATION

6.1. CONCLUSION

The analysis of the thermal comfort and indoor air quality (IAQ) in free-running and mixed-mode office buildings during summer season were done and following conclusions are obtained:

- In case of free-running office building, with regard to the total, 84% office occupants voted that the thermal sensation in their office is neutral zone . In case of mixed-mode office buildings, with regards to the total, 64% office employees voted that the thermal sensation in their office is neutral zone. It indicates that the majority perceive the indoor environment as neither too cold nor too warm. Whereas in thermal preference ,39% in case of free-running and 31% in case of mixed-mode voted for no change. In terms of Thermal Sensation, the free-running office building appears to have a higher level of satisfaction among occupants, as indicated by the higher percentage of neutral sensation. In terms of Thermal Preference, both groups show a substantial preference for no change, implying that the majority are content with the current thermal conditions. There is a correlation between thermal preferences and thermal sensation votes, with a notable preference for a bit cooler environments and a substantial portion of respondents reporting sensations within their comfort zones.

- Comfort temperature is determined by using Griffths' method and found to be 27.21ºC and 26.81ºC in free-running and mixed-mode office buildings respectively during summer season. The findings should be beneficial in suggesting that when designing new office buildings, these elements should always be considered for building efficiency.
- By following ASHRAE 62 guidelines, it guarantees that the air inside investigated free-running and mixed-mode office buildings (NT, AKG and CIS) is clean and fresh, also has sufficient ventilation, which can enhance the productivity of occupants. This suggests that one of the most essential design criteria for achieving thermal comfort is to use free running or mixed-mode in office buildings.
- This study explores the relationship between yearly comfort temperature (obtained from Table 17) and outdoor temperatures from 1981 to 2021. The findings suggest a strong correlation between comfort temperature and both maximum and minimum outdoor temperatures. The observed trends underscore the importance of considering climate change effects on thermal comfort when designing buildings and implementing passive building design systems.

6.2. RECOMMENDATION

- Neutral thermal sensation means that they neither feel too hot nor too cold, which is often the desired state in indoor environments to maintain occupant satisfaction and productivity. In summary, while both types of buildings show a generally positive outcome in terms of thermal comfort, there may be room for improvement, especially in the mixed-mode buildings, to bring the satisfaction level closer to that of free-running buildings. Regular monitoring and adjustments based on occupant feedback will be crucial for maintaining a comfortable indoor environment.
- However, an average indoor air temperature was higher than the 28 °C standard in 50% of the situations, this could indicate that the investigation period was quite brief. This also indicates running the buildings in FR mode presented difficulties

because they were intended to operate in AC mode. This study recommends conducting extensive field research considering all the parameters related with indoor environment in office in Kathmandu to develop specific norms for adaptable comfort.

- In free-running and mixed-mode buildings, reliance on natural ventilation reduces the need for mechanical systems, leading to lower energy consumption. Continuous monitoring of CO_2 levels allows for precise control of ventilation, preventing over-ventilation and unnecessary energy use. This aligns with the principles of sustainability and energy efficiency, contributing to a greener and more environmentally friendly building operation. In summary, the incorporation of ASHRAE 62 guidelines in the design and operation of free-running and mixed-mode office buildings can ensure clean and fresh indoor air, sufficient ventilation, and enhanced productivity. The continuous monitoring of CO_2 levels further allows for efficient control of ventilation, minimizing energy use while maintaining optimal thermal comfort for occupants.
- It suggests that future building designs should account for the changing outdoor conditions to provide optimal comfort for occupants. In summary, the study highlights the potential challenges posed by climate change to maintaining thermal comfort and emphasizes the importance of adapting building designs and systems to address these challenges.

The findings underscore the need for a nuanced approach to building design, taking into consideration all the factors that influence thermal comfort and indoor air quality. It highlights the importance of considering different building types, their operational modes, and seasonal variations to create energy-efficient and comfortable office spaces for occupants. Architects and designers should use this information to make informed decisions that prioritize both sustainability and occupant well-being in the built environment.

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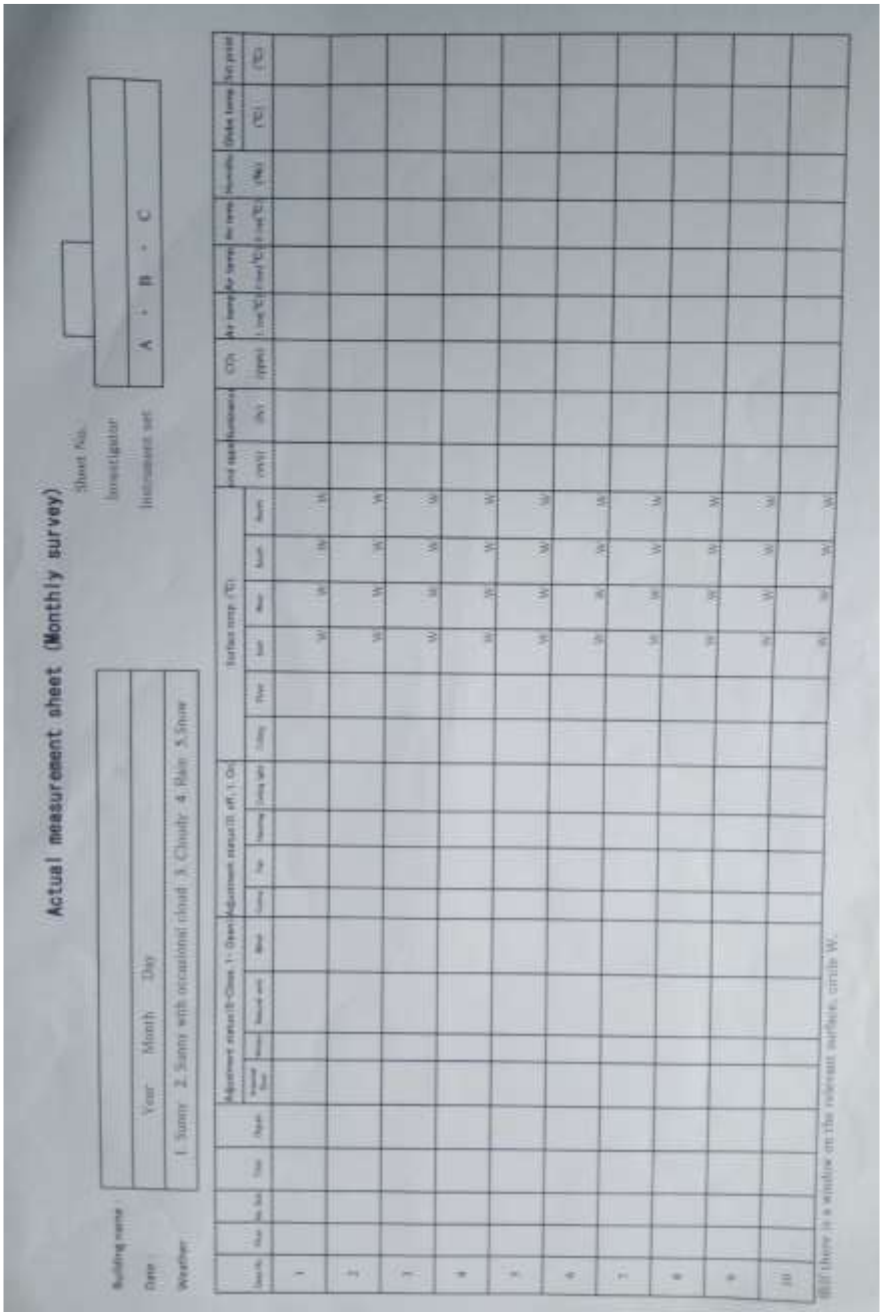
ANNEX

Annex-1: Actual Measurement sheet


Actual measurement sheet (Monthly survey)

Building name

Date

Weather

Year Month Day

1 Sunny 2 Sunny with occasional cloud 3 Cloudy 4 Rain 5 Snow

Sheet No.

Investigator

Instrument set

A · B · C

Annex-2: Questionnaire

Office name: **Date:**

Name: **Age/sex:** 20-30 40-50 30-40 50-60 **Time:**

1.a. How do you feel about hotness and coldness now?

1	2	3	4	5	6	7
Cold	Cool	Slightly cool	Neutral	SLightly warm	Warm	Hot

1.c. How do you prefer now?

1	2	3	4	5
Much cooler	A bit cooler	No change	A bit warmer	Much warmer

2.a. How do you feel "air quality"(freshness) now?

1	2	3	4	5	6
Very Bad	Bad	Slightly Bad	Slightly good	Good	Very Good

2.b. What would you prefer to have?

1	2	3	4	5
Much more air movement	A bit more air movement	No changes	A bit less air movement	Much less air movement

3.a. What do you find the humudity?

1	2	3	4	5	6	7
Very humid	humid	Slightly humid	Neutral	Slightly dry	Dry	Very dry

3.b. What would you prefer to have?

1	2	3	4	5
Much drier	A bit drier	No changes	A bit more humid	Much more humid

Annex-4: Data sheet of Nepal Telecom

ANNEX-4: Questionnare survey of Nepal Telecom

Office	Date	Instrument No	Name	Gender	Age	height	weight	exercise	ve of therm	ence of	ence of	sound	smell	often live	b positi	ob type
Nepal telecom	13-Jun	1	Yagya bijaya	1	8	6	7	7hr	4	3	3	2	2	1	5	2
		1	Surendra Parsad Khanal	1	7	6	6	7hr	2	2	2	2	2	1	6	8
		2	Arjun Kumar Pokheral	1	6	6	6	10.5hr	1	3	3	1	1	1	6	9
		3	Keshav Raj Devkota	1	8	6	7	10hr	2	1	3	2	3	1	3	7
		4	Krian kumar pokhrel	1	6	4	10	3hr	4	3	3	4	2	1	5	2
		4	Madan sitayla	1	5	7	7	1hr	2	3	3	2	2	1	2	2
		5	Ghanshyam Parsad Pokh	1	7	6	4	21hr	2	1	1	4	4	1	6	2
		6	Dhruva lal	1	6	7	6	7.5hr	3	1	1	2	4	1	6	5
		7	Madan suwal	1	5	5	9	6hr	2	3	3	4	2	1	5	2
		7	Lok Bahadur Katwal	1	8	7	8	14hr	1	1	3	4	4	1	5	2
		8	Parshuram Pandit	1	5	7	4	7hr	2	3	3	1	4	1	6	9
		9	Indra Bahadur Dahal	1	7	6	4	21hr	2	1	1	4	4	1	6	2
		10	Rabindra manandhar	1	6	6	6	30min	2	2	2	3	3	1	1	2
		11	Megh Bahadur KC	1	6	6	5	7hr	2	3	3	4	4	1	5	2
		12	Kumar Giri	1	6	7	8	7hr	2	1	1	2	2	1	6	2
		12	Shyam bhatta	1	6	7	7	7hr	1	1	3	1	3	1	6	2
		13	Krishna pd bhattari	1	8	4	5	3.5hr	2	3	3	3	2	1	5	2
		13	Yubaraj paudyal	1	6	5	4	7hr	2	3		2	3	1	6	9
		14	Amrita Katwal	2	4	5	5	3hr	3	3	3	4	2	1	5	2
		15	Binod kumar yadav	1	6	6	8	15min	2	2	2	2	2	1	6	8
		16	Sudarsan Sigdel	1	6	7	7	7hr	1	1	3	1	3	1	6	2
		17	Hari Parsad Poudel	1	5	7	4	30min	1	3	3	1	1	1	1	9
		18	Narayan raj pokhral	1	4	5	7	1hr	1	1	3	4	4	1	3	9

birthplace						Adjustment status (0–Close, 1– Open)				Adjustment status (0. off, 1. On)				Surface temp. (℃)						ind spe	Iluminace	CO2
	Data No.	Floor	No. Sub	Time	[illegible]	Internal Door	Window	Natural vent	Blind	[illegible]	Fan	Heating	Ceiling light	Ceiling	Floor	East	West	South	North	(m/s)	(lx)	(ppm)
Sunsari			2	10:50AM		0	1	0	1	0	1	0	1	29.2	29.4	29.5	29.6	30	29.1	0.1	21.7	545
Bharatpur			2	10:50AM		0	1	0	1	0	1	0	1	29.2	29.4	29.5	29.6	30	29.1	0.1	21.7	545
Sinduli			1	11:00AM		1	1	0	1	0	1	0	0	30.4	30.7	32.4	30.4	31.2	29.6	1.6	96	526
Dang			1	11:10AM		1	0	0	1	1	1	0	0	30.3	29.1	33.5	29.6	29.9	28.8	0.1	193	566
siraha			2	11:20AM		1	1	1	1	0	1	0	0	29.4	29.3	29.6	29.4	30.9	29.3	0.4	391	436
sunsari			2	11:20AM		1	1	1	1	0	1	0	0	29.4	29.3	29.6	29.4	30.9	29.3	0.4	391	436
khotang			1	11:25AM		1	0	1	1	0	1	0	1	29.3	30.1	29.5	29.2	30.2	29.5	0.15	125	523
jaleshwar			1	11:35AM		1	1	0	1	0	1	0	0	29.5	30.1	29.6	30	31.5	29.6	0.15	229	469
Dang			2	11:45AM		1	1	1	1	0	1	0	1	29.5	29.9	29.5	29.6	31.3	30.1	0.1	150	454
sankhuwasabha			2	11:45AM		1	1	1	1	0	1	0	1	29.5	29.9	29.5	29.6	31.3	30.1	0.1	150	454
sarlahi			1	11:55AM		1	0	0	1	1	0	0	0	47.6	26.8	27	27.6	27.7	30.8	0.3	132	563
Pokhara			1	12:05PM		0	0	0	1	0	1	0	1	28.5	29.1	27.5	28.2	28.8	28.3	0.13	93	678
kathmandu			1	12:17PM		1	1	0	1	0	1	0	1	29.4	30.6	29.5	29.6	29.2	31.8	0.4	750	435
Pyuthan			1	12:30PM		1	1	1	1	0	1	0	1	29.4	30.1	29.5	29.1	30.3	29.4	0.35	270	570
kathmandu			2	12:35PM		1	0	1	1	0	1	0	1	28.5	29.4	29.6	28.8	29.3	29	0.25	75	471
Darchula			2	12:35PM		1	0	1	1	0	1	0	1	28.5	29.4	29.6	28.8	29.3	29	0.25	75	471
Bara			2	12:50PM		1	1	1	1	0	1	0	0	28.2	28.6	28.7	28.6	28.6	29.6	0.1	299	420
Sindupalchowk			2	12:50PM		1	1	1	1	0	1	0	0	28.2	28.6	28.7	28.6	28.6	29.6	0.1	299	420
kathmandu			1	12:54PM		0	0	0	0	0	0	0	0	28.6	30.8	28.1	30.8	29.4	29.6	0.1	245	580
janakpur			1	1:04PM		0	1	1	1	0	0	0	0	28.8	30.3	29.2	29.4	32.9	29.2	0.01	488	505
Chitwan			1	1:15PM		0	0	0	1	0	1	0	0	28.4	28.9	27.8	28.3	31	28.7	0.1	375	700
syangja			1	1:25PM		0	0	0	1	1	0	0	1	28.5	28.9	28.6	27.2	27.9	29.3	0.05	139	680
Biratnagar			1	1:40PM		0	0	0	1	1	1	0	1	27.8	29	28	20.3	30	27.5	0.05	312	631

Air temp. 1.1m(°C)	Air temp. 0.6m(°C)	Air temp. 0.1m(°C)	Humidity (%)	Globe temp. (°C)	set point	Thermal Environment				Humidity		Wind		II	Brightness		qualit	Produ		Sweat	ctivity and adjustmen		
						feel	prefer	accept	room t	feel	prefer	feel	prefer	therm	feel	prefer	y	ctivity	iredness	ing	Activit	behavi	Action
29.6	29.8	29.4	47	29.7		5	4	1	30	5	2	4	2	4	6	3	5	4	1	2	6	0	1,3
29.6	29.8	29.4	47	29.7		7	5	2	31	1	1	3	1	2	4	3	4	2	2	3	2	1	1,3,10
30.9	30.9	30.6	43	30.9		5	4	2	28	3	1	5	1	4	4	3	4	3	1	1	2	1	2
29.3	29	27.3	43	29.3		5	4	0	25	5	4	4	3	4	4	3	4	3	1	2	2	1	1,2
29.4	29.5	29.3	45	29.5		3	3	1	28	4	3	5	2	5	4	3	4	3	1	1	2	1	1,2,3
29.4	29.5	29.3	45	29.5		6	4	2	27	3	2	3	2	4	5	2	4	4	1	1	2	1	1,2
29.8	30.3	29.8	43	29.9		5	4	2	28	4	3	4	3	5	4	3	4	4	2	1	2	1	1
30.2	29.5	29.4	43	29.9		5	4	0	27	5	3	4	3	5	4	3	5	5	1	1	2	1	3,7,8
30.1	29.8	29.6	43	30		5	4	1	27	4	3	4	3	5	4	3	4	4	1	2	6	0	1
30.1	29.8	29.6	43	30		6	5	1	28	4	3	2	2	4	4	3	5	4	2	2	2	0	1
27.2	25.1	24.1	36	27	25	4	3	0	25	7	4	3	2	2	4	3	3	5	1	2	6	1	1,10
28.3	28.1	27.9	34	28.1		4	3	0	26	3	4	4	2	5	2	3	4	4	2	1	1	1	1,2,3,7
29.4	29.4	29	46	29.4		4	3	0	26	3	2	4	3	5	4	3	4	5	1	1	2	1	1,7
29.7	29.7	29.2	47	29.7		5	4	0	30	3	2	4	3	4	4	3	4	4	1	2	6	1	1
29.4	29.4	29.2	46	29.4		4	4	0	30	4	3	4	3	5	3	2	5	4	1	1	5	0	1
29.4	29.4	29.2	46	29.4		4	3	0	30	4	3	4	3	4	4	2	3	4	1	1	6	1	1
28.9	28.7	28.5	48	28.9		5	4	0	26	4	3	4	2	5	4	3	4	5	1	1	6	1	1,7
28.9	28.7	28.5	48	28.9		6	4	1	33	2	2	4	2	3	2	2	5	4	1	1	6	1	1
29.2	29	28.2	49	29.1		5	4	0	30	5	4	3	2	4	4	3	4	4	2	3	2	0	1
29.2	29	28.8	48	29.6		7	4	0	33	5	2	4	3	5	4	3	5	5	1	2	1	0	8
28.2	28	27.9	35	28.3		5	4	0	25	4	3	5	3	5	3	3	5	5	1	1	1	1	1
27.7	26.5	25.6	36	27.4	20	4	4	0	27	4	2	4	2	5	4	3	5	5	2	1	2	0	1
28	26.6	25.7	42	27.7	16	4	3	0	24	4	3	4	2	5	4	3	3	5	1	1	2	1	1

Annex-5: Data sheet of EVS

ANNEX-5: Questionnare survey of Expert Visa Services (EVS)

Office	Date	Name	Gender	Age	height	weight	exercise	ve of therm	ence of	ence of	sound	smell	often live	b posit	ob type	birthplace	Data No.	Floor
EXPERT	10/3/2023	Pujan Sangraula	2	2	3	4	7	1	2	2	2	2	2	3	5	Jhapa	A6	GF
		Sweta Shrestha	2	3	4	9		1	2	2	3	3	1	1	7	Kathmandu	A6	GF
		Seema Rauniyar	2	1	1	2	7	2	1	2	2	2	1	6	7	Kathmandu	A2	GF
		Sangeeta Joshi	2	4	4	9	7	3	2	2	3	1	1	3	7	New Delhi	A4	GF
		Sagar KC	1	3	8	11	9	2	1	3	3	3	1	6	7	Lalitpur	A3	GF
		Juna Pun	2	1	5	2		4	2	2	1	1	1	6	7	Bgalung	A5	GF
		Anuj Simkhada	1	2	7	5	10	3	2	3	2	1	1	6	7	Kathmandu	A2	GF
		Riya Chaudhary	2	2	3	2	7	3	1	1	3	3	2	6	6	Dang	A3	GF
		Samjhana Pokhrel	2	2	3	7	3	2	2	2	2	2	1	6	7	Arghakhachi	A3	GF
		Krishna Maharjan	1	2	8	9	2	1	1	2	2	2	1	6	7	Bhaktapur	A3	GF
		Payal Dhakal	2	2	7	2	7	3	2	2	3	4	1	6	7	Biratnagar	A4	GF
		Ganga Dahal	2	6	5	5	1	2	1	3	3	1	1	6	7	Kavre	A4	GF
		Umida Singh	2	1	6	4	7	1	2	3	2	2	2	6	7	Kathmandu	A4	GF
		Biraj Bhandari	1	3	5	6	2	2	2	2	2	1	1	6	7	Lalitpur	A4	GF
		Akriti Bimali	2	2	4	4	2	4	1	3	3	1	1	5	8	Jhapa	A3	GF
		Monu Thapa	2	2	5	8	30	2	2	2	3	3	1	6	8	Kathmandu	A3	GF
		Kabindra Mainali	1	3	5	8	7	2	1	1	3	2	1	5	7	Jhapa	A1	FF
		Merina Pradhan	2	1	2	3	1	4	2	2	2	2	1	5	7	Kathmandu	A5	GF
		Pooja Maharjan	2	2	4	4	2	4	1	3	3	1	1	5	8	Kritipur	A2	FF
		Bipul Gyawali	1	2	7	5	5	2	1	2	1	4	1	1	7	Dailekh	A2	FF
		Urmila Thapa	2	4	5	3	7hr	3	1	3	2	2	1	5	3	Lalitpur	A2	FF
		Neha Ghimira	2	2	5	5	7hr	1	1	2	3	3	2	5	9	Duwakot	A1	FF

			Adjustment status (0-Close, 1- Open)				Adjustment status (0. off, 1. On)				Surface temp. (℃)						ind spe	luminanc	CO_2	Air temp.	Air temp.
No. Sub.	Time	Output	Internal Door	Window	Natural vent	Blind	Cooling	Fan	Heating	Ceiling light	Ceiling	Floor	East	West	South	North	(m/s)	(lx)	(ppm)	1.1m(℃)	0.6m(℃)
2	11:30 AM		1	1	0	1	1	1	0	1	27.1	27.5	28.1	27.6	28.7	27.3	0.25	115	898	27.6	27.1
2	11:30 AM		1	1	0	1	1	1	0	1	27.1	27.5	28.1	27.6	28.7	27.3	0.25	115	898	27.6	27.1
5	11:45 AM		1	1	0	1	1	1	0	1	27.1	27.5	28.1	27.6	28.7	27.3	0.25	115	898	27.6	27.1
3	12:00 PM		1	0	0	1	0	0	0	0	27.4	27.1	28.3	27.4	27.9	27.3	0.05	55	664	28	27.8
5	12:15 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
2	12:30 PM		1	0	0	1	0	0	0	0	27.9	28.1	28.6	29.7	29.1	28.2	0.02	292	805	28.5	27.9
5	12:45 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
3	12:45 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
5	12:55 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
3	1:00 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
4	1:00 PM		1	0	0	1	0	0	0	0	27.4	27.1	28.3	27.4	27.9	27.3	0.05	55	664	28	27.8
4	1:15 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
4	1:15 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
3	1:25 PM		1	0	0	1	0	0	0	0	27.4	27.1	28.3	27.4	27.9	27.3	0.05	55	664	28	27.8
5	1:25 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
5	1:35 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
2	1:35 PM		1	0	0	1	1	0	0	0	34.5	26.6	27.8	28.1	28.8	27.8	0.15	480	864	27.8	26
	1:45 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
	1:45 PM		1	0	0	1	1	0	0	0	34.5	26.6	27.8	28.1	28.8	27.8	0.15	480	864	27.8	26
	1:55 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3
	2:00 PM		1	0	0	1	1	0	0	0	34.5	26.6	27.8	28.1	28.8	27.8	0.15	480	864	27.8	26
	2:00 PM		1	1	0	1	1	0	0	1	26.3	26.9	27.1	26.8	26.7	26.7	0.1	102	757	27.6	27.3

Air temp	Humidity	lobe tem	Set point	Thermal Environment				Humidity		Wind		II	Brightness		qualit	Produ		Sweat	ctivity and adjustmen		
0.1m(℃)	(%)	(℃)		feel	prefer	accept	room t	feel	prefer	feel	prefer	therm	feel	prefer	y	ctivity	iredne	ing	Activit	behavi	Action
27	39	27.6	25	6	4	1	29	6	4	4	1	3	4	2	4	3	3	3	2	1	1,7,10,
27	39	27.6	25	6	4	1	6	5	4	4	3	3	6	2	5	4	2	3	2	1	1,2,3,4
27	39	27.6	25	6	4	1	29	6	4	4	1	3	4	2	4	3	3	3	2	1	1,7,10,
27.1	39	27.9		4	3	0	29	4	3	3	3	5	4	3	4	5	1	1	2	0	6
27	41	27.4	25	6	4	1	25	3	2	3	2	3	5	3	3	3	1	2	6	0	1
27.5	39	28.4		6	4	0	24	3	3	4	3	3	6	3	4	4	3	1	5	0	4,10,1
27	41	27.4	25	5	4	1	20	4	3	2	2	4	4	3	4	5	2	3	5	1	10,13
27	41	27.4	25	5	4	1	20	4	3	2	2	4	4	3	4	5	2	3	5	1	10,13
27	41	27.4	25	5	3	0	23	4	3	4	2	5	4	3	4	4	1	2	3	0	1,2
27	41	27.4	25	6	3	0	19	5	4	3	2	3	4	3	4	5	3	2	2	0	2,7
27.1	39	27.9		7	4	1	3	3	3	3	2	4	4	3	3	4	3	3	2	0	2,4,9,1
27	41	27.4	25	5	4	1	20	4	3	2	2	4	4	3	4	5	2	3	5	1	10,13
27	41	27.4	25	5	3	0	23	4	3	4	2	5	4	3	4	4	1	2	3	0	1,2
27.1	39	27.9		6	4	0	29	5	3	4	3	5	4	3	5	4	3	2	1	1	1,2,4,8
27	41	27.4	25	4	3	0	29	5	3	2	2	3	5	4	3	3	2	2	1	0	2,10,1
27	41	27.4	25	5	4	1	29	5	4	5	4	4	5	2	4	4	3	2	2	0	8,10
25.9	29	27.9	18	5	4	0	30	3	3	3	2	5	6	3	4	3	2	2	2	0	10
27	41	27.4	25	6	3	0	19	5	4	3	2	3	4	3	4	5	3	2	2	0	2,7
25.9	29	27.9	18	5	4	0	30	3	3	3	2	5	6	3	4	3	2	2	2	0	10
27	41	27.4	25	6	3	0	19	5	4	3	2	3	4	3	4	5	3	2	2	0	2,7
25.9	29	27.9	18	5	4	0	30	3	3	3	2	5	6	3	4	3	2	2	2	0	10
27	41	27.4	25	6	3	0	19	5	4	3	2	3	4	3	4	5	3	2	2	0	2,7

Annex-6: Data sheet of HECAF

ANNEX-6:Questionnaire survey of HECAF 360

Office	Date	Instrument No	Name	Gender	Age	height	weight	exercise	ve of therm	ence of	ence of	sound	smell	often live	b posit	job type	birthplace	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Adjustment status (0: Close, 1: Open) [illegible]	[illegible]	[illegible]	[illegible]
HECAF 360	6272023	1	Sarita Goja	2	2	4	4	15hr	1	2	2	2	2	1	5	2	Bhaktapur		GF	3	12:30PM		1	1	0	1
		1	Sharmila Khanal	2	2	2	3	21hr	1	1	1	2	1	1	5	2	Rautahat		GF	3	12:30PM		1	1	0	1
		1	Sujata Awal	2	3	5	6	14hr	4	1	2	3	3	1	5	2	Bhaktapur		GF	3	12:30PM		1	1	0	1
		2	Rabina Shrestha	2	2	5	4	7hr	4	1	1	2	2	1	5	2	Kathmandu		GF	1	12:50PM		1	1	0	1
		3	Shreya Shrestha	2	2	3	6	12hr	4	1	2	1	1	2	5	7	Kathmandu		GF	2	1:10PM		1	1	0	1
		3	Pragyesh Ratna Bajracha	1	1	8	9	10hr	1	1	1	3	3	1	6	3	Kathmandu		GF	2	1:10PM		1	1	0	1
		4	Sunita Budhathoki	2	2	5	2	7hr	2	1	3	1	2	1	5	2	Ramechhap		GF	1	1:40PM		1	0	1	1
		5	Bimala Dumaru	2	3	1	5	21hr	2	1	2	2	2	1	6	2	Bhaktapur		GF	2	1:50PM		1	0	1	1
		5	Shrawasti Karmacharya	2	4	3	5	14hr	1	1	2	3	3	2	1	2	Bhaktapur		GF	2	1:50PM		1	0	1	1

Adjustment status(0: off, 1: On) [illegible]	[illegible]	[illegible]	[illegible]	Surface temp (°C) [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Wind speed (m/s)	Illuminance (lx)	CO2 (ppm)	Air temp [illegible] (°C)	Air temp [illegible] (°C)	Air temp [illegible] (°C)	Humidity (%)	Globe temp (°C)	Dew point	Thermal Environment feel	prefer	accept	room t	Humidity feel	prefer	Wind feel	prefer	[illegible] therm	Brightness feel	prefer	quality	Productivity	tiredness	Sweating
0	1	0	1	28	28.3	28.1	27.8	28.3	28.1	0.2	240	612	28.3	28.3	28.1	68	28.3		5	4	1	28	5	4	1	1	3	4	3	3	3	1	1
0	1	0	1	28	28.3	28.1	27.8	28.3	28.1	0.2	240	612	28.3	28.3	28.1	68	28.3		4	3	0	25	2	3	4	2	5	4	3	2	2	2	1
0	1	0	1	28	28.3	28.1	27.8	28.3	28.1	0.2	240	612	28.3	28.3	28.1	68	28.3		5	4	0	35	5	3	1	1	3	3	2	2	3	2	1
0	1	0	1	28.6	28.3	28.7	28.2	28.4	28.6	0.3	230	655	28.6	285	28.4	66	28.5		6	4	1	24	4	2	1	1	3	4	3	3	3	2	2
0	1	0	1	28.5	28.6	29	29	28	28.5	0.4	125	690	28.7	28.5	28.3	65	28.9		5	4	1	28	3	2	2	2	3	4	3	3	3	3	2
0	1	0	1	28.5	28.6	29	29	28	28.5	0.4	125	690	28.7	28.5	28.3	65	28.9		5	4	0	25	4	2	1	1	5	7	3	5	5	1	2
0	0	0	0	28.3	28.1	27.4	27.6	27.5	28.4	0.1	270	438	28	27.2	26.7	65	28		5	4	0	23	5	2	3	2	2	4	3	4	4	1	1
0	0	0	1	28	27.5	27.5	27.7	27.6	27.9	0.02	80	551	27.8	27.6	27.3	66	27.8		6	5	0	28	4	3	2	1	4	5	3	3	3	3	2
0	0	0	1	28	27.5	27.5	27.7	27.6	27.9	0.02	80	551	27.8	27.6	27.3	66	27.8		5	4	0	30	5	4	1	1	4	6	3	5	4	2	2

Annex-7: Data sheet of IS

ANNEX-7: Questionnare Survey of AKG

Office	Date	Instrument No	Name	Gender	Age	height	weight	exercise	ve of therm	ence of	ence of	sound	smell	often live	b posit	job type
AKG	6132023															
		1	Dipak Shrestha	1	1	7	7	14hr	2	1	2	2	3	1	5	7
		1	Krishna Regmi	1	1	7	11	7 hr	4	1	3	3	3	1	5	7
		1	Sagar Adhikari	1	1	7	8	12hr	4	1	2	2	2	1	5	7
		1	Priya Thapa	2	1	6	5	3.5hr	2	2	2	3	1	1	6	7
		1	Aanchal Kumari Sah	2	1	3	1	3hr	2	1	1	2	2	1	5	7
		1	Bibek Suyal	1	1	5	3	5hr	2	1	2	3	2	1	5	7
		1	Susmita Tamang	2	1	2	3	1	4	2	2	2	2	1	5	7
		1	Adish Dhakal	1	1	1	1	1	1	1	1	1	1	1	1	1
		1	Darba Sing Poudel	1	1	6	5	8	2	2	2	2	2	1	5	7
		2	Achyut Kumar Ghimire	1	3	5	6	10.5hr	4	2	2	2	2	1	1	7
		3	Raja Ram Kadel	1	3	6	7	8hr	2	1	1	3	3	1	6	9
		4	Sriya Bhurtel	2	2	3	3	3.5hr	2	2	2	4	3	2	5	7
		5	Shambhu Khadkha	1	1	6	4	12hr	2	2	2	1	2	1	5	9
		5	Roshan Neupane	1	1	5	7	7hr	2	3	3	3	3	1	5	9
		5	Bikram Kumar Baishya	1	1	5	5	3hr	2	2	2	3	3	1	5	2
		6	Surendra Pokharel	1	2	8	6	7	3	1	1	2	1	1	1	Directo
		6	Dipika Budal	2	1	4	4	7hr	2	1	1	2	2	1	5	2
		6	Bibek Kharel	1	3	5	7	3hr	1	1	1	2	2	1	5	2

birthplace	Data No.	Floor	No. Sub.	Time	Depart.	Adjustment status (0=Close, 1= Open) Internal Door	Window	Natural vent	Blind	Adjustment status (0. off, 1. On) Cooling	Fan	Heating	Ceiling light	Surface temp. (°C) Ceiling	Floor	East	West	South	North	wind speed (m/s)	Illuminance (lx)
Dhading		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Kathmandu		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Lamjung		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
India		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Birgunj		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Dhading		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Kathmandu		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Itahari		SF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Dhankuta		FF	9	11:56AM		1	1	1	1	0	1	0	1	29.6	30.1	30.1	29.9	30.6	29.9	1.3	200
Ramechhap		FF	1	12:18PM		1	1	1	1	0	1	0	1	31.2	30.2	30.1	30	30.3	29.6	0.75	75
		FF	1	12:30PM		1	1	1	1	0	1	0	1	30	30.1	30.3	30.2	31.9	30.3	1	268
Lalitpur		FF	1	12:40PM		1	0	0	0	0	1	0	1	29.7	29.8	29.6	29.9	29.9	29.5	0.8	50
Dolakha		SF	3	12:59PM		1	1	0	1	0	1	0	0	29.9	30	30.2	29.9	30.1	30.4	0.35	400
Dolakha		SF	3	12:59PM		1	1	0	1	0	1	0	0	29.9	30	30.2	29.9	30.1	30.4	0.35	400
Bhairahawa		SF	3	12:59PM		1	1	0	1	0	1	0	0	29.9	30	30.2	29.9	30.1	30.4	0.35	400
Chitwan		SF	3	1:10PM		1	1	1	1	0	1	0	0	29.9	30.1	30.3	30.2	33.5	30.5	0.65	540
Kanchanpur		SF	3	1:10PM		1	1	1	1	0	1	0	0	29.9	30.1	30.3	30.2	33.5	30.5	0.65	540
Kathmandu		SF	3	1:10PM		1	1	1	1	0	1	0	0	29.9	30.1	30.3	30.2	33.5	30.5	0.65	540

CO_2 (ppm)	Air temp. 1.1m(°C)	Air temp. 0.6m(°C)	Air temp. 0.1m(°C)	Humidity (%)	Globe temp (°C)	set point	Thermal Environment feel	prefer	accept	room t	Humidity feel	prefer	Wind feel	prefer	Il therm	Brightness feel	prefer	qualit y	Produ ctivity	iredne	Sweat ing
670	30.3	30.6	30.3	52	30.4		5	2	1	27	3	4	3	2	3	3	3	4	4	2	2
670	30.3	30.6	30.3	52	30.4		6	4	1	30	2	1	3	2	3	3	2	1	2	3	3
670	30.3	30.6	30.3	52	30.4		3	3	0	20	4	3	3	2	4	6	2	4	4	1	1
670	30.3	30.6	30.3	52	30.4		5	4	0	26	4	2	2	1	4	4	3	4	4	2	2
670	30.3	30.6	30.3	52	30.4		5	4	0	27	4	3	4	2	3	4	4	4	4	3	3
670	30.3	30.6	30.3	52	30.4		6	4	1	29	5	2	4	4	2	4	2	2	3	3	2
670	30.3	30.6	30.3	52	30.4		4	4	0	27	4	3	3	2	4	5	4	5	5	3	3
670	30.3	30.6	30.3	52	30.4		4	3	0	28	4	3	3	4	5	4	3	5	4	2	1
670	30.3	30.6	30.3	52	30.4		5	3	1	28	3	3	3	2	4	3	2	4	5	2	2
493	30.3	30.5	30.4	49	30.5		5	3	0	35	4	3	3	1	4	4	3	5	5	1	3
462	30.9	31	31	48	31		6	4	0	28	4	3	5	2	4	6	3	5	4	1	1
551	30.2	30	30.2	51	30.3		7	5	2	25	4	4	4	3	5	4	3	1	3	4	4
567	30.3	30.5	30.4	53	30.4		5	2	0	28	3	2	3	2	4	3	2	4	4	1	1
567	30.3	30.5	30.4	53	30.4		5	4	1	22	2	2	1	1	3	5	4	1	3	3	2
567	30.3	30.5	30.4	53	30.4		4	3	0	30	3	2	3	2	4	5	3	4	3	4	1
475	30.7	31	306	50	30.9		5	4	0	28	5	2	4	3	4	4	2	4	5	1	2
475	30.7	31	306	50	30.9		5	4	0	28	4	3	5	2	4	4	2	3	4	1	1
475	30.7	31	306	50	30.9		5	4	1	30	4	3	4	3	3	4	3	4	4	1	2

Annex-8: Data sheet of IS

ANNEX-8: Questionnare Survey of Informative Solutions(IS)

Data No.	Floor	No. Sub.	Time	Depart.	Adjustment status (0=Close, 1= Open) Internal Door	Window	Natural vent	Blind	Adjustment status (0. off, 1. On) Cooling	Fan	Heating	Ceiling light	Surface temp. (°C) Ceiling	Floor	East	West	South	North	wind speed (m/s)	Illuminance (lx)	CO_2 (ppm)
	GF	7	11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF		11:40AM		1	1	0	1	0	1	0	0	26.8	27.6	27.1	26.9	27.6	27.9	0.15	304	794
	GF	5	11:50AM		1	1	1	1	0	1	0	1	25.1	24.8	26	24.7	24.9	25.6	0.15	99	891
	GF		11:50AM		1	1	1	1	0	1	0	1	25.1	24.8	26	24.7	24.9	25.6	0.15	99	891
	GF		11:50AM		1	1	1	1	0	1	0	1	25.1	24.8	26	24.7	24.9	25.6	0.15	99	891
	GF		11:50AM		1	1	1	1	0	1	0	1	25.1	24.8	26	24.7	24.9	25.6	0.15	99	891
	GF		11:50AM		1	1	1	1	0	1	0	1	25.1	24.8	26	24.7	24.9	25.6	0.15	99	891

Air temp.	Air temp.	Air temp	Humidity	Globe temp	set point	Thermal Environment				Humidity		Wind		ll	Brightness		qualit	Produ		Sweat
1.1m(℃)	0.6m(℃)	0.1m(℃)	(%)	(℃)		feel	prefer	accept	room t	feel	prefer	feel	prefer	therm	feel	prefer	y	ctivity	iredness	ing
28.6	29.1	28.5	62	28.4		4	4	0	25	4	3	3	2	4	4	3	5	5	1	1
28.6	29.1	28.5	62	28.4		5	5	1	28	5	4	2	2	4	4	3	4	4	2	1
28.6	29.1	28.5	62	28.4		4	4	0	25	5	3	3	2	4	6	5	4	3	1	1
28.6	29.1	28.5	62	28.4		4	3	1	26	4	3	5	3	4	4	3	4	4	1	2
28.6	29.1	28.5	62	28.4		4	3	0	20	4	3	4	2	5	3	2	5	5	1	2
28.6	29.1	28.5	62	28.4		4	4	0	24	4	2	4	2	5	3	3	5	5	2	2
28.6	29.1	28.5	62	28.4		3	2	1	20	4	3	5	4	4	4	4	4	5	5	1
27.5	27.4	27.4	66	27.6		3	2	1	22	4	3	4	3	4	4	3	4	5	1	1
27.5	27.4	27.4	66	27.6		4	3	0	28	3	3	5	3	3	4	3	2	5	2	1
27.5	27.4	27.4	66	27.6		5	4	0	24	4	3	4	3	5	6	3	4	5	2	1
27.5	27.4	27.4	66	27.6		3	3	0	24	4	2	4	2	5	4	3	4	5	2	2
27.5	27.4	27.4	66	27.6		6	2	1	27	1	5	4	5	4	4	6	34	5	2	2

Annex-9: Data sheet of CIS

ANNEX-9: Questionnare Survey of CIS

Office	Date	Instrument No	Name	Gender	Age	height	weight	exercise	ve of therm	ence of	ence of	sound	smell	often live	b posit	ob type
CIS	6302023															
		1	Moon Thapa	2	2	7	6	3.5hr	2	1	3	3	1	1	6	2
		1	Pooja Manandhar	2	2	6	3	21hr	1	2	3	3	3	1	6	4
		1	Shristi Neupane	2	2	4	1	14hr	4	2	2	2	2	1	5	9
		1	Rakshya Adhikari	2	2	4	3	7hr	3	1	1	3	2	1	3	2
		1	Ramesh Subedi	1	4	7	4	8hr	4	2	3	3	2	1	6	9
		1	Suvekshya Sitaula	2	2	5	5	7hr	1	1	2	3	3	2	5	9
		1	Sajina Manandhar	2	4	5	4	7hr	3	3	1	2	2	1	6	3
		2	Kriti Yadav	2	1	5	4	9hr	4	2	2	3	2	1	6	9
		2	Saugat Poudel	1	1	6	4	7hr	2	2	2	2	2	1	6	6
		3	Jitendra Kumar Das	1	2	7	7	7hr	2	1	1	1	1	1	6	2
		3	Dina Shakya	2	4	5	3	7hr	3	1	3	2	2	1	5	3
		3	Nitish Sah	1	1	6	4	3.5hr	2	1	1	2	2	1	5	3
		3	Ritesh Gupta	1	2	6	4	7hr	1	1	1	3	2	1	5	3
		3	Ravi Kumar Sah	1	3	7	6	10.5hr	1	2	2	3	1	1	6	3
		4	Rashmi Shakya	2	4	5	5	10.5hr	2	3	3	3	3	1	5	7

birthplace						Adjustment status(0-Close, 1- Open)				Adjustment status(0. off, 1. On)				wind speed	Illuminance	CO_2	Air temp.	Air temp.	Air temp	Humidity	Globe temp
	Data No.	Floor	No. Sub.	Time	Depart.	Internal Door	Window	Natural vent	Blind	Ceiling	Fan	Heating	Ceiling light	(m/s)	(lx)	(ppm)	1.1m(℃)	0.6m(℃)	0.1m(℃)	(%)	(℃)
Kathamndu		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Kathamndu		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Syangja		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Syangja		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Ramechhap		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Duwakot		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Kathamndu		GF	7	2:00PM		1	1	0	1	0	0	0	1	0.02	70	570	26.7	26.5	25.9	64	26.6
Biratnagar		GF	2	2:20PM		1	1	0	1	0	0	0	1	0.15	40	660	26.7	26.2	25.4	65	26.7
Rupakot		GF	2	2:20PM		1	1	0	1	0	0	0	1	0.15	40	660	26.7	26.2	25.4	65	26.7
		FF	5	2:30PM		1	1	0	1	0	0	0	1	0.03	90	635	27.5	27.2	26.6	62	27.4
Lalitpur		FF	5	2:30PM		1	1	0	1	0	0	0	1	0.03	90	635	27.5	27.2	26.6	62	27.4
Siraha		FF	5	2:30PM		1	1	0	1	0	0	0	1	0.03	90	635	27.5	27.2	26.6	62	27.4
Rajbiraj		FF	5	2:30PM		1	1	0	1	0	0	0	1	0.03	90	635	27.5	27.2	26.6	62	27.4
Siraha		FF	5	2:30PM		1	1	0	1	0	0	0	1	0.03	90	635	27.5	27.2	26.6	62	27.4
Lalitpur		FF	1	3:00PM		1	1	1	1	0	0	0	0	0.25	2.4	500	26.5	26.4	25.9	63	26.6

Thermal Environment				Humidity		Wind		ll	Brightness		qualit y	Produ ctivity		Sweat ing	ctivity and adjustmen			window open	Clothing insulation
feel	prefer	accept	room t	feel	prefer	feel	prefer	therm	feel	prefer			iredness		Activit	behavi	Action		
3	3	0	19	4	3	5	3	5	4	3	3	3	4	1	2	1	3,8	2,7	0.16
4	3	1	24	3	3	4	3	5	4	3	4	5	2	1	2	0	6,8,15	2,12,13,18	0.42
6	4	0	28	3	3	4	3	4	3	2	4	4	2	1	2	0	8	2,4	0.24
4	2	0	24	4	3	3	4	5	2	5	4	4	3	1	2	1	1,2,8,1	3	0.22
5	4	1	24	5	3	4	4	4	5	4	4	4	2	2	5	1	16	11	0.74
4	3	0	24	5	4	2	2	5	4	2	3	5	1	1	1	0	2	7,12	0.61
4	3	0	25	4	3	4	3	5	4	3	5	5	2	1	2	0	2	12	0.53
4	2	0	28	4	3	4	3	5	6	2	5	5	1	2	2	0	2	2	0.3
4	3	0	23	4	3	2	2	5	4	3	3	5	1	1	1	1	16	2	0.4
5	4	0	26	2	2	1	2	4	3	2	3	3	2	3	2	1	7	2,11,15,16	0.37
5	4	0	27	5	3	3	2	3	4	3	4	4	1	1	2	0	7,12,1	11	0.35
5	4	1	25	5	2	1	2	3	6	3	5	3	2	1	2	0	7,14	2,4,5	0.27
5	4	1	26	5	2	2	2	3	6	3	4	4	1	1	2	0	1,4,7,8	2,5,13	0.3
6	2	2	32	2	2	2	4	3	3	2	2	3	1	1	2	1	1,2,8,1	2,7	0.63
4	3	0	26	4	3	3	3	5	6	3	4	5	1	1	2	0	8	14	0.27

Annex-10: Arrangement of instrument during surveyed period

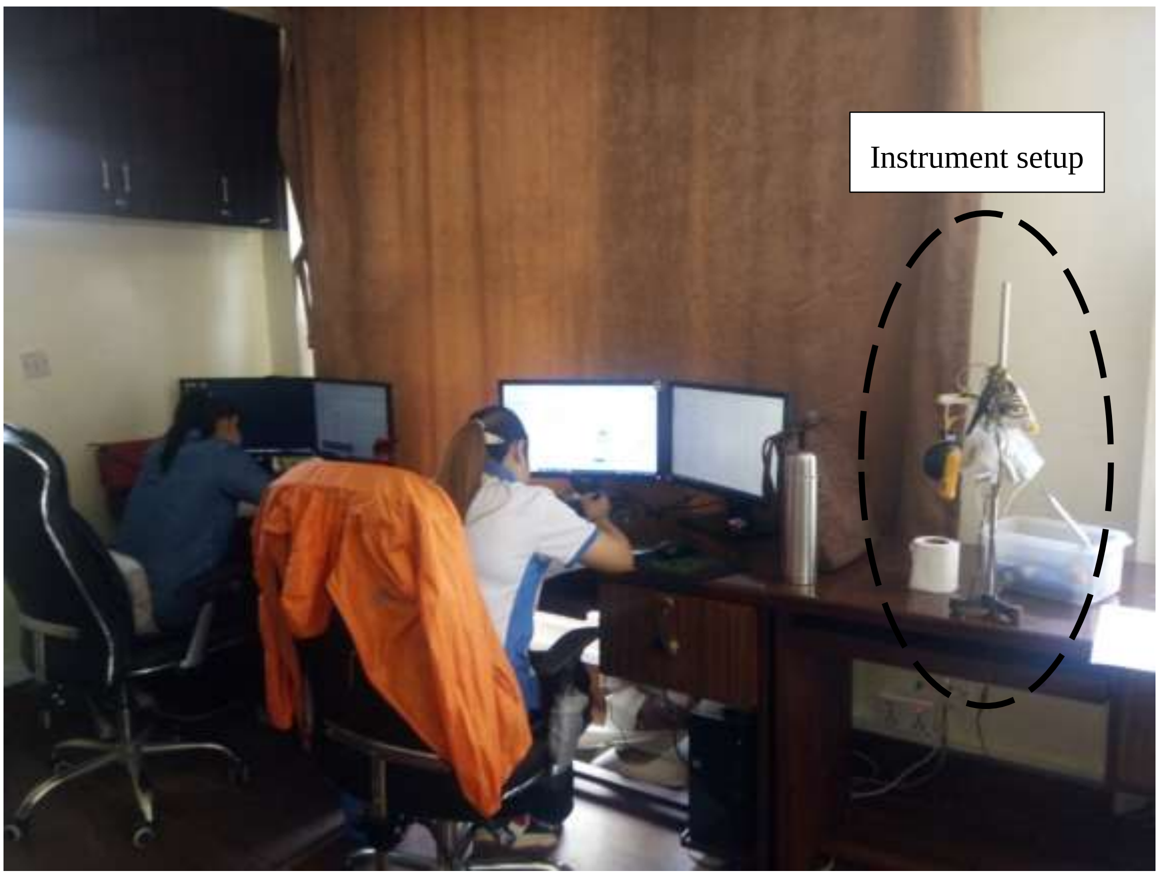


Figure 74: Digital Instrument set up and questionnaire survey

Annex-11: Abstract of Accepted Article in 14th IOE Graduate Conference

ANALYSIS OF THERMAL COMFORT AND INDOOR AIR QUALITY (IAQ) IN FREE RUNNING (FR) OFFICE BUILDINGS DURING SUMMER SEASON: A CASE STUDY OF KATHMANDU VALLEY

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ABSTRACT

Due mostly to adult work requirements, youngsters spend 75% of their time indoors, and adults have spent up to 90% of their time indoors within the past fifty years. In office buildings, indoor environmental quality (thermal comfort and indoor air quality) significantly influences occupants' comfort and productivity; hence, for occupants to work effectively, a productive and comfortable working environment is a crucial and fundamental requirement. The scientific and technical community concerned with building analysis has been increasingly interested in thermal comfort and indoor air quality issues, as seen by the most recent revision to Directive 2018/2001/EU on the energy performance of buildings. This study will help to report the thermal environment conditions of free-running office buildings and thermal perception of office employee during work. The results of this field study depicts thermal comfort and indoor air quality (IAQ), based on investigations in free-running (FR) office buildings inside Kathmandu Valley. The field study was conducted through physical parameter monitoring and survey questionnaires during the summer season (June-July, 2023). Comfort temperature is determined using Griffiths' method and found to be 27.21 °C during the summer season in free-running buildings inside Kathmandu valley. In this field survey, the indoor thermal comfort temperature ranges from 21 °C to 32.8 °C. Out of total votes, 84% of office employees voted that the thermal sensation in their office is neutral zone and revealed the occupants' tolerance to CO_2 exposure, validating the findings of previous studies. Furthermore, in free-running mode, CO_2 concentration limitations were significantly within the limit as per the ASHRAE 62 guideline indicating, good indoor air quality, sufficient ventilation and the well-being of the occupants.

Key words: Thermal Comfort survey, Comfort temperature, free running (FR), Indoor air quality (IAQ), CO_2 concentration level

Annex-12: Poster presentation at 14TH IOE Graduate Conference

Annex-13: Certificate of participation in IOE Graduate Conference

IOE Graduate Conference

Certificate of Participation

This certificate is awarded to

Anju Rai

in recognition of an invaluable contribution as

Poster Presenter

at the 14th IOE Graduate Conference

Organized by Tribhuvan University, IOE, Curriculum and Instructional Material Development Unit (CIMDU) held from November 29 to December 1, 2023 at Pulchowk Campus, Lalitpur, Nepal.

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Annex-14: Thesis Report Plagiarism check

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