EVALUATION OF COMBINED COMFORT INDEX AND ENERGY CONSERVATION OF INSTITUTIONAL BUILDINGS USING MULTI-CRITERIA DECISION-MAKING

Submitted in partial fulfilment of the requirements
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CIVIL ENGINEERING

By

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Dedicated to ***Late KanakaRatnam Yarramsetty*** *(my mother), and*

to my ***God father Er. Ashok Kumar Jain****, Sree Krishna Institue,*

Adambakkam, Chennai.

NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL

CERTIFICATE

This is to certify that the thesis entitled **"EVALUATION OF COMBINED COMFORT INDEX AND ENERGY CONSERVATION OF INSTITUTIONAL BUILDINGS USING MULTI-CRITERIA DECISION-MAKING"** being submitted by **Mr. YARRAMSETTY SUBBARAO** for the award of the degree of **DOCTOR OF PHILOSOPHY** in the Department of Civil Engineering, National Institute of Technology, Warangal, is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for the award of any degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled **“Evaluation of Combined Comfort Index and Energy Conservation of Institutional Buildings using Multi-Criteria Decision-Making”** is a bonafide work done by me under the supervision of Prof. P. Anand Raj & Dr. M.V.N. Sivakumar and is not submitted elsewhere for the award of any degree.

I declare that this written submission represented my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact / source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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ABSTRACT

This study explores the multifaceted factors influencing national development, emphasizing the pivotal role of quality education and university infrastructure. It introduces an innovative approach to identify and evaluate Key Performance Indicators for institutional buildings, blending global insights with local contexts. The study underscores the critical need for energy optimization due to accelerating urbanization, advocating for building orientation, envelope design, and the development of a Combined Comfort Index. Despite the urgency of this issue, there is a dearth of extensive research, making this study particularly relevant and timely

To fortify the validity of this research, a survey is deployed among professionals representing diverse fields, each possessing a wealth of experience exceeding 15 years. The study's credibility is further underscored by a robust Cronbach's alpha value surpassing 0.8, affirming the reliability of the collected data. Employing the Fuzzy Analytic Hierarchy Process, the research unravels the relative significance of key performance indicators, with a notable emphasis on Thermal, Illumination, and Aural Conditions as pivotal contributors to overall user comfort. The study extends its gaze to encompass additional indicators such as air quality, user satisfaction, and cleanliness, projecting implications that reverberate on an international scale, casting a profound influence on both design principles and Facility Management practices. Proposing the prioritization of Thermal, Illumination, and Aural Condition during the initial design phases aligns seamlessly with the globally resonant mantra of user-centric design, empowering facility personnel to promptly address crucial indicators, thereby enhancing energy efficiency and elevating the overall user experience. Shifting the focus to the realm of educational infrastructure, this research intricately explores the dynamic relationship between a country's developmental status and the standards of its educational institutions. Introducing a ground breaking metric, the study seamlessly integrates parameters such as thermal, acoustic, and visual elements to holistically assess environmental comfort. The canvas for this exploration is set at the National Institute of Technology Warangal campus in India, where a meticulous combination of objective measurements and subjective surveys weaves a rich tapestry of insights. Three singular measures— a Thermo-hygrometric Index, an Audio comfort Index and a Visual Illumination Index — are introduced, each normalized within a 0-1 range denoting comfort and discomfort conditions. This study maintained a dedicated focus on single sharing rooms to ensure coherence and uniformity within the analytical framework. A total

comfort index for each room is established by assigning appropriate weights to the three factors, culminating in an overall comfort rating of 0.64 out of 1.

Transitioning to the arena of sustainable design, the study offers a nuanced examination of the influence of building orientation on energy savings. Drawing inspiration from a multi-storied residential house in Afghanistan as a case study, the research unfolds in two distinct steps. First, a meticulous 3D model of the building is crafted, and second, energy scenarios for different orientations are scrutinized through simulations. The energy analysis encompasses 24 test scenarios, each representing a 15° rotation in building orientation, with the actual orientation as the reference. The findings resonate with financial implications, revealing potential savings of $1393 per annum when opting for the most favourable orientation (+ 315° clockwise) compared to the least favourable (+ 165° clockwise) from the reference axis. The simulated electricity demand is further validated against actual bills, demonstrating a close correspondence with a marginal difference of 2.65%.

Concluding this expansive exploration is a foray into predictive modelling, leveraging the power of a Multi-Layer Perceptron model. Employing a rigorous training and testing regimen, the study utilizes 75% of observed data for model training and 25% for testing. The Multi-Layer Perceptron model consistently demonstrates high accuracy in predicting and reconstructing a Combined Comfort Index, unveiling valuable insights into the interplay between predictors Thermal, Visual, Acoustical indexes and the target variable Combined Comfort Index. Individual parametric data reconstruction adds an additional layer of depth to the evaluation, providing a nuanced understanding of the model's conformity with actual data.

The index aids in assessing and enhancing comfort in India's diverse climatic zones, including hot and dry, warm and humid, composite, temperate, and cold zones as per NBC 2016. It enables design adaptations tailored to each zone, emphasizing strategies like natural ventilation and shading in hot and dry areas, and humidity control in warm and humid regions. Additionally, the index supports energy-efficient building designs by optimizing insulation, glazing, and shading based on specific climatic conditions. Architects, engineers, and policymakers can utilize the index to ensure compliance with NBC 2016's thermal comfort requirements across India's varied climatic zones.

This research, therefore, transcends the boundaries of conventional studies, not only advancing the realm of institutional building performance evaluation but also laying a robust foundation for further investigations in the domains of sustainable design and predictive modelling. It stands as a testament to the interconnectedness of diverse factors influencing the educational landscape and the built environment, resonating on a global scale and beckoning future explorations in these critical domains.

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ACRONYMS

GHG	Greenhouse gas
IEQ	Indoor Environmental Quality
5R's	Reduce, Replace, Reuse, Repair, and Renovate
AEC	Architecture, Engineering and Construction
AECOO	Architectural, Engineering, Construction, Owner and Operator
AHP	Analytic Hierarchy Process
AI	Acoustic comfort Index
AI	Artificial Intelligence
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
ANN	Artificial Neural Networks
ANN MLP	Artificial Neural Network Multilayer Perceptron
AS	Air Speed
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
AT	Air Temperature
AW	Away from Window
BEST-D	Building Energy Simulation Tools - Directory
BIM	Building Information Modelling
BN	Bayes Networks
BO	Building Orientation
BPNN	Back-Propagation Neural Network
BREEAM	Building Research Establishment Environmental Assessment Method
C	Core
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CC	Correlation Coefficient
CCI	Combined Comfort Index
CD	Computational Design
CI	Clothing Insulation
CMC	Cement mortar + carpet
CMU	Concrete masonry unit
CP	Cement Plaster
CR	Center of the Room

dB	Decibels
dBA	A-weighted Decibels
DoE	Department of Energy
DT	Decision Trees
ES	Exterior side
FAHP	Fuzzy Analytic Hierarchy Process
FFNN	Feed-Forward Neural Network
FL	Floor
FM	Facility Management
FSDS	Federal Sustainable Development Strategy
gbXML	Green Building XML
GCI	Global Comfort Index
GD	Generative Design
GIS	Geographical Information System
GLM	General Linear Model
GP	Gypsum Plaster
GRIHA	Green Rating for Integrated Habitat Assessment
GWP	Global Warming Potential
HRIDAY	Heritage Cities Development and Augmentation Yojana
HVAC	Heating, ventilation, and air conditioning
IAG	Annoying Glares Index
IAL	Artificial Light Index
IAQ	Indoor Air Quality
IBM SPSS	International Business Machines Statistical Package for the Social Sciences
IBPSA	International Building Performance Simulation Association
IBPT	International Building Physics Toolbox
ICN	Corridor Noise Index
IDN	Daily Noise Index
IIH	Internal Heat Index
IIN	Internal Noise Index
INH	Natural Heat Index
INL	Natural Light Index

INR	Reflection Light Index
ION	Occasional Noise Index
IoT	Internet of Things
IPMV	Predicted Mean Vote Index
IRN	Rest Noise Index
IS	Interior side
ISN	Study Noise Index
KMBR	Kerala Municipal Building Rules
KPIs	Key Performance Indicators
LC	Life Cycle
LDC	Least Developed Countries
LEED	Leadership in Energy and Environmental Design
LP	Lime plaster
MCDM	Multi-Criteria Decision Making
ML	Machine Learning
MLP	Multi-Layer Perceptron
MP	Mud plaster
MPC	Mud plaster + Carpet
MPP	Mud plaster + plastic sheet
MR	Metabolic Rate
MRT	Mean Radiant Temperature
MSD	Mean Square Deviation
MSE	Mean Squared Error
NBS	National Building Specification
NC	Near to the Corridor
NECB	National Energy Code for Buildings
NITW	National Institute of Technology Warangal
NNARX	Neural Network Auto Regression with eXogenous
nZEBs	nearly Zero Energy Buildings
NSE	Nash-Sutcliffe Efficiency
NW	Near to the Window
NZCBs	Net Zero Carbon Buildings

NZEBs	Net Zero Energy Buildings
O&M	Operation and Maintenance
O.Q	Overall Questions
OECD	Organization for Economic Co-operation and Development
PDVC	Percentage of Dissatisfaction in Visual Comfort
PIs	Performance Indicators
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PTC	Parametric Technology Corporation
RBFN	Radial Basis Function Networks
RFs	Random Forests
RH	Relative Humidity
RMSD	Root Mean Square Deviation
S.Q	Specific/Single Question
SB-Tool	Sustainable Building Tool
SDGB	Sustainable Development of Green Building
SDGs	Sustainable Development Goals
SSD	Sum of Squares of Deviation
SVM	Support Vector Machines
TI	Thermal comfort Index
TOPSIS	Order of Preference by Similarity to Ideal Solution
TPL	Textual Programming Languages
TSV	Thermal Sensation Vote
UN	United Nations
VI	Illumination Index
VPL	Visual Programming Language
WCED	World Commission on Environment and Development
WCM	Water proof + Cement mortar
WRI	World Resources Institute
WSN	Wireless Sensor Networks
WWR	Window-to-Wall Ratio
ZEBs	Zero Energy Buildings

NOMENCLATURE

A_{fn}	Afghan Afghani currency (؋)
Pi	Closeness Ratio
CI	Consistency index
CR	Consistency ratio
α	Cronbach's alpha
ε	Error
S_n^+	Euclidean distance
C_N	Geometric mean
a_k	hidden neuron
x	input variable
r_{ai}	Normalization of Performance Scores
z_k	Output for the hidden neuron
y_j	Output neuron
r	Pearson's correlation coefficient
y	Target variable
thm	Therm
ψ	transfer function
$vn-$	virtual anti-ideal alternative
$vn+$	virtual ideal alternative
V_{ai}	Weighted scores

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The United Nations' 2030 agenda for Sustainable Development Goals (SDGs) aims to eliminate poverty, enhance the quality of education, and mitigate the factors contributing to climate change. Consequently, nations worldwide have redirected their attention to addressing environmental concerns alongside social and economic challenges and opportunities (Allen et al., 2017). The escalating global warming and climate change result in greenhouse gas (GHG) emissions, underscoring the urgency to take immediate action to avert perilous consequences for future generations. India features over 1.52 million educational institutions, comprising both public and private establishments, making a significant contribution to corporate greenhouse gas emissions (MHRD, 2018). In 2021, buildings, covering both their operations and construction, contribute to a substantial 37% of global energy-related CO_2 emissions and represent approximately 36% of the world's total energy consumption during the operational phase alone (BEE, 2023; UNEP, 2021). Typically, 80%–90% of individuals spend their lives indoors, a figure that rose to 100% during the COVID-19 pandemic. Even after the pandemic, people persist in spending 90% of their time indoors, underscoring the crucial importance of Indoor Environmental Quality (IEQ). This chapter addresses the imperative of enhancing energy efficiency to ensure a comfortable indoor environment in educational buildings. It takes into consideration the regional context, climate conditions, and geographical factors.

1.2 RESEARCH BACKGROUND

More than half of the global population resides in urban areas. According to the United Nations (UN) report, it is projected that by the year 2050, approximately 6.3 billion people worldwide will be living in cities (Berardi, 2015; UNDESA, 2014). This rapid increase in urban inhabitants necessitates substantial infrastructural development for transportation, housing, health, and education. However, this unintended population growth poses challenges related to natural resource depletion, increased energy consumption, and heightened pollution, contributing to environmental degradation (Franco et al., 2017; Ritchie & Roser, 2018). **Figure 1.1** illustrates the growth statistics of urbanization from 1950 to the projected expectations in 2050. The growth of urbanization in 1950 was around 30% globally, with India at 16%, and these figures have since increased to approximately 58% globally and 37% in India by 2024. The projected urbanization rates for 2050 are estimated to be around 68% globally and 53% in India. This data indicates a significant increase in urbanization trends, particularly from 2024 to 2050, with a rapid increase expected during this period. From 1950 to 2024, the average annual increase in urbanization in India has been approximately 0.28%, while from 2024 to 2050, this rate is predicted to increase to around 0.62% per year. This suggests a notable acceleration in urbanization trends in India in the coming years. On a global scale, the average annual increase in urbanization from 1950 to 2024 and from 2024 to 2050 predictions has been around 0.38%. It is evident that beyond the year 2024, both the percentage of urbanization and the demand for energy consumption increased asymptotically in India. This rapid urbanization underscores the imperative for additional infrastructure development.

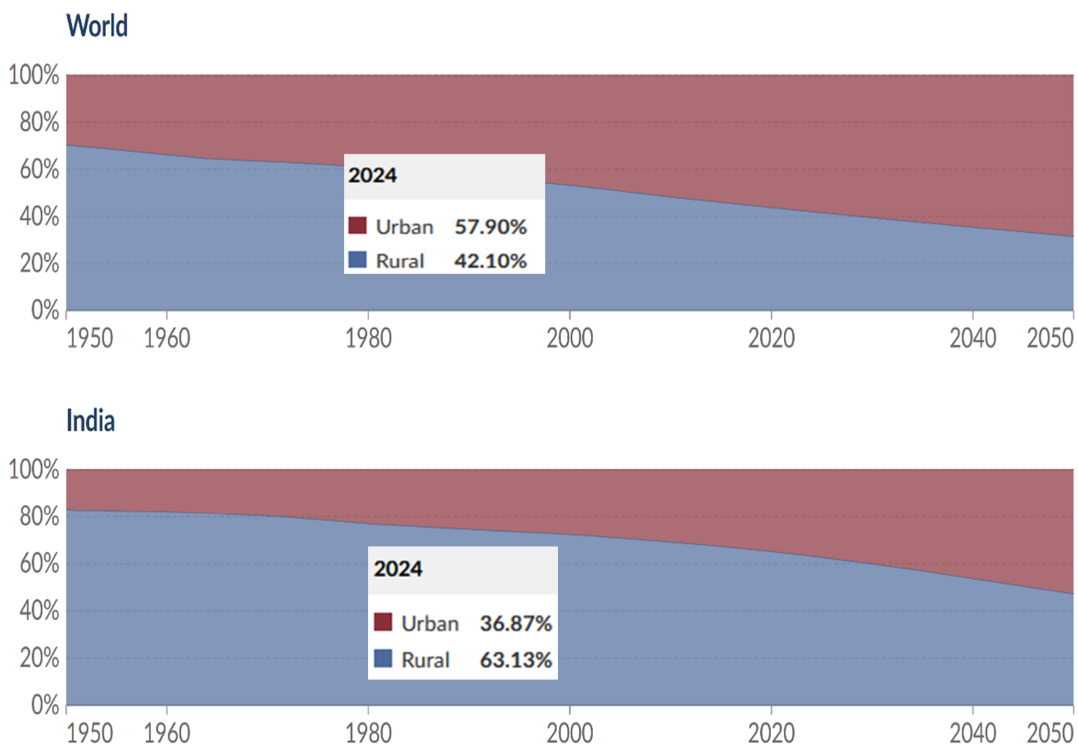


Figure 1.1 Urbanization between 1950 and 2050 (Source: Ritchie & Roser, 2018)

In 2023, Earth Overshoot Day occurs on August 2, Figure 1.2 illustrates the earth overshoot day from 1971 to 2023. This date signifies when humanity depletes nature's resources for the year. Subsequently, for the remainder of the year, we operate in an ecological deficit by depleting local resource stocks and increasing carbon dioxide levels in the atmosphere. It is a period of overshoot (Global Footprint Network, 2022). The unplanned and swift expansion of urbanization, coupled with increasing energy demands, poses a threat to sustainable development. This trend contributes to environmental degradation, social inequalities, and economic instability. CO_2 emissions in India experienced a significant rebound in 2021, surpassing 2019 levels by 80 Mt. This surge can be attributed to the increased use of coal for electricity generation. As illustrated in Figure 1.3, the majority of GHG emissions are primarily contributed by China and India (IEA, 2022). According to 2015 statistics, India held the position of the third-largest economy, second-largest population, and fourth-largest energy consumption (US EIA, 2014). However, in 2023, India has transitioned to being the fifth-largest economy, claiming the top spot for the largest population globally, surpassing China, and maintaining the third-largest energy consumption (IMF, 2023; OECD/IEA, 2023; Worldpopulation, 2022).

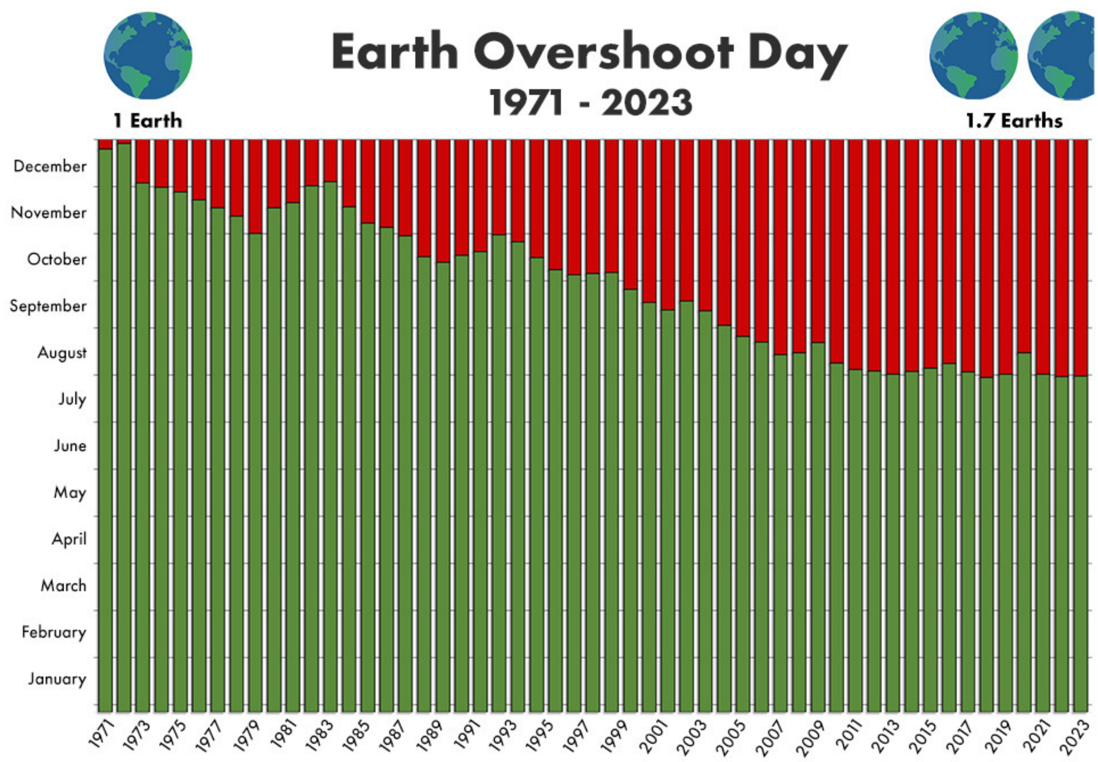


Figure 1.2 Earth overshoot day 1971-2023 (Source : Global Footprint Network, 2022)

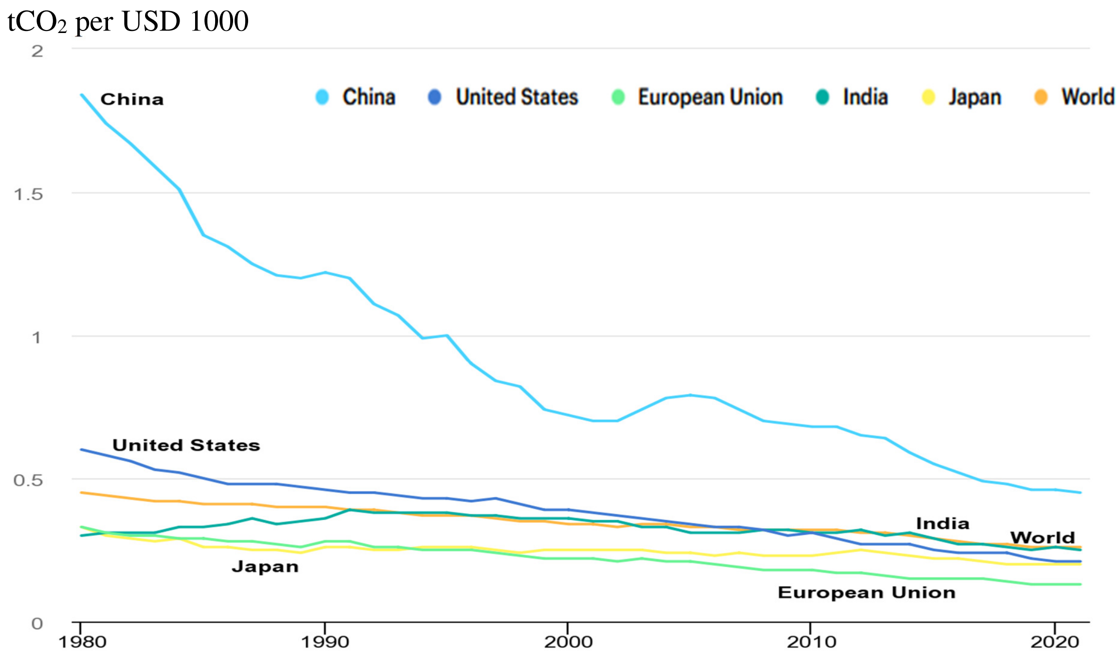


Figure 1.3 CO_2 emissions intensity of GDP, 1990-2021 (Source : IEA, 2022)

This shift poses significant challenges for urban development in India. Addressing the substantial growth in urban transformation necessitates a challenging yet essential solution is a paradigm shift towards sustainable urban development.

Sustainable development has been characterized in various manners, with the most commonly cited definition originating from report of the World Commission on Environment and Development (WCED): Our Common Future, commonly referred to as the Brundtland Report as well as from the National Building Code (NBC) "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" (IISD, 2022; NBC, 2016). Sustainability entails meeting human needs for a high quality of life without degrading the environment or compromising the well-being of the people (Vanegas et al., 1996). The World Resources Institute (WRI) recognizes sustainable development as a challenging, complex, and sometimes controversial concept (Illankoon et al., 2017). India is poised to utilize vast material resources at an unprecedented rate, driven by recent government initiatives such as the development of smart cities. However, these endeavours, including the Atal Mission for Rejuvenation and Urban Transformation (AMRUT), Smart City Mission, and Heritage Cities Development and Augmentation Yojana

(HRIDAY), may contribute to ecological imbalance and carbon footprint either directly or indirectly, particularly by stimulating the construction sector (Satya et al., 2016).

The rapid expansion of infrastructure, as observed in the swift growth of building projects, raises concerns about environmental degradation and its potential impact on ecological balance. This urgency highlights the necessity of promoting and implementing sustainable principles and practices. To address environmental impact and climate change and strive for a better living world, the concept of the 5R's - Reduce, Replace, Reuse, Repair, and Renovate - is crucial (Vyas & Jha, 2016). For example, the significant proportion of Indian demolition waste, constituting over 30% of total solid waste, demands attention. The findings suggest that in 2016, India produced between 112 and 431 million tonnes of construction and demolition waste. These estimates are considerably higher than what official records indicate (Jain et al., 2021). The disposal of such waste contributes to greenhouse gas emissions and introduces toxic materials that pose risks to both human health and the environment. Moreover, the extraction, manufacturing, and transportation involved in these processes further damage natural environmental conditions. Urgent attention is required to address these challenges, mitigating global issues such as global warming, pollution, carbon footprint, and natural resource depletion.

As the world addresses the challenges of climate change and reduces greenhouse gas emissions, net zero energy buildings emerge as important solutions. These buildings generate their own renewable energy and minimize energy consumption, reducing carbon footprint and saving costs for building owners and operators. Net Zero Energy Buildings (NZEBs) are a significant advancement in sustainable building design, aiming to balance energy consumption with on-site renewable energy generation. These buildings prioritize high energy efficiency, achieved through advanced insulation, efficient lighting, and Heating, Ventilation, and Air Conditioning (HVAC) systems. They also incorporate onsite renewable energy sources like solar panels or wind turbines to meet their energy needs. NZEBs are characterized by their energy monitoring and management systems, which optimize energy use and maximize renewable energy production. Additionally, their orientation and design are carefully planned to maximize natural light and ventilation while minimizing energy losses. The building sector plays a crucial role in achieving carbon neutrality, as it is responsible for 38% of carbon emissions globally. To address this, strategies like nearly Zero Energy Buildings (nZEBs), ZEBs/NZEBs, and Net Zero

Carbon Buildings (NZCBs) are being implemented. NZCBs, in particular, aim for zero operational and embodied carbon emissions, making them key in decarbonizing the construction sector. Despite their importance, NZCBs face barriers such as high initial costs, legislative issues, and socio-cultural factors that hinder their widespread adoption. Strategies like embodied carbon reduction, operational carbon reduction, increasing renewable energy supply, and carbon offsetting and storage are crucial for the success of NZCBs. Integrating circular economy principles and passive design, along with renewable energy production, can help achieve the goal of zero carbon emissions in buildings. However, with advancements in technology and growing awareness of sustainability, NZEBs and NZCBs are becoming more feasible and are paving the way for a more resilient and sustainable built environment. (IEA, 2021; Tirelli & Besana, 2023). The study conducted by Ohene et al., 2022 has highlighted a steady and gradual increase in research on NZEBs since 2006, focusing on themes such as energy efficiency, zero energy building, life cycle assessment, embodied energy, building simulation, and residential buildings. Influential jurisdictions and outlets have been identified. Future research directions include strategies for retrofitting existing buildings, promoting NZEBs at the neighbourhood scale, developing innovative business models for delivering NZEBs, and fostering stakeholder partnerships and synergies in promoting NZEBs.

Several exemplary net-zero energy buildings around the world showcase innovative design strategies and sustainable practices that contribute to achieving carbon neutrality. For instance, in Norway, the Multikomforthus pilot building stands out as an early demonstration of achieving a net zero balance for both embodied and operational emissions. This showcases key design strategies for achieving net-zero greenhouse gas emission balance in new-build single-family residential buildings. Similarly, the Powerhouse Kjorbo office building in Norway underwent a successful retrofit to achieve a net zero balance for both embodied and operational emissions. This retrofit serves as a model for achieving net-zero greenhouse gas emission balance in the retrofit of commercial office buildings (Sørensen, Andresen, Kristjansdottir, et al., 2017; Sørensen, Andresen, Walnum, et al., 2017). In the United Kingdom, the GLP Magnitude Logistics Centre is the first "net-zero carbon for construction" building, certified in line with the UKGBC Net Zero Carbon Buildings Framework Definition. This industrial building demonstrates innovative design strategies for achieving net-zero carbon emissions in new construction. Additionally, the Max Fordham Office in the UK, originally constructed in 1850, underwent a retrofit with the goal of achieving "net-zero carbon:

operational" ambition, showcasing the potential of retrofitting existing buildings for carbon neutrality (RE, 2020; UKGBC, 2019). In the United States, the National Renewable Energy Laboratory (NREL) serves as an example of a large zero-energy multifunctional building that incorporates sustainable design and advanced energy-efficient technologies. This building demonstrates the possibilities of achieving carbon neutrality in large-scale structures. The Houston Advanced Research Centre (HARC) in the US is another noteworthy example, being the first net-zero energy office building in Texas, showcasing sustainable design and energy efficiency (CC, 2020; Nrel, 2012). In Singapore, the NUS School of Design and Environment 4 serves as a net-zero energy educational building and a living laboratory for sustainable development research. The Building and Construction Authority Headquarters in Singapore, built-in 2009, is the first net-zero energy office building in the country (BCA, 2023; NZEB, 2015c). Indira Paryavaran Bhawan in New Delhi, India, is a trailblazer as the country's first net-zero building completed in 2014. It showcases a blend of active and passive strategies, including optimal block orientation, extensive green cover, and maximized natural lighting, setting a benchmark for sustainable commercial construction. Similarly, Avasara Academy in Pune, Maharashtra, completed in 2020, represents India's commitment to sustainable architecture. Designed by Case-Design Architects, the school campus achieves net-zero energy status through innovative design and efficient technologies, reducing energy consumption by an impressive 85% (NZEB, 2015b, 2015a).

These buildings demonstrate a range of passive strategies tailored to their climate locations, emphasizing the importance of context-specific design approaches for achieving carbon neutrality in the built environment. Passive strategies for operational energy use and subsequent reduction in operational greenhouse gas emissions are widely integrated into each net-zero building case. These buildings prioritize optimal orientation, onsite renewable energy generation, and maximizing daylight potential. The specific passive strategies employed correlate closely with the climate of each location. In heating-dominated climates like Norway and the United Kingdom, net-zero buildings focus on thick thermal insulation, energy-efficient windows, and airtightness to significantly reduce heat loss. Conversely, in cooling-dominated climates such as the United States and Singapore, strategies emphasize increasing natural ventilation, shading solutions, and using energy-efficient glazing to reduce heat gain and, consequently, lower cooling energy consumption.

To foster sustainable and inclusive growth in emerging economies, it is recognized that developing countries necessitate coordinated efforts and advancements in the essential areas (Economic Policy Forum, 2014; World Economic Forum, 2024):

1. Long-term Structural Transformations: The world is undergoing significant structural changes such as the rise of AI, climate change, geopolitical shifts, and demographic transitions. These forces require global, pervasive, and momentum-driven responses.
2. Policy and Regulation: There is a need to fortify regulatory authorities and enhance existing laws to address the challenges posed by these transformations.
3. Capacity and Skills: Addressing the shortage of technical skills, particularly in the construction process, is imperative for adapting to these structural transformations.
4. Awareness and Understanding of Benefits: Overcoming the lack of awareness regarding sustainability/green practices and their associated benefits is vital for mitigating risks and enhancing resilience.
5. Localized Strategies and Collective Actions: Localized strategies, breakthrough endeavours, and collective actions are essential for reducing the impact of global risks. Both the public and private sectors can play a key role in extending benefits to all.
6. Cross-Border Coordination: Cross-border coordination remains crucial for addressing the most critical risks to human security and prosperity, emphasizing the importance of international cooperation.

There exists a widely recognized need for individuals, organizations, and societies to find models, metrics, and tools for articulating the extent to which, and how current activities are unsustainable. Hence, it is evident that there is an overarching necessity to explore methods for measuring building performance, comfort, and energy conservation methods to achieve sustainability in the construction industry.

1.3 NEED OF THE PRESENT WORK

With 141 million enrolled students and a gross enrolment ratio of 27.1, India's higher education system ranks among the largest globally. Over recent years, the number of higher education institutes in India has experienced a compounded annual growth rate of 11% (ASHE, 2021). Moreover, according to the census of India, the literacy rate in the country rose from 74.04% in 2011 to 77.7% in 2020, signifying an improvement in access to education (Nilangni, 2023). These statistics suggest that the coming years will usher in substantial expansion in India's higher education sector, translating to a significant increase in the sheer number of institutional buildings and classrooms.

An increase in the level of development is associated with a greater contribution from higher educational levels, especially when comparing the Organization for Economic Co-operation and Development (OECD) and Least Developed Countries (LDC). Conversely, physical capital appears to have played a more substantial role in OECD nations. The Lucas production function suggests structural differences in how educational investment correlates with growth, aligning with and reinforcing the conclusions drawn in Barro (2000), particularly those related to secondary and higher education (Barro, 2002; Petrakis & Stamatakis, 2002).

1.3.1 Need for the Performance Indicators (PIs)

The sustainability of a building project is achieved only when all indicators of sustainability are comprehensively addressed. It is essential to emphasize that a Sustainable or Green building is intricately designed to minimize environmental impacts and optimize resource consumption throughout various stages of its life cycle (VillarinhoRosa & Haddad, 2013). The emphasis on implementing and adopting sustainable building practices underscores the need for specific indicators and criteria to establish a comprehensive building assessment framework. Key Performance Indicators (KPIs) allow for a better understanding of the effects of interventions over time, identifying which operations work best, and defining areas for improvement and optimization. System KPIs are formulated in a new context to represent various types of performance, including energy use, peak demand, load shape, occupant thermal comfort and visual comfort, ventilation, and water use (H. Li et al., 2020). It is noteworthy that directly transferring indicators and criteria from an existing building assessment framework developed in one country may fall short in incorporating the regional context, culture, heritage, and geographical conditions of another country (Ali & Al Nsairat, 2009; Patil et al., 2016). Successful technology transfer occurs only when the current priorities and prevailing conditions of a specific location are thoroughly integrated. An assessment tool tailored for one nation or region may not be suitable for another. Thus, developing a building comfort index based on criteria and/or indicators necessitates the active participation of experts from various domains within the construction industry to consider the real-time conditions of a specific region.

1.3.2 Need for the Combined Comfort Index (CCI) Approach

Comfort is a nuanced state of well-being intricately tied to an individual's sensory perceptions within a given environment. This state is meticulously shaped by factors such as temperature, air humidity, noise level, and brightness present in the surroundings. This comprehensive definition illuminates the subtle yet crucial distinctions among thermal comfort, acoustic comfort, and visual comfort. Environmental comfort, in a broader sense, encapsulates the psychophysical well-being of individuals across diverse settings, including homes, offices, museums, educational institutions, shopping centers, and more. It's a perceptible sensation influenced by specific environmental conditions that are not left to chance but are intentionally designed. The responsibility for shaping these conditions lies squarely with the designer, covering the entire spectrum from initial conceptualization through implementation to ongoing management, especially in the realm of smart homes or, more expansively, smart/green buildings. Notably, the absence of optimal environmental comfort can exert a profound impact on the learning capacity of students. Abundant research attests to the idea that a comfortable environment not only boosts productivity among workers but is equally applicable to students.

Comfort, alongside safety and energy efficiency, has perennially stood out as a pivotal aspect in the realm of "home and building automation" and the broader domain of "indoor environments." The knowledge derived from the Global Comfort Index (GCI) holds significance across various fundamental aspects, encompassing health, productivity, building renovation, comfort prediction, energy efficiency, and the overarching understanding and enhancement of the potential for improvement within indoor environments. The foundation of the concept of human comfort, or Indoor Environmental Quality (IEQ), rests upon the perception of the indoor environment through the senses of its occupants. This facet is particularly crucial as it has been demonstrated to have a tangible impact on the physical and mental well-being of the occupants, directly influencing health and comfort. In light of heightened concerns regarding socio-economic issues and the environmental sustainability of buildings, researchers are increasingly directing their attention to the repercussions of IEQ on health, performance, and human comfort. Several studies have proposed various overall comfort indices, employing diverse methodologies (Al horr et al., 2016; Amaratunga et al., 2000; Buratti et al., 2018c; Cao et al., 2012; Douglas, 1996; Guan et al., 2020; Huang et al., 2012; Jin et al., 2020; Krü & Zannin, 2004; Kylili, Fokaides, Amparo, et al., 2016; Nagano & Horikoshi, 2005; Ruparathna et al., 2015, 2017a; Sediso & Lee, 2016; Shek & Chan, 2008; W.

Yang & Moon, 2019). While some focus on measuring sustainable performance by considering one or more indicators (Kylili et al., 2016), criteria such as safety, satisfaction, functionality, renewable energy, and environmental factors in most studies are often assumed to be oriented toward specific indicators like thermal, acoustical, visual, etc., potentially overlooking the interconnected significance of these indicators across the broader spectrum.

1.3.3 Need for the Development of Energy Conservation Strategies

The term "energy conservation" is increasingly prevalent in today's discussions. It's important to note that energy conservation doesn't simply entail stretching limited resources until they are exhausted; such an approach would only delay a crisis until the eventual depletion of energy resources. Instead, conservation involves the strategic reduction of demand on a finite supply, allowing that supply to gradually regenerate. Often, the most effective way to achieve this is by substituting the energy used with alternative sources. In the context of fossil fuels, conservation also encompasses discovering innovative methods to access the Earth's resources, ensuring that commonly exploited oil fields are not completely depleted. This strategy enables these fields to naturally replenish over time. However, it's crucial to understand that this process unfolds gradually. When we discuss replenishing natural resources, we are acknowledging the need to alleviate excess demand on the supply over centuries, allowing nature the necessary time to recover. The overarching goal of energy conservation techniques is multifaceted: reduce demand, safeguard and regenerate supplies, explore and utilize alternative energy sources, and address the environmental impact left by previous energy processes.

In recent years, substantial endeavors have been dedicated to enhancing energy efficiency and curbing energy consumption. The notion of energy efficiency in buildings revolves around the energy supply required to attain optimal environmental conditions that minimize overall energy usage. The key to designing an energy-efficient building lies in the optimization of design variables and construction parameters. The conceptual design phase stands out as the opportune moment to integrate sustainable strategies. Implementing these mechanisms right from the outset of the construction phase not only proves more effective but also mitigates implementation costs compared to their installation in later stages of construction. Undoubtedly, energy-efficient design methodologies confer added value, primarily benefiting the end user. A building crafted with energy-saving criteria translates to reduced economic costs over the building's lifecycle due to lower energy consumption, more than compensating for the initial higher investment. Additionally, since there are fewer carbon dioxide emissions released into the atmosphere throughout the building's life cycle, this brings about broader societal benefits as well.

In the realm of passive solar design for buildings, the orientation stands out as the paramount factor, extensively examined in numerous studies. The quantity of direct solar radiation reaching a building's facade is contingent on the azimuth in the wall, thereby hinging on the building's orientation angle. The orientation of the facade also plays a pivotal role in other aspects of passive design, including shading considerations and the efficacy of the solar envelope.

Optimal building orientation yields several advantages:

- It constitutes a cost-effective measure applicable in the initial phases of project design.
- It diminishes energy demand.
- It mitigates the necessity for more intricate passive systems.
- It enhances the effectiveness of other intricate passive techniques.
- It augments the quantity of daylight, thereby reducing the energy demand for artificial lighting and contributing less to the internal heating load of the building.
- It optimizes the performance of solar collectors.

The building envelope, comprising the foundation, roof, walls, doors, and windows, along with the operational duration of the heating system, stands out as the most influential factor impacting the overall energy consumption of a building. The envelope plays a crucial role in determining the interior climate conditions, thereby affecting the additional energy demand for heating and cooling. Interventions in the elements constituting the building envelope can yield positive impacts on certain energy requirements while potentially leading to negative effects on others. Consequently, it becomes imperative to assess the overall performance of the building as an integrated system. Among the components, window glazing emerges as a vulnerable thermal control point within building interiors. In a typical family residence, 10–20% of all heat loss occurs through the windows.

1.3.4. Need for the development of Artificial Neural Network (ANN) building assessment model

Presently, numerous global comfort indices play a crucial role in quantifying the comfort within specific indoor environments or buildings, offering the additional capability of predicting comfort levels for various purposes. The primary objective often revolves around automating the control of different actuators to enhance building performance, particularly in terms of energy efficiency. Comfort prediction powered by Artificial Intelligence (AI) has become a focal point in various studies, with Machine Learning (ML) serving as a key technique. Notable ML techniques employed include:

- Artificial Neural Networks (ANN)
- Decision Trees (DT)
- Support Vector Machines (SVM)
- Bayes Networks (BN)
- General Linear Model (GLM)

Studies frequently leverage ANN, specifically utilizing models like Multilayer Perceptron (MLP) and Neural Network Auto Regression with eXogenous (NNARX) input to predict indoor temperature and relative humidity. For outputs such as Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV), other models like Back-Propagation Neural Network (BPNN), Feed-Forward Neural Network (FFNN), Radial Basis Function Networks (RBFN), and Random Forests (RFs) are applied. However, these studies often focus on predicting quantities or indices related to thermal comfort, with limited inclusion of various Indoor Environmental Quality (IEQ) aspects. The evolving landscape necessitates the incorporation of as many comfort factors as possible, extending beyond thermal comfort. The integration of the Internet of Things (IoT) and Wireless Sensor Networks (WSN) has significantly contributed to this widespread endeavour.

1.4 STRUCTURE OF THE THESIS

The present thesis is organized into eight chapters, and the details included in each chapter are highlighted below:

Chapter 1 briefly introduces the research background, and need for the present study, thermal, visual, and acoustical comfort and factors, and the work in the educational institute environment.

Chapter 2 presents a detailed literature review on combined comfort energy conservation strategies of institutional buildings and ANN MLP work. Various factors of comfort, indices, predicting models of comfort, the international standard of thermal comfort, and various approaches to estimate the comfort, and correspondingly reviewed numerous comfort investigations carried out on the educational buildings and its related work environment in global and Indian scenarios. Identification of research gaps based on the extensive literature survey and prepared the current study's research questions, simultaneously aim and objectives of recent work presented, and the study's hypothesis.

Chapter 3 discusses the scope and objective of the study along with the research methodology adopted.

Chapter 4 describes the performance indicators, and extraction of KPIs of the hostel building of an educational institute.

Chapter 5 presented the combined comfort index evaluation methods and results based on the objective and subjective measurements with the thermal, visual, and acoustical indices. Simultaneously graded the building comfort performance.

Chapter 6 describes the various energy conservation strategies including the variation of building orientation, building envelopes, and WWR for optimal energy estimates.

Chapter 7 presents the analysis of ANN-MLP modelling of combined comfort of the educational building considering various parameters. The baseline model has been validated by comparison with developed CCI using field measurement data and determined the predicted CCI based on developed model.

Chapter 8 summarizes the overall work outcomes, conclusions obtained based on the present work, and limitations of the present study with future scope in this domain.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The preceding chapter shed light on the causes of natural resource over-exploitation and its environmental impact. It emphasized the significance of the 5R's concept – Reduce, Replace, Reuse, Repair, and Renovate. The chapter also delved into the future needs for rapid urban growth, infrastructure demand, and energy generation. Additionally, it underscored the importance of building orientation and material energy demand in building assessments. The imperative to measure building performance for sustainability in developing nations, exemplified by India, was addressed. Building upon the topics introduced in the preceding chapter, this section conducts a literature survey, the findings of which are presented here. The literature review encompasses various aspects of indoor comfort, including factors, indices, predictive models, occupant comfort zones, and different standards with estimating approaches. Energy conservation strategies, such as the application of Building Information Modelling (BIM) at the planning stage, building orientation, envelope variations, and Window-to-Wall Ratio (WWR), are explored. Simultaneously, the chapter discusses relevant research conducted on building comfort and energy conservation in global and Indian institutional environments.

The chapter emphasizes the importance of exploratory studies to establish priorities and gain insightful perspectives for decision-making. Furthermore, it delves into the significance of Multi-Criteria Decision Making (MCDM) methods for identifying Key Performance Indicators (KPIs) and assessing building alternatives. Finally, the literature related to the development of Artificial Neural Network Multilayer Perceptron (ANN MLP) models, attempted by previous researchers, is reported.

The literature review considered articles from the main databases, including Scopus, Google Scholar, and Thomas Reuters' Web of Science. Additionally, supplementary information was sourced from various databases like sciencedirect.com, mdpi.com, researchgate.net, and others to ensure a comprehensive examination. The research focus revolved around specific keywords related to building comfort, indoor environment aspects (thermal, aural, visual, or lighting), energy conservation, building orientation, window-to-wall ratio (WWR), BIM, integration of Artificial Intelligence (AI) into building comfort, and the development of comfort indices. Relevant publications were also searched for in specific journals and conference proceedings associated with building science, such as Sustainable Energy Reviews, Energy and Buildings, Building and Environment, and Indoor and Built Environment, as well as IEEE conference proceedings. During the search, keywords such as thermal comfort, ML, AI, adaptive PMV, thermal comfort control, indoor environment, indoor thermal comfort, comfort index, indoor air temperature control, and control strategy were utilized, both individually and in combination, to ensure a comprehensive review of the literature. In selecting relevant literature, the inclusion criteria prioritize peer-reviewed articles, conference papers, and pertinent books published within a specified timeframe. Conversely, exclusion criteria involve filtering out non-English publications, irrelevant topics, and studies lacking empirical evidence.

To enhance the exploration of the collected literature, network analysis techniques are applied. Visualizations such as keyword co-occurrence networks (refer to Figure 2.1), overlay visualization networks (refer to Figure 2.2), and density visualization of key research areas (refer to Figure 2.3) are employed to provide a comprehensive overview of the research landscape spanning from 2010 to 2017. In the visual representations, each circle corresponds to a distinct research topic, with its size directly proportional to the number of associated publications. The proximity of two circles signifies a higher degree of co-citations between the respective topics. To enhance clarity, closely related research domains are differentiated by distinct colour visualizations. This graphical approach serves to efficiently convey the interconnectedness of research themes and the relative significance of each topic based on publication volume. The presentation of bibliometric findings through network diagrams aims to facilitate clarity and accessibility, contributing to a holistic understanding of significant advancements, identifying gaps, and outlining potential future directions within this crucial research domain.

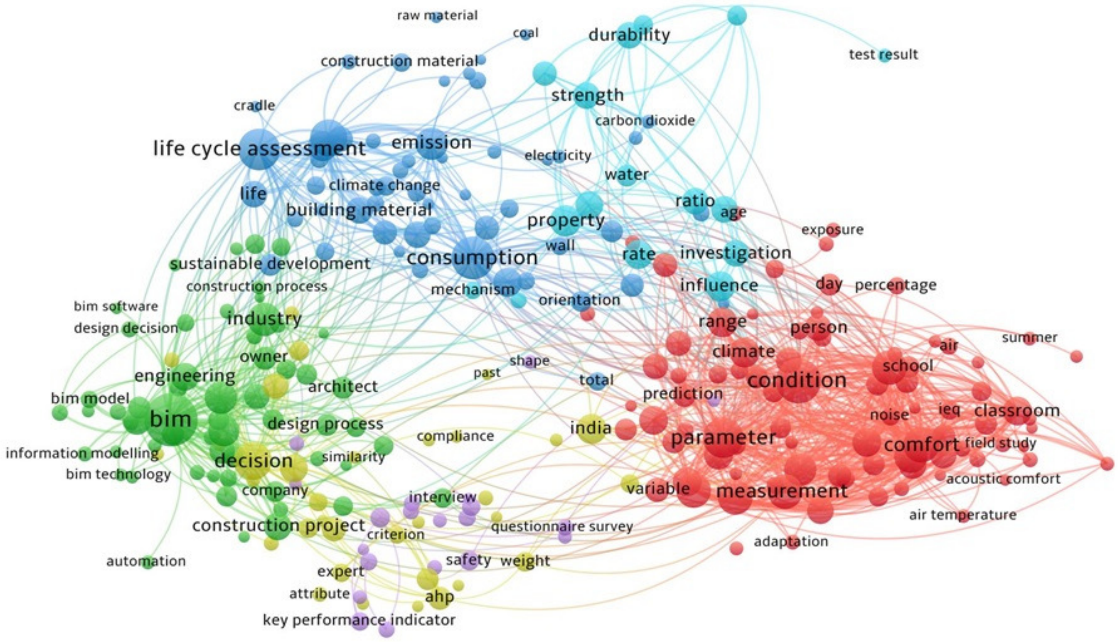


Figure 2.1 shows the co-occurrence analysis of the keywords in literature. (Source: VOSviwer, 2022)

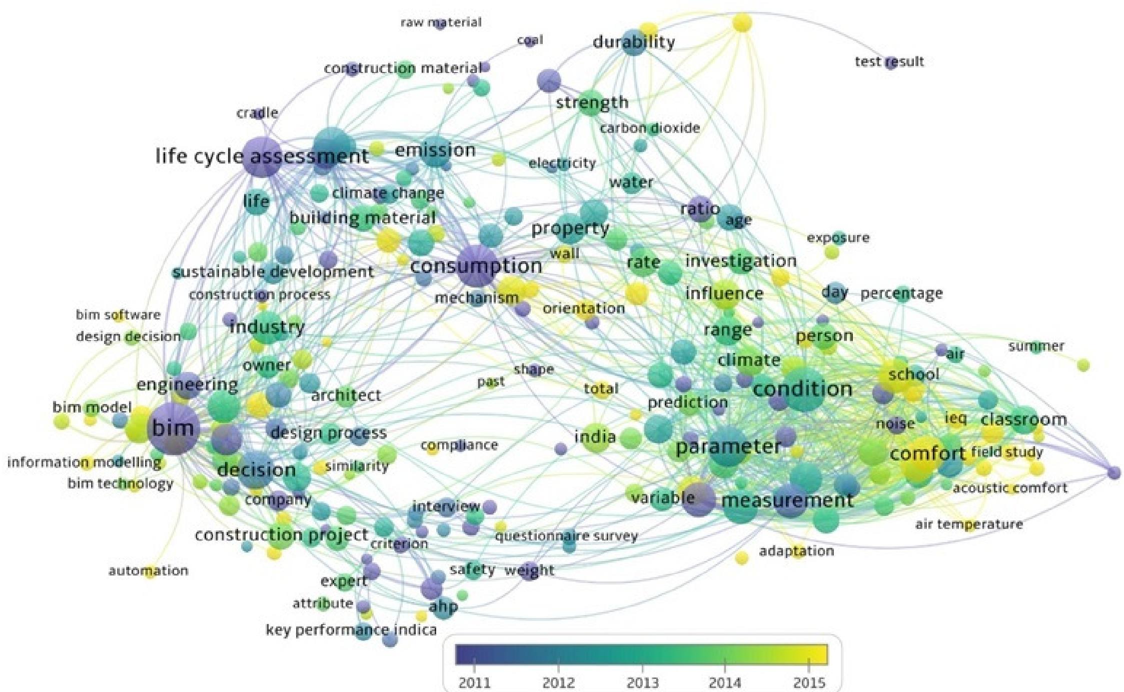


Figure 2.2 Shows time Overlay Visualisation (Source: VOSviwer, 2022)

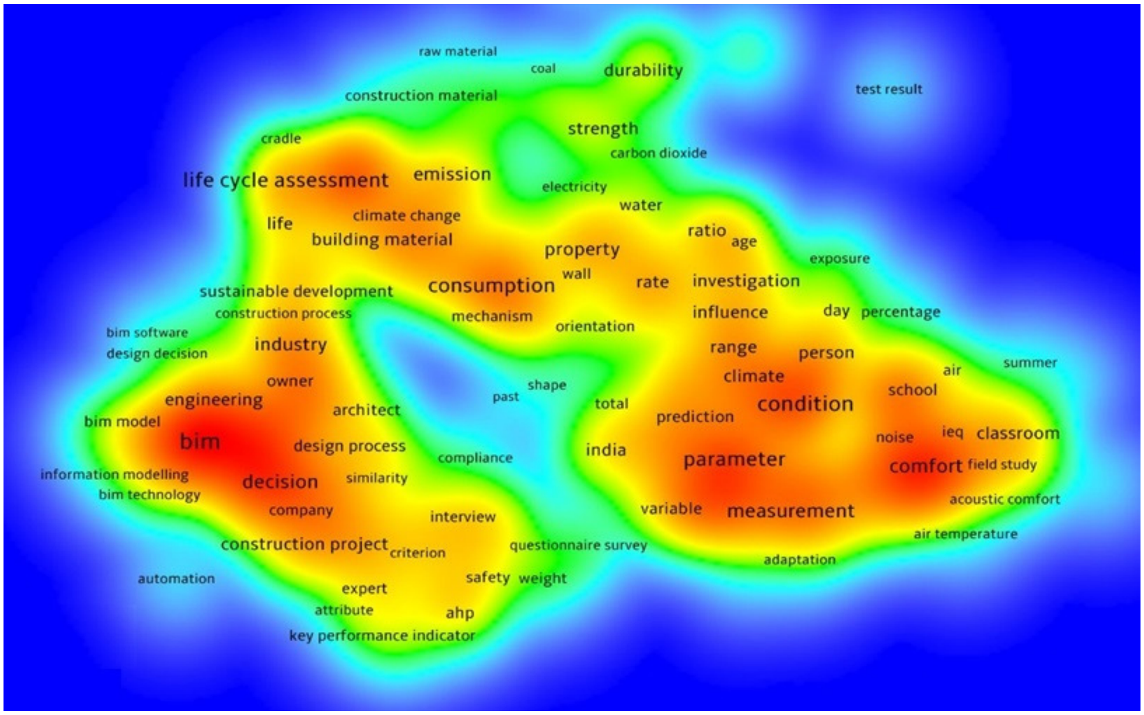


Figure 2.3 Shows the density visualisation of research (Source: VOSviwer, 2022)

2.2 PERFORMANCE INDICATORS AND KEY PERFORMANCE INDICATORS

A performance indicator, as defined by Ben-Daya et al., (2009), encompasses one or multiple aspects and serves as a quantifiable measure to indicate the level of performance. These indicators play a versatile role, enabling the measurement of status, facilitating comparisons and assessments, identifying objectives and targets, planning improvement actions, and providing a continuous measure of changes over time. To be effective, indicators should exhibit certain characteristics: they must be generic, featuring standardized measurements; reasonably simple for universal usability; flexible, adaptable to various building types; relevant and reliable, minimizing errors and biases while faithfully representing the intended metrics. Moreover, indicators should be easily converted into knowledge and garner trust from all stakeholders involved. Notably, the active participation of stakeholders in the indicator development process is crucial. As emphasized by Innes and Booher, (2000), when stakeholders are engaged in developing indicators and can relate them to their own contexts and perspectives, the indicators become ingrained in their thinking and ordinary decision-making processes. This involvement ensures that the indicators align closely with the stakeholders' needs, enhancing their effectiveness and acceptance in practical decision-making scenarios.

In their work from 2002, Chiang and Lai outline a methodology for developing a comprehensive indicator designed to assess indoor environments. The outcomes of the study consist of a collection of physical indicators, weightings assigned to various physical categories, and evaluated scales that match the values measured in the field. These findings prove to be effective for evaluating the built environment and promoting the health of occupants. The insights of experts, informed by the current situation and the local environment, play a crucial role. The overarching goal is to extract essential indicators through expert consultation, enabling a quantitative assessment of existing buildings.

It observes a shift in human focus from necessity to the standard of living. The work by Chatterjee, (2009), advocates five pivotal facets for fostering sustainable construction in India. It emphasizes comprehending the interdependency of energy and material flow, efficient conservation based on thermodynamic principles, integrating survival designs, appreciating natural systems and ecosystem diversity, and ensuring buildings' adaptability to change for resilience in diverse environmental conditions. These facets collectively form a foundation for sustainable construction practices, addressing the need for a holistic understanding of energy, conservation, ecological systems, and adaptability in the Indian context.

The evaluation of environmental performance is primarily achieved through the systematic use of KPIs. These KPIs, categorized for specific functions, play a dual role by facilitating the comparison of diverse design solutions and ensuring the continuous monitoring of a building's performance throughout its operational lifespan. This structured approach allows for a comprehensive assessment of various aspects, including energy efficiency, indoor air quality, and sustainable material usage, among others. This approach not only supports the comparison of design alternatives but also enables the tracking and assessment of a building's real-time performance during its operational life. The data derived from these KPIs offer stakeholders a holistic perspective on the environmental impact and efficiency of the building, contributing to informed decision-making and fostering sustainable practices in architecture and construction (Conte & Monno, 2012).

In the year 2011, Lavy adopted a qualitative research approach, leveraging existing literature to identify KPIs through an extensive literature search. The exploration revealed that previous studies categorized KPIs into varying sets of four to seven categories. However, these categories, as found in other studies, either excessively emphasize specific aspects of performance measurement or are overly broad, leading to repetitive or overlapping classifications. In response to these observations, this study takes a different approach by categorizing KPIs into three overarching groups: financial, physical, and functional. This categorization is grounded in the specific purposes and content of the KPIs. Lavy posits that this reorganization holds the potential for more practical utility among facility management practitioners, providing a structured and purpose-driven framework for the effective application of KPIs in their field. This approach is expected to enhance the clarity and relevance of performance measurement in facility management.

In 2015, Zhong and Wu undertook an analysis of the performance of reinforced concrete and structural steel framed buildings, focusing on environmental, economic, and constructability as KPIs in Singapore. The study placed significant emphasis on creating safety and health through ecological design and resource efficiency. The findings indicate that structural steel is costlier and less effective in preventing noise pollution. Strict regulation policies in Singapore also limit construction safety and duration. On the other hand, reinforced concrete surpasses steel framed buildings in terms of construction, maintenance, and financial costs. However, steel buildings exhibit superior performance in recyclability, waste reduction, water consumption, construction durability, and quality.

The initiative to minimize the environmental impact of public sector buildings while ensuring user comfort resonates with the objectives outlined in the Federal Sustainable Development Strategy (FSDS) of Canada. In 2015, Ruparathna et al. brought attention to a notable oversight in numerous studies related to asset management. In response, It is devised a comprehensive framework to evaluate the level of service provided by a municipal government-operated recreational centre building. The credibility of this framework is bolstered by the application of the fuzzy synthesis method, incorporating a range of indicators and meticulous calculations of data precision and weights. To mitigate potential biases, a diverse group of experts is actively engaged in the development of the level of service index for the building. The study's findings identified a poor level of service for the recreational building, reflected in an index value of 28.16, prompting the recommendation for immediate improvements. This research introduces an innovative approach to the life cycle asset management of public sector buildings, addressing a critical aspect that has previously been overlooked in the field. The emphasis on holistic evaluation and the call for immediate improvements contribute to advancing the understanding and practice of sustainable building management. In 2017, the author expanded their research to evaluate the comfort services provided by a public aquatic building, focusing on key performance categories and indicators during the operational phase. The study identified various indicators, including building performance indicators, system performance indicators, and component performance indicators, to comprehensively assess the building's performance. A total of twenty-two indicators were categorized into nine distinct categories, offering a nuanced and detailed evaluation of the different facets of the building's operational effectiveness (Ruparathna et al., 2015, 2017b).

In 2016, Vyas and Jha carried out a comprehensive analysis, comparing several widely used building assessment tools such as LEED, BREEAM, SB-Tool, LEED-India, CASBEE, Eco-housing, and GRIHA. Their examination uncovered significant disparities and limitations when applying these tools in the Indian context, underscoring the need for the development of a new building assessment tool. Employing Principal Component Analysis, the study methodically identified key indicators for the evaluation of building performance. These indicators cover a spectrum of crucial aspects, including environment, site selection, building resources, innovative techniques, building services and management, indoor air quality, and economic considerations. This meticulous approach ensures a more nuanced and customized assessment of building performance that takes into account the specific requirements of the Indian context.

Saraiva et al., (2018) conducted research emphasizing the significance of incorporating environmental comfort indicators in sustainability assessment tools for school buildings. The examination of Indoor Environmental Quality (IEQ) consistently emerges as a crucial element in various sustainable development assessment tools, aiming to enhance occupant comfort, health, and safety within buildings. Specifically tailored to educational institutions, methodologies like LEED for School, SBTool for School, and BREEAM Education highlight indicators such as thermal, acoustic, and noise comfort, ventilation, contamination levels, as well as illumination and lighting. Despite the inclusion of key comfort aspects in existing assessment schemes, there is a recognized necessity to broaden the scope beyond conventional indices. Notably, ergonomic considerations become imperative, particularly in school environments where students spend approximately 5 hours daily seated in school chairs. Consequently, integrating ergonomic comfort indicators into sustainability assessment methodologies for schools becomes crucial, requiring an evaluation of the suitability of spaces and furniture to meet the unique needs of students.

In their 2017 study, Lai and Man meticulously identified a comprehensive set of 71 indicators, systematically categorized into five distinct groups: physical, financial, environmental, safety, and equipment-related. To establish a robust framework for the identification of applicable performance indicators, it is innovatively introduced an integrated process-hierarchy model. This model seamlessly incorporates both the Facility Management (FM) organizational hierarchy, encompassing strategic, tactical, and operational levels, and the intricate mechanism of facilities services delivery, spanning input, process, and output phases. The outcome of this endeavour is the formulation of KPIs specifically tailored for the evaluation of engineering facilities in existing commercial buildings. Notably, these indicators are meticulously designed to suit the unique challenges and intricacies presented by densely built metropolises, with Hong Kong serving as a pertinent exemplar. This research thus contributes a nuanced and applicable framework for the evaluation and enhancement of performance in the field of engineering facilities within the context of urban environments.

In 2018, researchers Roslan and Shafri conducted an in-depth study on the internal climate conditions of university buildings located in Selangor, a state on the west coast of Peninsular Malaysia. The primary focus of the investigation was to discern the factors influencing the building climate. Utilizing advanced Geographical Information System (GIS) technology, the study sought to visually represent and analyse the building's climate information. Several key contributors to the building climate were identified, encompassing elements such as the building's design, the materials used in its construction, its orientation towards the sun, and the overall climatic conditions in its immediate surroundings. To provide a comprehensive evaluation, the researchers developed a building comfort index using cutting-edge geospatial technologies. The investigation involved an in-depth analysis of building climate factors, drawing insights from the data collected across various building samples. This study contributes valuable knowledge to the understanding of factors shaping the indoor environment in university buildings within the Selangor region.

Bortolini and Forcada (2018) conducted a literature review and convened a focus group with facility management experts to systematically collect and analyse perceptions from facility managers regarding operational indicators suitable for assessing building performance. The outcomes highlighted that fundamental indicators for evaluating a building's operational performance encompass aspects related to safety, proper functioning of assets, health and comfort, space functionality, and energy efficiency. Moreover, the study identified three primary sources for obtaining these indicators, facility managers/operators engaged in corrective maintenance, regular users through satisfaction questionnaires, and periodic users. These identified indicators and their respective sources contribute significantly to a comprehensive analysis of building performance and aid in devising measures for enhancing performance during the operational phase of a building.

In 2019, Teng et al. devised a dynamic system utilizing the statistical package for social sciences and advanced mortar systems to delve into the driving forces crucial for realizing the sustainable development of green buildings. Employing structural equation modelling, the study aimed to intricately model the dynamic interactions among these driving forces, leveraging data obtained from a meticulously structured questionnaire survey. The study's revelations underscored that market development geared toward environmental aspects, economic value, stakeholder participation, and ecological significance exerted the most substantial influences on sustainability. Similarly, a 2016 study by Anadon et al. accentuated the pivotal role of technological innovation in implementing actionable proposals for achieving sustainability. This perspective takes into account socio-economic, cultural, and environmental dimensions, aligning with the sustainable development goals that strive to enhance human well-being. These findings collectively contribute to a nuanced understanding of the multifaceted elements steering sustainable development in the realm of green building initiatives.

Modern buildings often boast cutting-edge facilities, but their peak performance relies on consistent maintenance and timely application of appropriate retrofits during the operational phase. In the absence of such measures, buildings may fall short of meeting intended purposes and user demands. Although there is considerable research on building retrofits, a significant gap exists in studies focusing on the comprehensive identification of KPIs for holistic retrofit evaluations. In 2021, Ho et al. addressed this gap by identifying 62 performance indicators applicable to building retrofit evaluations. Through a focus group, these were refined to 19 KPIs, categorized into economic, environmental, users' perspective, and health & safety groups, constituting 37%, 26%, 26%, and 11%, respectively. This proposed set of KPIs not only facilitates building retrofit assessments and contributes to a more sustainable environment but also holds potential applications across various domains.

It has been emphasized that the categories of performance, along with examples of operational indicators, as identified in studies conducted by various authors, can be succinctly summarized as technical, functional, behavioural, aesthetic, and environmental.

2.3 COMBINED COMFORT INDEX

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE-55., 2013). Building upon the studies and theories of P. Ole Fanger, it is established that the perception of thermal comfort within a building is intricately tied to the interplay between subjective variables and environmental factors. Recent investigations into building comfort underscore that, beyond these variables, the experience of comfort is intimately connected to an individual's psychological, cultural, and social dimensions. Additionally, it is influenced by external factors such as weather conditions and an individual's adaptive capacities. Consequently, quantifying the state of well-being is a complex task, necessitating considerations of factors like age, gender, and health. This contemporary perspective is known as the adaptive method (Brager & de Dear, 2000; Fanger, 1973; Nicol & Humphreys, 1998).

Comfort, safety, and energy efficiency have consistently remained focal points within the realms of "home and building automation" and the broader domain of "indoor environments." The knowledge derived from the global comfort index holds significance across various fundamental aspects, including health, productivity, building renovation, comfort prediction, energy efficiency, and a holistic comprehension of the potential for improvement within indoor environments. The core concept of human comfort, encapsulated in IEQ, revolves around the perception of the indoor environment through the senses of its occupants. This facet assumes particular importance as it has been established to influence the physical and mental well-being of individuals, directly impacting their health and comfort. Researchers are increasingly directing their attention toward understanding the implications of indoor environmental quality on health, performance, and human comfort. This shift in focus is driven by growing concerns about socio-economic issues and the imperative for environmental sustainability within the realm of building design and management (Hedge, 2000).

A structure comprises various components, each contributing to specific environmental effects. Given that a building's complexity surpasses the mere sum of its parts, it should be regarded as a distinct entity. The primary objective is to furnish occupants with optimal comfort conditions, minimizing energy consumption, and limiting environmental impact (Franzitta et al., 2011).

Building performance evaluation can be undertaken at three distinct levels, in alignment with the hierarchical structure of building services: the whole-building level, the system or service level, and the component or equipment level. In the scope of this study, a system refers to the amalgamation of individual equipment and components (e.g., pipes and ducts) that collectively provide a specific building service (e.g., lighting, heating, cooling, ventilation, service hot water, or miscellaneous electronic equipment). On the other hand, components denote the individual equipment constituting building systems (e.g., lighting fixtures in a lighting system, chiller and boiler in an HVAC system). The assessments are further divided into two types, (1) Feature-specific methods, these methods scrutinize the implementation of specific energy efficiency technologies in the building. Typically conducted through building audits, this approach verifies the presence of certain features. (2) Performance-based methods, considered more precise and quantitative than feature-specific methods, these methods utilize measurable indicators such as energy use intensity. They compare a building against a baseline model, often one compliant with ASHRAE 90.1 standards. (S. Wang et al., 2012).

Comfort is distinctly defined as a specific state of well-being, intricately tied to an individual's sensorial perceptions within a given environment. This state is determined by factors such as temperature, air humidity, noise level, and brightness present in the surroundings. Notably, this definition draws attention to the nuanced subcategories of comfort, namely thermal comfort, acoustic comfort, and visual comfort. Environmental comfort, extending beyond physical sensations, is synonymous with the psychophysical well-being of individuals in diverse settings like homes, offices, museums, shopping centers, and more. Crucially, environmental comfort hinges on specific environmental conditions, often meticulously planned and falling under the purview of designers. This responsibility spans the design, implementation, and management phases of smart homes or, more broadly, smart/green buildings. While energy efficiency remains a pivotal focus in green buildings, there has been a notable shift among researchers towards prioritizing user comfort. Parameters such as thermal comfort, visual comfort, and air quality have gained prominence, reflecting a comprehensive approach to enhancing the overall quality of the indoor environment (Dounis & Caraiscos, 2009; Ullah & Kim, 2017).

The primary variables influencing thermal comfort, dependent on both internal and external climatic conditions of buildings, include, air temperature, mean radiant temperature, operating temperature, relative humidity of indoor air and airspeed. The Fanger model gives rise to two thermal comfort indices, namely the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). These indices are derived from the relationships between human body functions and the perception of thermal comfort, as outlined in the EN ISO 7730 standard (ISO, 2005). The PMV serves as an index assessing an individual's state of well-being based on personal and environmental variables. It is a mathematical function producing a numerical result on a scale from -3 (indicating too cold) to +3 (indicating too hot), with zero representing a state of thermal comfort. Notably, since PMV is an average index for a group of individuals, a PMV of 0 doesn't necessarily imply that the entire group has reached a state of well-being. Fanger articulated the comfort criteria established through a synthesis of theoretical, experimental, and statistical studies. The calculation of Predicted Mean Vote (PMV) involves the application of Fanger's equations once data on air temperature (AT), mean radiant temperature (MRT), relative humidity (RH), airspeed (AS), metabolic rate (MR), and clothing insulation (CI) have been gathered. The initial four variables (AT, MRT, RH, and AS) are environmental factors, while the latter two (MR and CI) are physiological in nature. Figure 2.4, illustrates the six variables crucial for the computation of PMV.

Figure 2.4 Variables for PMV evaluation, adopted from Guenther (2021).

In recent years, there has been growing scepticism among researchers regarding the validity of the traditional approach to thermal comfort assessment. This approach is criticized for its failure to consider several crucial factors, including climatic, cultural, social, and contextual elements. In response to these limitations, researchers have introduced the concept of adaptation, emphasizing how an individual's unique context and thermal history can significantly influence their expectations and preferences regarding the thermal environment. This evolving perspective acknowledges the diverse and dynamic nature of human experiences, offering a more nuanced understanding of thermal comfort that goes beyond a one-size-fits-all approach. The adaptive thermal comfort model departs from the passive view of building occupants presented in the static model (Fanger PMV). Instead, it positions occupants as active agents engaged at all levels with their environment. This model proposes a correlation between the occupant's comfort temperature (operative temperature) within a building and the external air temperature (prevailing mean outdoor temperature). In embracing the adaptive approach, the model recognizes that occupants dynamically interact with their surroundings, adjusting their comfort expectations and preferences based on contextual factors, thus offering a more dynamic and individualized perspective on thermal comfort (Abeyrathna et al., 2023; Pawlak & Sinacka, 2023; Yarramsetty et al., 2023).

Numerous bioclimatic indices and charts, such as the Olgyay bioclimatic chart (1969) and the psychrometric bioclimatic chart, have been developed. These indices consider both single parameters and combinations of multiple parameters, reflecting researchers' efforts to establish a comprehensive link between the human body and climatic variations within a single formula. However, it becomes apparent that thermal comfort is influenced by a myriad of parameters encompassing individual, social, physical, and geographical aspects. Consequently, the absence of a universal planetary index that accommodates all these conditions is evident. Defining a singular and universally acceptable formula applicable across diverse climatic and geographical conditions to determine the appropriate thermal comfort level for specific health requirements remains a challenging task (Olgyay, 2015).

Achieving good acoustic comfort involves analysing primary noise sources and implementing solutions for effective acoustic isolation. Acoustic comfort is characterized by an individual not being disturbed by external sounds and noises, and their hearing system remains unaffected by prolonged exposure to loud noises. In many buildings, poor acoustic comfort stands out as a common source of disturbance, underscoring the importance of prioritizing acoustic considerations during the design and construction phases. This involves assessing the building's performance concerning external and neighbouring noise. In the context of green building design, careful choices of materials, furniture, machinery, fixtures, and coatings become crucial to prevent unwanted noises within the building envelope and ensure acoustic well-being. The assessment criterion for acoustic comfort is rooted in the concept of noise levels, directly linked to sound pressure levels measured in decibels (dB). The "A-weighted" scale (dBA) is occasionally used to adjust for variations in how people perceive sound. Establishing a maximum noise threshold, defined based on the purpose and activities within the environment, serves as a criterion for normal tolerability. Exceeding this threshold results in a loss of well-being. Effectively controlling the emission of noise sources emerges as a fundamental strategy for mitigating noise pollution (EN 12354, 2009; Olesen, 2015).

Ensuring visual comfort necessitates the provision of appropriate light quantity during both daytime and night-time to prevent eye strain. In daylight conditions, it is crucial to facilitate the entry of sufficient natural light. This involves considerations such as the number of windows, their size and spacing, the positioning of window shutters, the choice of glass, and other related factors. Additionally, for night-time or cloudy days, proper artificial lighting becomes essential. Modern advancements in artificial light design offer a diverse array of light sources, enabling us to optimize visual comfort in various settings. To facilitate efficient and accurate visual tasks, appropriate lighting is imperative. The visibility and comfort levels hinge on the nature of the workplace, the undertaken activities, and their duration, as outlined in standards such as EN12464-1. Illuminance levels should be strategically designed to integrate both daylight and electric light, or a combination of both. In many cases, prioritizing the use of daylight is preferable for reasons of both comfort and energy efficiency. This choice is influenced by factors such as standard occupancy hours, autonomy (the duration of occupancy with sufficient daylight), the building's location (latitude), the number of daylight hours during different seasons, and other relevant considerations (Olesen, 2015).

A proper quantity of light is essential for ensuring good visibility and the effective performance of occupants' activities. Inadequate or excessive lighting can lead to various issues. Illuminance, a physical quantity, is crucial for determining the amount of light reaching a specific spot over a surface. Illuminance can be employed directly or integrated with other indices as a key input. The primary indices used to evaluate light quantity include illuminance, daylight factor, daylight autonomy, continuous daylight autonomy, spatial daylight autonomy, useful daylight illuminance, frequency of visual comfort, and intensity of visual discomfort. These indices collectively contribute to a comprehensive assessment of the quantity of light in a given environment. The multitude of visual comfort indices serves to evaluate specific characteristics of luminous environments or the human eye's perception within these environments. To aid building designers in optimizing visual comfort for occupants, a multi-objective optimization approach should be employed to consolidate visual comfort factors. With this in mind, the initial step involves detecting and subsequently identifying, enhancing, or developing reliable metrics. This approach ensures a comprehensive understanding of the elements influencing visual comfort, enabling designers to make informed decisions and optimize the design of new buildings for the well-being of their occupants. (Carlucci et al., 2015).

Various studies have identified that different weights are assigned to individual comfort parameters, and some studies exclude one or more parameters to determine the comfort index. These studies employ diverse data analysis techniques, such as Pearson correlation, the Analytic Hierarchy Process (AHP), and multivariate linear/logistic regression, to establish the "weights." For example, Marans and Yan (1989) merged heating and draft coefficients into the thermal category (Marans & Yan, 1989). Some studies, like Chiang and Lai (2002) and Marino et al. (2012), omitted specific categories or parameters, such as the electromagnetic fields (EMF) category and air velocity parameter, respectively (C.-M. Chiang & Lai, 2002; Marino et al., 2012). In Mui and Chan (2005), a negative coefficient for the visual category resulted in the removal of the percentage of dissatisfaction in visual comfort (PDVC) from the model (Mui & Chan, 2005). Humphreys (2005) combined coefficients for warmth, air movement, and humidity into the thermal category (Humphreys, 2005). Lai and Yik (2009) merged air cleanliness and odour coefficients into the Indoor Air Quality (IAQ) category (Lai & Yik, 2009). Bluyssen et al. (2011) considered the physical pollutants category in the thermal category and biological pollutants in the IAQ category (Bluyssen et al., 2011). Buratti et al. (2015, 2017), omitted IAQ category to assess the level of service of the public buildings (Buratti et al., 2018c). Wei et al. (2020) averaged multiple green building schemes, including BREEAM, KLIMA, DGNB, ITACA, LiderA, LEED, and NABERS, The analysis revealed that the thermal, acoustic, luminous environment, and air quality parameters contribute, on average, 27%, 17%, 22%, and 34%, respectively, to the overall Indoor Environmental Quality (IEQ) rating of a building (Wei et al., 2020).

Buratti & Ricciardi (2009) conducted a thorough experimental campaign in moderate environments, specifically focusing on university classrooms. They developed a multiple-choice questionnaire, which incorporated information for both the static and adaptive models outlined by UNI EN ISO 10551. The primary objective is to establish a correlation between experimental data collected through instruments and the subjective responses provided by occupants. The questionnaire is systematically administered during autumn, winter, and spring in classrooms at the University of Perugia, Terni, and Pavia. Throughout this extensive campaign, all requisite data for calculating Fanger and Wray comfort indices are meticulously gathered through instrumental surveys and the completion of questionnaires. An analysis of the results from both questionnaires and measurements leads to the establishment of correlations between pairs of parameters derived from Fanger and Wray. Specifically, a linear correlation is identified for the first pair of parameters, which includes Predicted Mean Vote versus the difference between Equivalent Uniform Temperature and Comfort Uniform Temperature. Meanwhile, a second-degree polynomial relation is obtained for the second pair, encompassing Predicted Percentage of Dissatisfied versus the absolute value of the same temperature difference. It is noteworthy that a superior correlation is observed in measurement data compared to questionnaires (Buratti & Ricciardi, 2009).

The influence of indoor environmental conditions on student productivity and well-being is pivotal. Nevertheless, existing literature reviews often focus on the impact of individual parameters on human comfort, neglecting a comprehensive evaluation that considers various facets such as thermal, acoustic, and visual conditions. To bridge this gap, this paper proposes an index for assessing environmental comfort by incorporating thermal, acoustic, and lighting conditions. The study examines seven university classrooms, measuring environmental factors, including thermal, acoustic, and lighting parameters. Subjective evaluations are also gathered through specially designed survey questionnaires. For the comfort index formulation, three single indexes are proposed based on the strongest correlation between questionnaire responses and experimental results: a Predicted Mean Vote Index for thermo-hygrometric conditions, a Sound Index for acoustic comfort, and a Visual Index for lighting conditions. All indexes are dimensionless and normalized within a 0–1 range, where values approaching 1 indicate favourable comfort conditions, while values near 0 denote poor comfort conditions. By assigning distinct weights to the three aspects, a final combined comfort index is calculated for each classroom, which is then compared with questionnaire results (Buratti et al., 2018a).

The studies on comfort explore the multifaceted nature of building comfort, emphasizing the interplay between environmental conditions, human perception, and evolving paradigms. It introduces the adaptive thermal comfort model, challenges traditional static models, and discusses the importance of considering individual, social, and contextual factors. Building performance evaluation at different levels is highlighted for optimizing comfort and minimizing energy consumption. Specific indices for thermal, acoustic, and visual comfort are proposed, aligning with the contemporary shift toward user-centric design. The review underscores the complexity of defining a universal formula for thermal comfort and discusses studies assigning varied weights to comfort parameters, providing a comprehensive overview of building comfort assessment methodologies.

2.4 ENERGY CONSERVATION STRATEGIES

It is concluded by Chwieduk (2017) with a literature review on modern options for energy conservation in buildings that Careful examination of traditional and historical methods for conserving energy in buildings is highly beneficial. Embracing traditional practices that have historically influenced architecture and civil engineering in specific regions is a fundamental guideline. In the past, people possessed a profound understanding of leveraging their environment and maintaining a harmonious relationship with it. Despite lacking modern technology to minimize a building's energy requirements, they had acquired knowledge on how the environment could contribute to sustaining relatively comfortable thermal conditions. This encompassed insights into shaping buildings, selecting appropriate construction materials, determining optimal facade orientations, and harnessing environmental elements, particularly solar energy, to positively influence a building's energy balance. These age-old principles offer valuable lessons for contemporary sustainable practices in building design.

In countries with high latitudes, a common practice involved orienting the main facade of buildings toward the south, concentrating most openings and windows in this direction. The southern part of a building served as a living space for daily activities, while the northern part was designated for utility and storage rooms. Inclined roofs were favoured over horizontal ones to optimize sun exposure, facilitate quick snow melting, and mitigate the impact of wind. The strategic use of leafy trees for shading from the south and conifer trees for protection against strong winds and environmental factors from the north was customary. Solar spaces in the form of glazed verandas situated at the southern part of a building were already employed in the past, serving as buffer zones. Additionally, vestibules were incorporated to shield against wind and the surrounding ambient conditions, representing a traditional element of building design. Notably, the north part of a building typically lacked openings and windows, ensuring thermal tightness in this region. These historical practices showcase a thoughtful approach to environmental adaptation and energy efficiency in architectural design.

The interior layout of buildings in the past was meticulously designed. A customary practice involved placing a fireplace and stove in the central part of a building, and the heat was efficiently distributed either naturally or through dedicated air ducts, ensuring specific rooms received adequate warmth. In more extensive structures such as large buildings, palaces, and castles, an innovative underfloor system akin to contemporary heating systems was employed to disseminate heat from the central kitchen throughout the entire building. Additionally, certain spaces or rooms were closed off during the winter months, resembling a precursor to the modern concept of organizing heated spaces with temperature zoning. These historical approaches exemplify a thoughtful and strategic use of heating systems for optimal comfort and efficiency.

Numerous advanced ideas and solutions were previously discovered and effectively applied in the past. Unfortunately, these insights have been overlooked in recent decades. It is now our responsibility to carefully examine traditional avenues for energy conservation in buildings within a specific region. Leveraging modern technology, we can implement numerous innovative solutions for reducing energy consumption in buildings. It is crucial to acknowledge that these solutions should be grounded in traditional methods of energy conservation and the principles of traditional construction and harmonious coexistence with the environment. The concept of eco-buildings and energy conservation has already been developed, tested, and validated. Implementing innovative energy conservation methods rooted in traditional architecture emerges as a robust solution for current and future energy conservation challenges in buildings (Chwieduk, 2017).

A substantial portion of energy consumption is attributed to space cooling, space heating, lighting, and appliances. Notably, energy demands for space heating in cold climates and space cooling in hot climates stand as major global challenges. The integration of renewable technologies in European countries is anticipated to lead to a significant reduction in energy consumption for heating and cooling, potentially reaching up to 70% by the year 2050 (EUC, 2016). In Asian countries, projections suggest a substantial increase in average cooling energy requirements, with estimates indicating a potential rise of up to 750% for residential buildings and 275% for commercial buildings by the year 2050 (Santamouris, 2016). The energy demands are exacerbated by the influence of direct and diffuse solar radiation on urban centers, leading to elevated surface and air temperatures. This phenomenon contributes to the creation of an urban heat island, characterized by a persistent reservoir of heat during both day and night. The urban heat island phenomenon has implications for local, regional, and global climates. While it diminishes the need for heating in certain instances, it simultaneously amplifies the demand for cooling measures due to the heightened air temperatures. Hence, the quantity of incident solar radiation (insolation) that reaches the surfaces of buildings serves a crucial function in influencing energy demands and the global climate. The resulting distribution of incident, reflected, absorbed, and transmitted energy within a building can be contingent on factors such as geographical location, local climate, urban context, design, thermal mass, and materials.

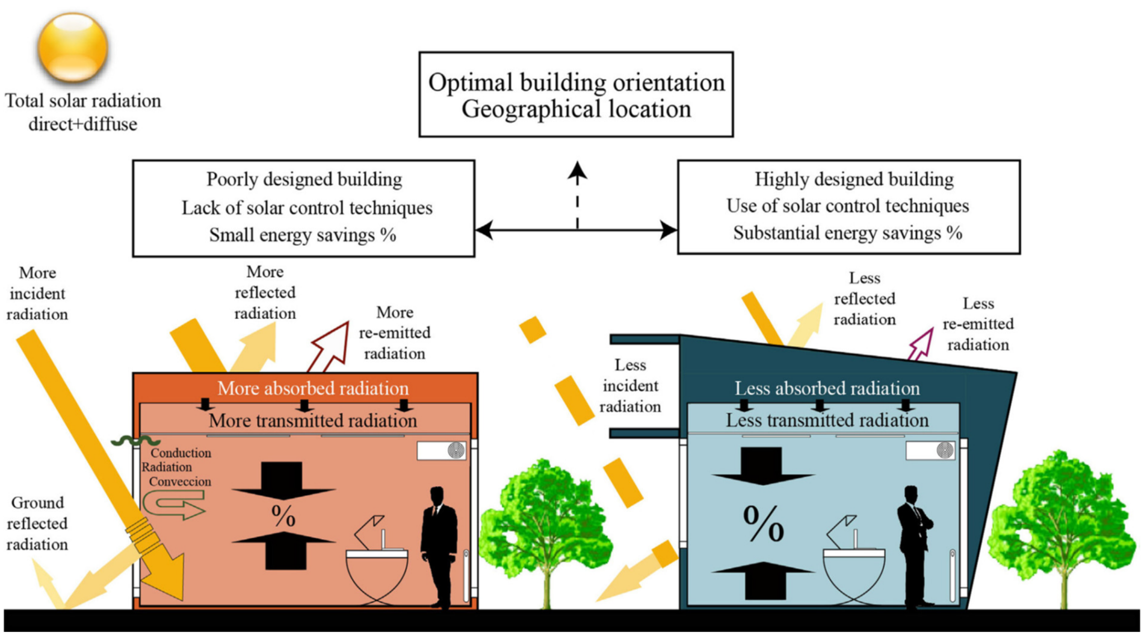


Figure 2.5 Comparison of insolation and energy savings in buildings with and without passive design, adopted from Chwieduk (2017).

A study conducted by Santamouris (2016) asserts that inadequately designed buildings are prone to absorbing solar radiation, leading to rapid heat accumulation that amplifies the need for cooling energy (Santamouris, 2016). The removal of such heat gains can be challenging, requiring additional support from natural, renewable, or mechanical systems (Gagliano et al., 2016). In contrast, well-designed buildings not only manage the effects of solar radiation but also mitigate the transfer of heat, subsequently lowering internal energy demands and resulting in energy savings for air conditioning systems (HVAC). Figure 2.4and Figure 2.5 depicts a diagram illustrating insolation and energy savings in buildings with and without passive design.

Passive energy conservation strategies for controlling insolation in modern buildings include solar control techniques for solar protection and renewable solar cooling technologies designed for solar collection but with a cooling purpose. However, the effectiveness of these strategies in terms of thermal, daylighting, and visual performance depends on factors such as available renewable sources, the selected strategy, and their orientations. These strategies encompass various methods that can be carefully designed to mitigate the impact of solar radiation on the building envelope and interior space, ultimately reducing the demand for cooling energy. The primary categories, including facade self-shading, shading devices, window-to-wall ratio, and building orientation, play a crucial role in decreasing insolation, providing shading, and minimizing energy requirements. Nevertheless, the improper selection and application of these strategies may compromise daylighting and visibility comfort (Liu et al., 2015; Taleb, 2014).

Building Orientation (BO) refers to the alignment of the building layout on a horizontal plane or along the sun's path, indicated by azimuth angles ranging from 0° to 360°. Commonly, N corresponds to 0° or 360°, E to 90°, S to 180°, and W to 270°. The primary objective of proper building orientation is to mitigate insolation impacts in summer and maximize daylighting in winter. This principle is especially evident in rectangular buildings. Therefore, well-oriented elongated shapes are frequently employed in various climatic conditions. These shapes, with larger facades oriented towards the under heated period, enhance daylighting in winter, while the shorter facades facing the overheated period control excessive insolation in summer. The reduction in the surface area exposed to solar radiation contributes to energy savings for cooling. It's important to note that each facade's exposure to the sun varies in each hemisphere. Generally, facades facing south in the Northern Hemisphere and those facing north in the Southern Hemisphere experience higher sun altitudes in summer and lower altitudes in winter. Facades facing north-south receive double the sunlight in winter, while those facing east-west receive at least four times the insolation in summer. Figure 2.6 illustrates a rectangular building in the summer sun's path in both the Northern and Southern Hemispheres, adopted from (Valladares-Rendón et al., 2017).

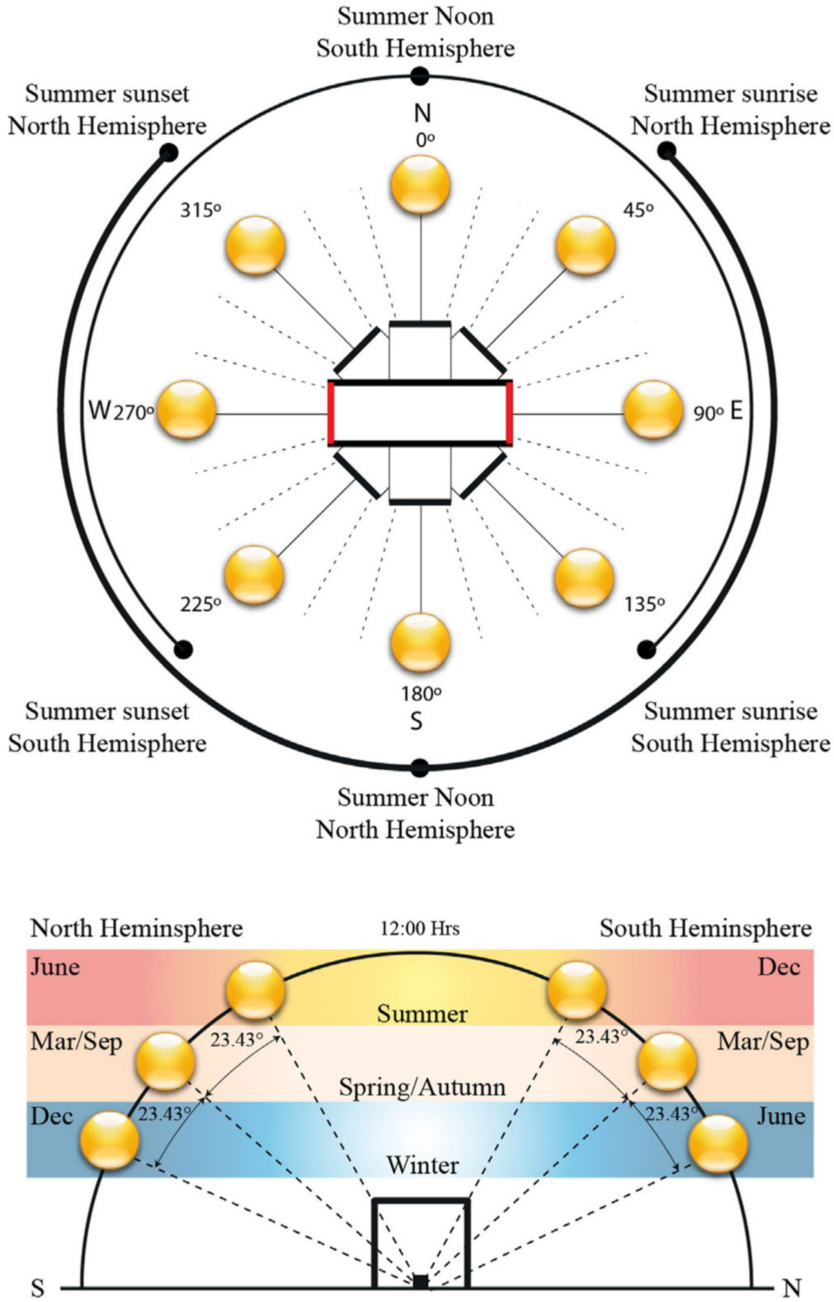


Figure 2.6 Illustrates a schematic plan and section in 2D view of a rectangular building positioned in the summer sun's path in both the Northern and Southern Hemispheres

The Window-to-Wall Ratio (WWR) represents the percentage of glazing area compared to the total wall area of a building facade. The primary goal of WWR is to minimize solar heat gains while enhancing heating, cooling, daylighting, and ventilation. Both the National Energy Code for Buildings (NECB) 2011 and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) have integrated WWR standards into their guidelines for new building construction. WWR is typically measured on a scale ranging from 0% to 100%, or a factor of 0–1, representing no windows to full windows, respectively. Extreme values on this scale can lead to adverse effects on energy efficiency, daylighting, and visibility.

BIM, or Building Information Modelling, is a digital representation of a facility's physical and functional characteristics. It offers significant potential for life-cycle modelling and building management. While BIM policies have evolved to meet the needs of the Architectural, Engineering, Construction, Owner, and Operator (AECOO) trades, its application has primarily focused on large-scale commercial or residential projects, often overlooking small-scale residential sectors. BIM can be broadly categorized into two areas: modelling and analysis. Modelling focuses on creating digital representations, while analysis includes energy simulations, quantity take-offs, environmental impacts, and data communication among stakeholders. BIM is multidimensional, with dimensions like 3D-BIM for modelling, 4D-BIM for adding a time dimension, 5D-BIM for cost estimation, 6D-BIM for sustainability simulations, and 7D-BIM for building performance management and operation. Several reputable BIM software tools are used for residential purposes, such as VisionREZ, Vertex BD, and Revit, each with its strengths and weaknesses. Designers and builders select software based on project requirements and complexity, often incorporating add-ins like Autodesk Insight 360 for extended analysis capabilities.

In terms of energy analysis and simulation, various software tools have been developed for energy optimization of buildings. Some are compatible with BIM for integration, while others are independent. The Building Energy Simulation Tools - Directory lists around 196 energy simulation tools, making it challenging to select a reliable tool. These tools range from whole-building simulators to building system calibrators and energy auditors, offering detailed analysis for energy conservation and fault detection purposes. These tools typically fall into three categories: applications with integrated simulation engines (e.g., Energy Plus, ESP-r, IES-VE, IDA ICE), software that docks to a specific engine (e.g., DesignBuilder, eQuest, RIUSKA, Sefaira), and plugins for other software enabling performance analysis (e.g., DIVA for Rhino, Honeybee, Autodesk Green Building Studio). Autodesk Revit is used as the BIM software, known for its comprehensive features and recognized as a top-rated software in the industry. The study also utilizes the Green Building Studio add-on to Revit, Insight 360, for analysis purposes.

2.5 ARTIFICIAL NEURAL NETWORK MULTI LAYER PERCEPTRON MODELLING

Building operations account for a significant portion of total primary energy consumption worldwide, largely due to the widespread use of Heating, Ventilation, and Air Conditioning (HVAC) systems to enhance building comfort. Balancing the need for energy efficiency with maintaining comfortable indoor conditions presents a complex optimization challenge that requires intelligent system design. In recent years, various methodologies based on Artificial Intelligence (AI) techniques have been developed to address this challenge, aiming to optimize energy use in HVAC systems while ensuring occupant comfort. These AI tools encompass functions such as pattern recognition, optimization, and predictive control. However, despite significant advancements, the application of AI technology in building control is still evolving, with room for improvement in terms of performance. One of the key challenges is the requirement for large amounts of high-quality real-world data, which is often lacking in the building and energy sectors. Nonetheless, studies have shown promising results. For example, research by Halhoul Merabet et al., (2021) indicates that from 1993 to 2020, the application of AI techniques and personalized comfort models has led to average energy savings ranging from 21.81% to 44.36% and comfort improvement ranging from 21.67% to 85.77%. These findings underscore the potential of AI in enhancing energy efficiency and comfort in buildings, highlighting the ongoing need for further research and development in this field.

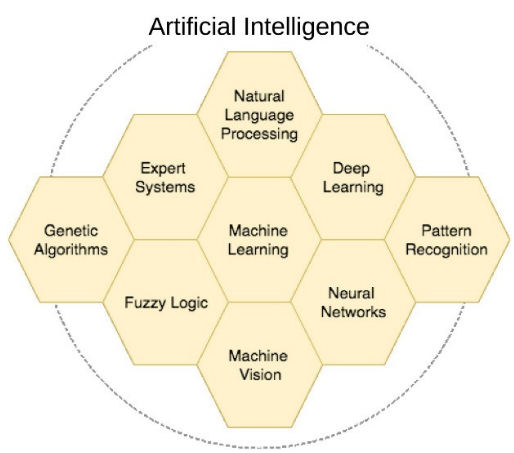


Figure 2.7 Different AI applications (Source: Panchalingam & Chan, 2021)

A recent state-of-the-art review by Panchalingam & Chan, (2021) on artificial intelligence for Smart Buildings identified several key AI technologies. These include expert systems, fuzzy logic, genetic algorithms, machine learning, machine vision, natural language processing, neural networks, and pattern recognition (see Figure 2.7). The review highlighted that while machine learning, neural networks, and pattern recognition are well-studied, other topics such as deep learning and natural language processing are less emphasized in the context of Smart Buildings. The quest for sustainable buildings that balance occupant comfort with improved energy efficiency remains a pressing research challenge. Leveraging AI to enhance energy efficiency while ensuring occupant comfort poses several research challenges and paves the way for future research avenues. As buildings become smarter with the integration of AI, networking, and the Internet of Things (IoT), new opportunities emerge to address complex operational, design, and user experience challenges. Connected buildings also offer solutions for smart cities and smart grid challenges. However, the success of AI predictive modelling in thermal comfort systems hinges on high-quality, representative data. Limited or biased datasets can lead to overfitting, emphasizing the need for genuine and diverse data collection efforts in sustainable building research. The study by Halhoul Merabet et al., (2021) highlights the need for more data for AI modelling, as well as the importance of IoT-enabled smart buildings for efficient management and data collection. Addressing challenges such as security, privacy, and data sensitivity in smart buildings, along with implementing context awareness mechanisms for dynamic comfort adjustments based on human behaviour, are crucial for future research. Additionally, involving humans in the comfort modelling loop and exploring mixed-method approaches that combine AI and ML techniques hold promise for achieving greater energy savings while maintaining occupant comfort in buildings.

In contemporary times, global comfort indices not only quantify the comfort of indoor environments but also possess predictive capabilities for various reasons. The primary motivation is to enable the automatic control of diverse actuators, particularly to enhance building performance, with a focus on energy efficiency (Qavidel Fard et al., 2022). Comfort prediction through artificial intelligence has been a subject of exploration in numerous studies, leveraging machine learning techniques such as Artificial Neural Networks (ANN), Decision Trees (DT), Support Vector Machines (SVM), Bayes Networks (BN) and General Linear Model (GLM). Among these, ANNs are frequently employed in AI implementation (Ashtiani et al., 2014; Moon et al., 2013; Moon & Jung, 2016; Moon & Kim, 2010; Özbalta et al., 2012). Some studies use specific models like Multilayer Perceptron (MLP) and Neural Network Autoregression with Exogenous Input (NNARX) to predict indoor temperature and relative humidity (Mba et al., 2016; Moon, 2015; Mustafaraj et al., 2010, 2011). Others targeting outputs like Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) deploy models such as Back-Propagation Neural Network (BPNN), Feed-Forward Neural Network (FFNN), Radial Basis Function Networks (RBFN), and Random Forests (RFs) (Atthajariyakul & Leephakpreeda, 2005; Buratti et al., 2015; Castilla et al., 2013; Chaudhuri et al., 2018; Moon, 2012; Ruano & Ferreira, 2014; von Grabe, 2016; Z. Wang et al., 2019). Nonetheless, these studies predominantly employ artificial intelligence to predict quantities or indices often associated with thermal comfort, rarely encompassing various Indoor Environmental Quality (IEQ) aspects. In the contemporary landscape, algorithms need to incorporate a comprehensive array of comfort factors beyond thermal considerations. The integration of Internet of Things (IoT) and Wireless Sensor Networks (WSN) has facilitated the extensive use of artificial intelligence algorithms, which typically demand substantial datasets for effective processing.

Building managers are increasingly adopting Artificial Neural Networks (ANN) for sophisticated thermal control within structures. These networks, modelled after the human brain's learning process, prove effective in managing non-linear systems or those with unclear dynamics. A notable characteristic of ANN models is their adaptability, achieved through a self-tuning process, distinguishing them from conventional mathematical models like regression or proportional–integral–derivative controllers. This adaptability enables precise decision-making even in the face of unusual perturbations, disturbances, or changes in the building's background conditions, eliminating the necessity for external expert intervention. This approach ensures accurate and efficient thermal regulation, contributing to enhanced building performance and occupant comfort on a global scale (Moon et al., 2009).

Moon & Kim (2010) propose a comprehensive control methodology comprising a thermal control logic framework encompassing four thermal control logics. This includes two predictive and adaptive logics utilizing Artificial Neural Network (ANN) models, along with a system hardware framework. The models aim to achieve thermal comfort in living areas by considering not only air temperature but also humidity or Predicted Mean Vote (PMV) as control variables. Additionally, the models strive to minimize overshoots and undershoots of control variables through ANN-based predictive and adaptive control. The performance of these thermal control methods was tested on a typical two-story single-family home in the U.S., modelled using International Building Physics Toolbox (IBPT) and MATLAB. The analysis indicated that the proposed ANN-based predictive and adaptive control strategies significantly improved thermal conditions compared to typical thermostat systems. This improvement was evident in the extended comfort periods for air temperature, humidity, and PMV, as well as the reduction of over and undershoots. Thus, the study suggests that the control methods utilizing ANN hold the potential for enhancing thermal comfort in residential buildings (Moon & Kim, 2010).

Summing up the insights gleaned from these studies, it becomes evident that artificial intelligence plays a pivotal role in crafting increasingly robust predictive models in this domain. Leveraging AI methods for predicting comfort levels holds paramount importance not only for enhancing occupant satisfaction but also for optimizing energy efficiency in buildings (Sajjadian et al., 2019). This application becomes instrumental in mitigating the well-known building performance gap, representing the variance between predicted and actual building performance.

2.6 SUMMARY

The literature review encompasses a comprehensive exploration of various aspects related to sustainable development, building performance, and occupant comfort. Teng et al. (2019) contributed by developing a dynamic system for the Sustainable Development of Green Building (SDGB), identifying market development, economic value, stakeholder participation, and ecological importance as crucial factors. Ruparathna et al. (2015) emphasized the significance of asset management in public sector buildings and proposed a framework for assessing the level of service in recreational center buildings. Comfort, a key element in building automation, was linked to achieving Sustainable Development Goals (SDGs), acknowledging the influence of technological innovation, socio-economic factors, and cultural aspects. The discussion on thermal comfort delved into ASHRAE standards, introducing the adaptive method that considers psychological, cultural, and social aspects. Factors influencing thermal comfort, including air temperature, mean radiant temperature, and humidity, were explored alongside the adaptive thermal comfort model, emphasizing occupants' active roles in interacting with their environment. Additionally, the review acknowledged various bioclimatic indices and highlighted the importance of visual and acoustic comfort in building design.

Passive energy conservation strategies, such as solar control techniques and renewable solar cooling technologies, were introduced. Strategies like facade self-shading, shading devices, WWR, and building orientation were discussed, emphasizing their impact on energy efficiency, daylighting, and visibility. The review concluded by highlighting the need to revisit traditional energy conservation methods and integrate them with modern technology for sustainable building practices. The role of artificial intelligence in predicting comfort levels was discussed, focusing on the use of ANN and the necessity of including various comfort factors in AI models. The importance of energy conservation in buildings, drawing from traditional methods, was underscored, stressing the potential for integration with modern technology.

CHAPTER 3

SCOPE AND OBJECTIVES

3.1 GENERAL

This section provides an overview of the scope and objectives of the study. It outlines the key research questions, the methodology adopted, and the significance of the study in the field of building comfort and energy efficiency. The following are the observations reported from the literature review of previous chapter.

1. Performance indicators in building design and operation facilitate measurement, comparison, goal identification, improvement planning, and continuous monitoring of changes over time. Effective indicators are simple, flexible, relevant, reliable, easily converted into knowledge, and garner trust from stakeholders.
2. Stakeholder engagement is crucial in developing indicators to ensure alignment with their needs and enhance effectiveness and acceptance. Various methodologies, such as expert consultations and literature reviews, are used to develop comprehensive indicators for assessing indoor environments and promoting occupant health.
3. Key Performance Indicators (KPIs) evaluate environmental performance, enabling comparison of design solutions and monitoring a building's performance over its lifespan. These KPIs assess aspects such as energy efficiency, indoor air quality, and sustainable material usage. Studies categorize KPIs into groups such as financial, physical, and functional for practical utility.
4. Incorporating environmental comfort indicators in sustainability assessment tools for school buildings is crucial for enhancing occupant comfort, health, and safety. Comprehensive frameworks for evaluating building performance provide a structured approach for assessing different facets of operational effectiveness and identifying areas for improvement. Dynamic systems, incorporating statistical modelling and advanced technologies, are used to understand the driving forces for sustainable development in green buildings.
5. Thermal comfort, defined by ASHRAE, is complex and influenced by various factors like psychology and environment, making it challenging to quantify.
6. A global comfort index, derived from studies, is vital for health, productivity, energy efficiency, and indoor renovation, providing a holistic view of comfort enhancement.

7. Human comfort, encapsulated in Indoor Environmental Quality (IEQ), is crucial for physical and mental well-being, linking to health, performance, and sustainability.
8. Building performance evaluation includes whole-building, system, and component levels, categorizing assessments into feature-specific and performance-based methods for comprehensive energy efficiency evaluation.
9. Historical architectural practices highlight the importance of harmonizing with the environment and optimizing building features for energy conservation, offering lessons for modern building design.
10. Traditional techniques, like orienting buildings towards the south and using strategic tree planting, were common in high latitude countries to optimize sun exposure and wind protection.
11. Historic buildings utilized efficient heat distribution methods, such as underfloor systems, and practiced seasonal space zoning, similar to modern practices.
12. Integrating traditional energy conservation methods with modern technology can lead to innovative solutions for reducing energy consumption in buildings.
13. Space heating, cooling, lighting, and appliances are significant contributors to energy consumption in buildings, with projections showing substantial increases in cooling energy requirements by 2050.
14. Passive energy conservation strategies, including solar control techniques and building orientation, can reduce the impact of solar radiation on buildings, leading to energy savings for cooling systems.
15. Artificial Intelligence (AI) techniques are increasingly used to optimize energy use in HVAC systems while ensuring occupant comfort. These techniques include pattern recognition, optimization, and predictive control, aiming to balance energy efficiency with indoor comfort.
16. Despite advancements, challenges remain in AI application for building control, such as the need for large amounts of high-quality real-world data. Studies have shown promising results, with AI techniques leading to significant energy savings and comfort improvements in buildings.
17. A review identified key AI technologies for Smart Buildings, including machine learning, neural networks, and pattern recognition. While machine learning and neural networks are well-studied, other areas such as deep learning and natural language processing are less emphasized in the context of Smart Buildings.

18. AI, particularly Artificial Neural Networks (ANN), is frequently used in predicting indoor comfort factors. Specific models like Multilayer Perceptron (MLP) and Neural Network Autoregression with Exogenous Input (NNARX) are employed for predicting indoor temperature and relative humidity, while models like Back-Propagation Neural Network (BPNN) and Feed-Forward Neural Network (FFNN) are used for Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV).
19. ANN models are effective in managing non-linear systems or those with unclear dynamics, providing adaptability and precise decision-making for thermal control. They can achieve accurate and efficient thermal regulation, enhancing building performance and occupant comfort.
20. Studies propose comprehensive control methodologies using ANN models for thermal control, aiming to achieve thermal comfort by considering variables such as air temperature, humidity, and PMV. These methodologies significantly improve thermal conditions compared to typical thermostat systems, indicating the potential for enhancing thermal comfort in residential buildings.
21. AI plays a crucial role in developing robust predictive models for enhancing occupant satisfaction and optimizing energy efficiency in buildings. It helps mitigate the building performance gap, representing the variance between predicted and actual building performance.

3.2 RESEARCH GAP

From the literature review (Chapter 2), it was observed that:

- **Importance of Buildings**: Buildings contribute significantly to global energy-related CO2 emissions (37%) and energy consumption (36%). Global CO2 emissions, mainly from fossil fuel consumption, reached 33 billion metric tons in 2021, with over 80% from fossil fuels. CO2 is a major greenhouse gas, trapping heat and causing global warming. Human activities, especially burning fossil fuels, are the main cause of this warming. India's CO2 emissions share was 6.8% in 2021, a 156% increase from 2000. Climate change effects include rising temperatures, more frequent heatwaves, changing precipitation patterns, and more intense extreme weather events, impacting ecosystems, agriculture, water resources, and human health.
- **Indian Education Landscape**: India has a vast educational sector (1,522,346 institutions), emphasizing the need for energy-efficient building maintenance.

- **Energy Conservation Strategies**: Current energy conservation strategies worldwide often lack comprehensive policies that address all sectors and aspects of energy use, leading to inefficient practices and slow adoption of renewable energy sources. In India, infrastructure challenges and ineffective policy implementation hinder the widespread adoption of energy-efficient technologies. Additionally, subsidized energy prices discourage conservation efforts, and there is a need for more awareness and education programs to inform the public about the importance of energy conservation. Balancing energy efficiency with human comfort parameters (thermal, visual, acoustical comfort) is essential for sustainable indoor environments. Bridging these gaps requires comprehensive policies, increased investment in renewable energy, and improved awareness programs.
- **Balancing Energy and Comfort**: Achieving balance is a challenge. Sustainability evaluation methods include calculation-based, measurement-based, and hybrid approaches. Prominent rating systems like BREEM, LEED, and GRIHA guide sustainable construction. Users often find comfort at temperatures below standards.
- **Application of AI in building sector:** The current application of AI in building comfort and energy conservation faces several gaps. These include limited integration of AI technologies into existing building management systems, challenges related to data accessibility and quality, complexity and interpretability of AI algorithms, cost and resource constraints, lack of clear regulatory frameworks, and the need for user acceptance and training. Addressing these gaps will require collaboration between stakeholders to develop and implement effective AI solutions that optimize building comfort and energy efficiency.

This review sets the context for the research, focusing on the critical factors and challenges in building comfort, energy conservation, and sustainability.

3.3 SCOPE AND OBJECTIVES OF THE RESEARCH WORK

3.3.1 Objectives of the Research

- Evaluation of KPIs using Fuzzy-AHP based on stakeholders' perceptions for tailored local parameters.
- Developing a framework for a Parameter Index based on data collection and alignment with standards, leading to the derivation of a novel comfort index for existing buildings.

- Developing an energy conservation approach utilizing BIM and building envelope information with energy data.

- Validation of the integrated comfort model through the ANN-MLP model.

3.3.2 Scope of the Research Work as Follows

- Evaluation of Key Performance Indicators (KPIs) for NIT Warangal buildings, with a focus on the 1.8k hostel complex (1,800 rooms). The identification of KPIs by determining weights via surveys, ensuring data reliability with consistency checks, and use FAHP for ranking.
- Establishment of a comprehensive comfort index for institutional buildings. The research endeavors to construct a holistic model that encompasses three vital dimensions of comfort: thermal, acoustic, and visual comfort.
- This research aims to reduce building energy consumption while maintaining comfort and environmental sustainability using BIM and energy simulation. Objectives include material assessment, 2D and 3D modeling, energy simulation, component analysis, orientation variation, and glazing impact assessment.
- Develop ANN-MLP model for Reconstruction of combined comfort and its validation using performance metrics.

3.4 RESEARCH METHODOLOGY

A comprehensive research methodology was developed based on the defined objectives and scope, organizing the work into four distinct phases.

Phase-1:

Performance indicators are extracted from the literature, with a focus on tailoring them to suit institutional buildings. Key Performance Indicators (KPIs) are then identified among these indicators using the Fuzzy-AHP method.

Phase-2:

Developing a unified comfort index by integrating indoor environmental parameters and stakeholder perceptions, which involved data collection and the creation of weighted questionnaires for evaluating comfort in the selected case study buildings.

Phase-3:

Formulating energy conservation strategies integrating building metrics, envelope, orientation, and Window-to-Wall Ratio (WWR). This phase also included 3D modelling and analysis using DoE 2.2 data, exploring different orientations, envelope materials, and actual energy consumption data.

Phase-4:

Development of a precise Artificial Neural Network (ANN) Multi-Layer Perceptron (MLP) model for predicting indoor comfort. This model is used to reconstruct and predict overall comfort levels using available data.

A schematic diagram of the research methodology adopted along with the variables considered in each phase is shown in Figure 3.1.

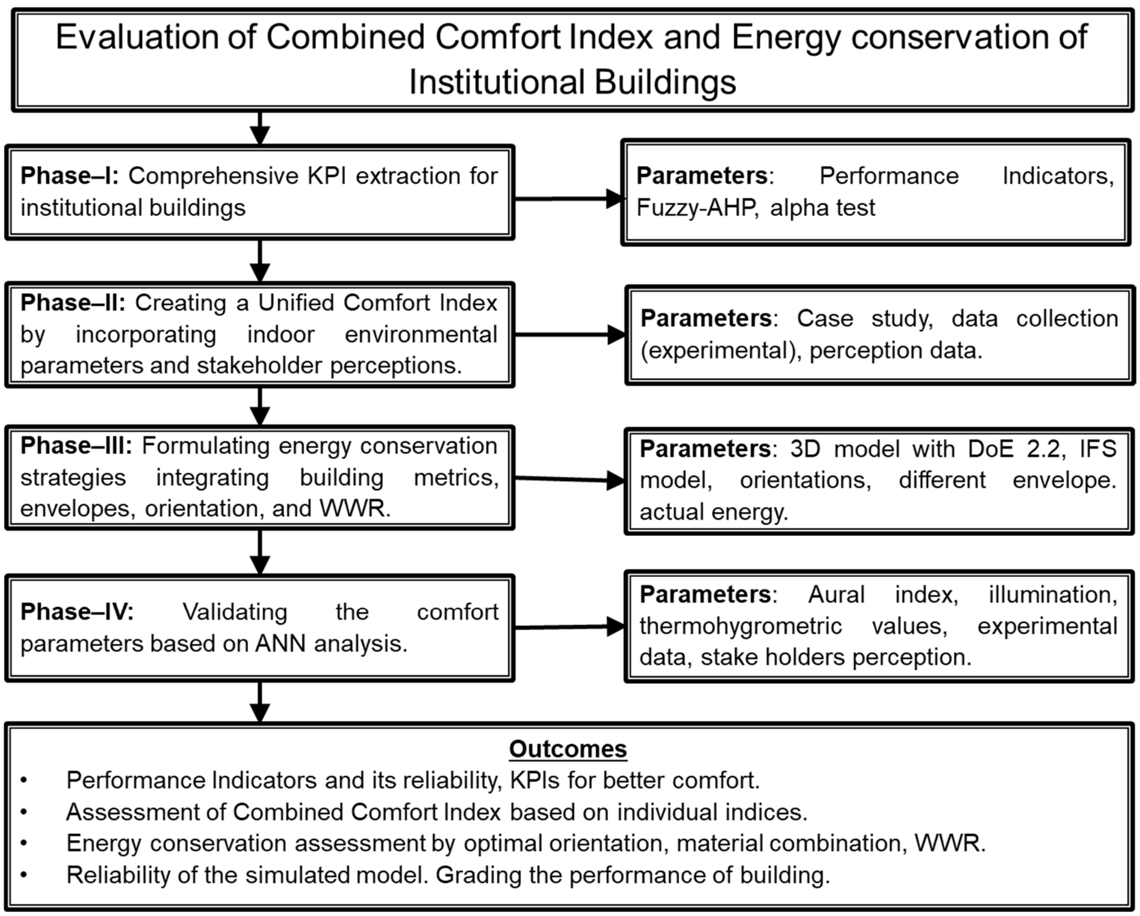


Figure 3.1 Schematic Diagram of the Research work

CHAPTER 4

EVALUATION KPIs FOR INSTITUTIONAL BUILDINGS

The primary aim of this study is to identify KPIs and assess the CCI in institutional buildings located at NITW, India, while also formulating energy conservation strategies. This primary objective is broken down into four sub-objectives, each of which undergoes detailed examination and presented in various chapters. This chapter addresses the first sub-objective, which involves the identification of performance indicators and the extraction of KPIs for institutional buildings.

4.1 INTRODUCTION

Building operations are responsible for minimizing costs while enhancing performance. Central to this process is the measurement of building performance, serving as the foundation for informed decision-making and future strategies (Ng et al., 2013). This approach takes into account local environmental conditions, as adjustments can significantly impact operational efficiency (Amaratunga et al., 2000; Amhaimedi et al., 2023). However, evaluating current service levels and crafting a strategy aligned with performance goals is crucial. Inefficient practices can result in ineffective, costly facilities that lack adaptability (Davis & Cable, 2005). Methods for assessing building performance encompass inter-building and intra-building approaches, with the former comparing performance against similar buildings and the latter focusing on individual performance metrics (Balamuralikrishnan et al., 2023; Bangia & Raskar, 2022; Douglas, 1996).

In a comparative analysis of research on KPIs for sustainable building performance evaluation, various research approaches and areas of focus become apparent. With an emphasize KPIs related to energy efficiency, indoor environmental quality and sustainability (Peng Xu et al., 2012), while Dufvelin., (2018) delves into KPIs connected to environmental, economic, and social aspects of sustainability (Dufvelin, 2018). A comprehensive literature review encompasses KPIs concerning energy, water, materials, indoor quality and site sustainability (Maslesa et al., 2018). Moreover, a study conducts a multi-stakeholder analysis, exploring KPIs associated with sustainability, affordability, and livability. (Angelakoglou et al., 2019). This comprehensive approach is complemented by a specific concentration on KPIs for building energy management, with a focus on energy consumption, efficiency, and conservation (Y. Li et al., 2017). The overarching emphasis on KPIs for sustainable buildings highlights energy efficiency and environmental sustainability. (Xu & Chan, 2013). Extending the global perspective, an evaluation centers on KPIs for green buildings in office settings in Malaysia, taking into account factors such as energy, water, indoor quality, and materials. (Mokhtar Azizi et al., 2013). Lastly, a comprehensive review of KPIs for sustainable buildings covers various aspects including energy efficiency, indoor quality, and environmental impact. (Ho et al., 2021a). This varied array of research approaches is interconnected, highlighting the multifaceted nature of KPIs in evaluating sustainability and performance in the built environment on a global scale.

The study encountered significant challenges, including the subjective nature of data, ambiguity in Performance Indicators (PIs) and logistical issues in surveying diverse professionals. However, the study meticulously addressed these issues, aiming to provide innovative insights into institutional building performance assessment. While AHP has its limitations in minimizing subjectivity and aggregating data, introducing Fuzzy Logic into the AHP framework proves valuable for addressing these complexities.

Despite these complexities, the study aimed to systematically address these issues, ultimately contributing innovative insights into the assessment of institutional building performance. However, AHP has limitations in terms of minimizing inherent subjectivity in data and aggregating response data into a single numerical value. As a result, researchers have advanced AHP with additional methods (Darani et al., 2018; Wicher et al., 2019). Introducing Fuzzy Logic into the AHP framework proves to be a valuable approach for addressing these complexities (Darani et al., 2018; Vyas et al., 2019), enhancing the ability to handle such challenges effectively.

In the quest for more efficient and user-centered approaches to assessing the performance of institutional buildings, this chapter delves into the meticulous evaluation of KPIs. Institutional buildings, often housing diverse functions and occupants, require a nuanced understanding of what contributes to their overall success. This chapter, crafted with international perspectives in mind, embarks on a journey to identify, evaluate, and prioritize these KPIs, drawing from a rich tapestry of existing literature and local contextual conditions.

Framing the Context: In the era of global urbanization and rapidly evolving architectural paradigms, the importance of institutional buildings cannot be overstated. They serve as hubs for education, research, healthcare, governance, etc., impacting the daily lives of countless individuals. The design and management of these structures have far-reaching implications for occupants, resource consumption and environmental sustainability. The assessment of institutional building performance is a multidimensional task that necessitates the quantification of both tangible and intangible factors. Such assessments offer insights into energy efficiency, user satisfaction, environmental impact and overall functionality. The challenge lies in identifying the most pertinent KPIs that encapsulate these factors.

Merging Global Insights and Local Relevance: This chapter's approach embraces international best practices while accommodating the nuances of local contexts. We consider a blend of objective and subjective methodologies, harnessing the expertise of professionals with over 15 years of experience in the field. The reliance on local experts ensures that the findings remain grounded in practicality, while the combination of objective and subjective data sources provides a holistic view of building performance.

KPIs and FAHP: A significant aspect of this chapter's methodology is the application of the FAHP. FAHP enables us to determine the relative importance of KPIs by accommodating the inherent subjectivity and vagueness in decision matrices. This approach not only aligns with international trends but also facilitates a more user-friendly assessment.

A Global Perspective on KPIs: The results of this research highlight the KPIs that wield the most influence over the overall comfort and efficiency of institutional buildings. Thermal Condition, Illumination and Acoustical Quality emerge as the leading parameters, surpassing their counterparts in significance. These findings resonate with the global shift towards prioritizing occupant well-being, energy efficiency and sustainability in building design and management.

Implications and Future Directions: The implications of this study extend to the domains of design and Facility Management, offering practical tools for enhancing building performance and user satisfaction. The insights provided aim to contribute to international discussions on sustainable building practices and user-centric design principles, ultimately enhancing the quality of institutional spaces on a global scale. While this chapter offers valuable insights into KPIs for institutional building assessment, it acknowledges the context-specific limitations and paves the way for future research to explore broader applications and employ advanced techniques in this evolving field.

4.2 METHODOLOGY

4.2.1 Identification of Indicators

The first stage is to select the most suitable norm to develop a set of indicators by considering the building performance, local conditions of the environment and goals of the organization (Roaf, 2005). The methodological approach and the comprehensive flowchart in Figure 4.1 demonstrate the systematic nature of this study. In this research, the selection of appropriate indicators is finalized through a review of available literature in the field of building performance and a survey conducted among professionals from various disciplines. Table 4. **1** shows various PIs used in the literature for different types of buildings.

Table 4. 1 List of PIs Vs types of building

Type of building	PIs
Educational Institutional Building/Schools/University Facilities (Buratti et al., 2018b; Y. Kim et al., 2018; Saraiva et al., 2018; Ulla et al., 2015; Zaki et al., 2017; Zhong, 2020b)	Pressure Thermal illuminance Acoustics Carbon dioxide Temperature and humidity Building maintenance costs Utility costs Operating costs Custodial and janitorial costs Deferred maintenance, and deferred maintenance backlog Capital costs Capital renewal cost Facility condition assessment cost Occupancy costs Churn costs Adequacy of space assignment Adequacy of facility security Customer satisfaction assessment

	Hours available
	Release of survey result
	Securement and management of workforce
	Training programs for worker enhancement of workers' skills
	Employee satisfaction assessment
	Communication among staff
	Adequacy of work space
	Task record
	Performance evaluation and report
	Resource consumption-Energy
	Safety management
	Space utilization
	Resource consumption-Water
	Security management
	Space management regulation
	Establishment of space timetable and reservation system
	Arrangement of management plan
	Computerized facility management system
	O&M plan for each facility
	Furniture
	Waste discharge
	Defining O&M work
	Assessment of space efficiency
	Indoor Environmental Quality (IEQ)
	Accessibility
	Work efficiency assessment
	Reflection of trend requisition
	Establishment of management plan
	Required performance level
	Condition assessment of equipment and tools

	Establishment of facility performance indicator
Public recreational buildings(Lavy et al., 2010; Ruparathna et al., 2017b)	Vandalism and security User satisfaction Indoor air quality Thermal comfort Cleanliness Indoor noise level luminance level Adequacy of building amenities Condition of building equipment Access to services in normal and emergency conditions Number of deaths, injuries and illnesses Non planned service interruptions Number of user days with no service interruptions Quality of swimming pool water Annual energy use intensity Annual renewable energy consumption Annual GHG emission reduction Annual water consumption per user Amount of water recycled Average cost of operation Amenities for persons with disability
Built Assets/Built environments (Arukala et al., 2019; Lavy, 2011b; Lavy et al., 2014)	cost and expenditures - operation and maintenance Energy Building functions Real estate Space adequacy Parking Current Replacement Value Building physical condition

Sanitary, plumbing and storm water
Indoor Environmental Quality
Productivity
Occupant satisfaction
Appearance
Selection of site
Protection of site
Land contamination
Mitigating ecological impact
Balancing site ecology
Protecting biodiversity
Ease of accessibility
Developing density
Intercommunity network
Safety of pedestrian
Car parking facility
HVAC
Rate of ventilation
Internal and external lighting
Provision of hot water
Heat transmission
Renewable technology on
Monitoring energy
Energy saving
CO_2 Strategy
Reducing the consumption of water
Harvesting water
Recycling of water
Innovative water recycling
Water conservation technique
Water irrigation technique
Groundwater recharge

Low impact environment material
Use of non- renewable resources
Material reuse
Using innovative technology for non- structure
Insulating component
Material finishing
Local resources utility
The efficiency of material over LC
Global warming potential for refrigerant
Noise pollution
Preventing pollution leaks
Water pollution
Effect of heat island
Source of NOx emission
Carbon emission
Fire safety
Natural Disaster
Level of noise emitting
Insulation to sound source
Absorption of sound acoustics
Active lighting
Lighting control
Open view
Measuring and control on glaring
Level of illumination
Daylight factor
Natural ventilation
Type of ventilation
Supply of purified and fresh air
Air monitoring sensor
Monitoring on carbon emission
Unstable compounds

	Pollution of electromagnetic
	Level of microbiological content
	Controlling zone
	Heating, cooling, humidity, vapour control, and comfort
Buildings renovation(Ho et al., 2021b; Kylili, Fokaides, & Lopez Jimenez, 2016; Vilutiene, 2018)	Direct cost
	Indirect costs
	Environmental friendliness
	Annual carbon emission
	Abiotic depletion potential
	Acidification of land and water resources
	Eutrophication
	Acoustic performance
	Visual impact
	Indoor Quality
	Energy
	Reuse/ Recycle
	Hazardous waste to disposal
	Public health
	Cultural heritage
	Public access Public
	Public perception
	Functionality
	Occupational safety Complaints

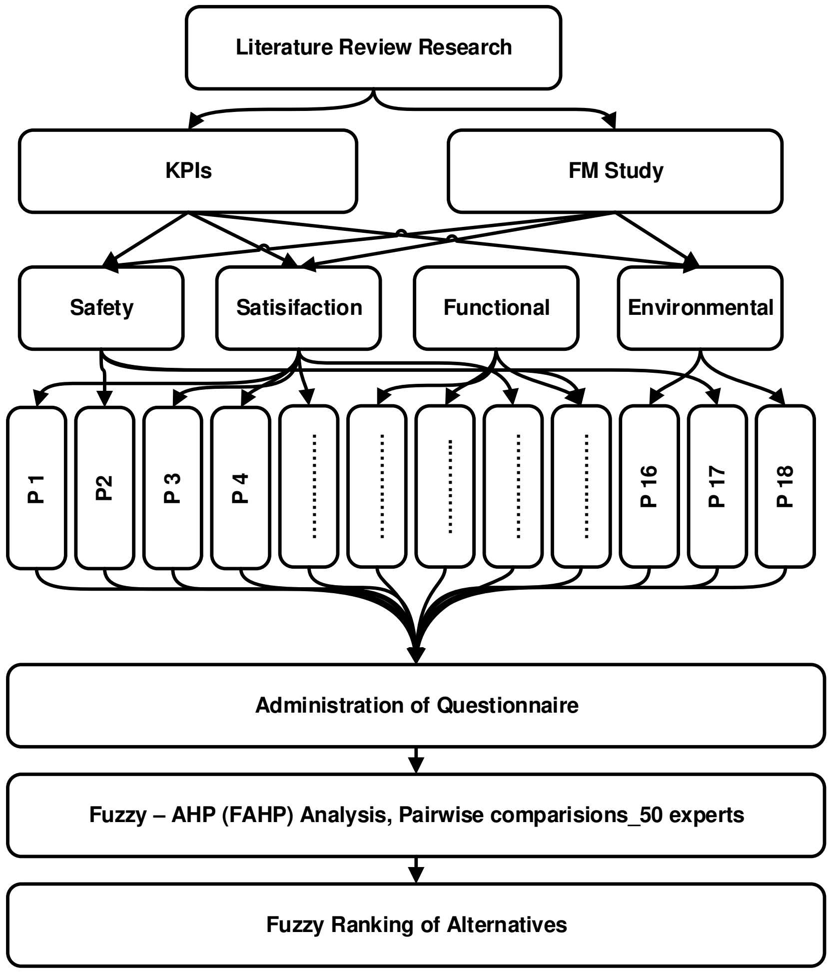


Figure 4.1 Flow chart of first sub-objective

Access to a significant number of professionals is not always feasible. Consequently, a restricted number of respondents are chosen from diverse professional backgrounds, including architects, academicians, research scholars, engineering consultants, and industry experts from India and working at different parts of India, majority of academicians, research scholars are from NIT Warangal. Architects, engineering consultants and industry experts from various places from India, who are involved in design, construction and maintenance of various buildings including educational buildings at various levels. The survey is conducted by soliciting responses from 50 professionals representing various domains and a range of expertise, as depicted in Figure 4.2. Its objective is to examine which indicators are the most appropriate for evaluating the performance of buildings within an institute.

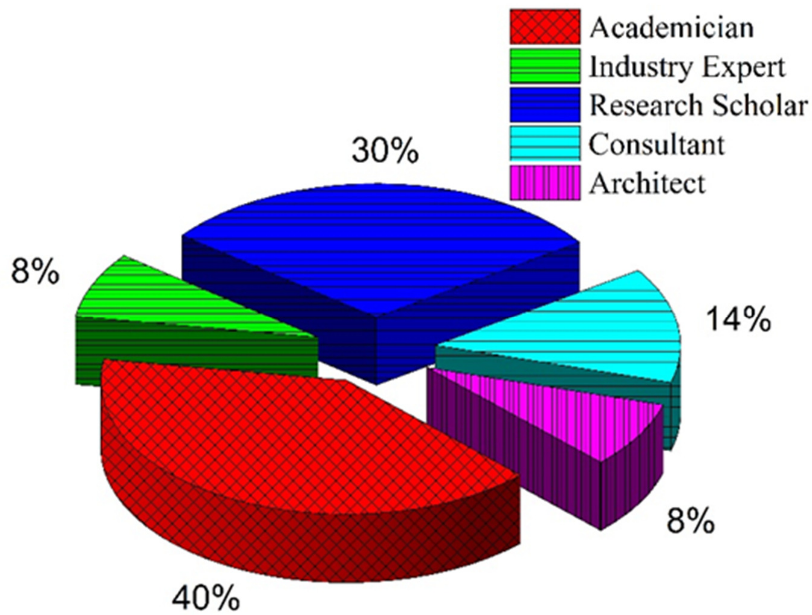


Figure 4.2 The details of the survey professional

The PIs encompass both quantitative and qualitative aspects. Handling quantitative data is more straightforward, allowing for the extraction and comparison of values. In contrast, qualitative data involves distinct definitions and metaphors, making comparisons more challenging. Ultimately, both quantitative and qualitative data are processed and refined to determine the KPIs. Previous studies have identified approximately 785 PIs associated with facility management services and institutional buildings (Y. Kim et al., 2018). Many of these PIs lack clear definitions, making interpretation difficult, and some are unsuitable for collecting data in the context of institutional buildings. A search for relevant PIs was conducted, leading to a selection of 18 PIs, as outlined in

Table 4.2. The screening process is adapted from Kim et al., as well as from recent literature sources (Hinks & Mcnay, 1999; Y. Kim et al., 2018; K. Lee et al., 2015; Leung et al., 2005; Roberts, 2009).

Table 4.2 List of indicators and their description

ID	Indicator	Description
P 1	User Satisfaction	User satisfaction survey on the building facilities
P 2	Security	Provisions against thefts and security measures
P 3	Air Quality	A measure of Indoor air quality (IAQ)
P 4	Thermal condition	Temperature comforts to the users of the institutional building
P 5	Cleanliness	Cleanliness and appearance comfort of the building
P 6	Noise level	A measure of the Indoor noise level
P 7	Lighting quality	Adequacy of Indoor illuminance level (lighting facility)
P 8	Amenities	Competency of the building facilities to the users (Based on availability and their maintenance)
P 9	Service Interruptions	Number of unplanned service interruptions (services like supply of drinking water, power, lifts)
P 10	Use of Energy	Annual energy consumption
P 11	Water usage	Annual water consumption per user
P 12	Facilities to Disabled	Features for disabled persons, like the ramp provisions to all the floors and buildings including to lift and toilet.
P 13	Cycling provision	Cycling convenience (including a track for bicycle users and parking facilities)
P 14	Illness	Number of Death, injuries, and illnesses
P 15	Condition of the Building	Condition rating of the Institute building for each and every structural element.
P 16	GHG emissions	Reduction in the GHG emission on the yearly basis
P 17	Emergency Access	Provisions to approach the building in Normal and Emergency condition

P 18	Renewable Energy	Percentage of Renewable energy usage out of total energy consumption

Specific categorization of PIs is not applied; Instead, the selection of PIs is tailored to the organization's goals, covering a range of domains (Lavy, et al., 2014). The chosen indicators have been clustered into four categories: Safety, Satisfaction, Functionality and Environmental, as illustrated in Table 4.3. Economic indicators are intentionally omitted in this study since institutional buildings operate as non-profit organizations.

Table 4.3 Grouping of indicators according to the domains

Domains	Performance Indicators	
Safety	P 2	Security
	P 14	Illness
	P 17	Emergency Access
Satisfaction	P 1	User Satisfaction
	P 3	Air Quality
	P 4	Thermal condition
	P 5	Cleanliness
	P 9	Service Interruptions
Functionality	P 6	Noise level
	P 7	Lighting quality
	P 8	Amenities
	P 12	Facilities for Disabled
	P 13	Cycling provision
	P 15	Condition of the Building
Environment	P 10	Use of Energy
	P 11	Water usage
	P 16	GHG emissions
	P 18	Renewable Energy

The studies on Key Performance Indicators (KPIs) for sustainable building performance evaluation employ a variety of data collection methods, each with its own advantages. Several studies use comprehensive literature reviews to compile existing KPIs from various sources, providing a broad overview of the subject area and identifying gaps in the literature. Others utilize multi-stakeholder analysis, consulting industry experts, policymakers, and end-users to ensure the identified KPIs are relevant and practical. Some studies gather data through focus groups and surveys, allowing direct input from individuals involved in sustainable building practices, providing valuable insights into their specific needs and challenges. Conversely, other studies use case studies to examine real-world examples of sustainable building practices, offering concrete examples of how KPIs are applied in practice and identifying best practices and lessons learned.

Each method has distinct advantages. Literature reviews are cost-effective and provide a comprehensive overview of existing knowledge. Multi-stakeholder analysis ensures the relevance and practicality of identified KPIs. Focus groups and surveys offer insights directly from stakeholders, and case studies provide real-world examples, demonstrating the effectiveness of KPIs in practice. In this study, a literature review and focus groups were used for the collection of PIs, while multi-stakeholder analysis was used to identify the KPIs. Focus groups, surveys, and case studies of buildings were used for the formation of the index.

The research methodology used in this study, which includes a literature review, focus groups, and multi-stakeholder analysis, is justified based on the disadvantages and limitations of other probable data collection methods.

1. **Literature Review**: While a literature review provides a broad overview of existing knowledge, it may be limited by the availability and quality of existing literature. Some sources may be outdated or biased, leading to incomplete or inaccurate information. Additionally, a literature review may not capture the most current practices or emerging trends in sustainable building performance evaluation.
2. **Focus Groups**: Focus groups allow for direct input from individuals involved in sustainable building practices, providing valuable insights. However, they are limited by the sample size and composition. The views expressed in focus groups may not be representative of the broader population, leading to potential biases in the data collected.
3. **Multi-stakeholder Analysis**: Multi-stakeholder analysis ensures that identified KPIs are relevant and practical. However, it can be time-consuming and resource-intensive.

Involving multiple stakeholders with varying interests and priorities can also lead to challenges in consensus-building and decision-making.

Despite these limitations, the research methodology used in this study is justified as it combines multiple data collection methods to mitigate these limitations. The literature review is supplemented by direct input from stakeholders through focus groups and multi-stakeholder analysis, providing a comprehensive and robust approach to data collection and analysis.

4.2.2 Analysis of Data Reliability

To evaluate the reliability of the questionnaire responses collected for each performance indicator, a Cronbach's Alpha reliability test is conducted (Vaske et al., 2017). Data reliability assessment is performed using IBM SPSS (International Business Machines Statistical Package for the Social Sciences) version 27. Average Scores and Cronbach's Alpha for the Performance Indicators are illustrated in Table 4.4. The Cronbach's Alpha value ranges from 0 to 1 and the level of reliability versus the alpha values are depicted in Table 4.5, where Values between 0.6 and 0.7 are considered reliable, while values exceeding 0.7 indicate strong reliability. Notably, the observed alpha values surpass 0.8, exceeding the minimum threshold of 0.7. This outcome underscores the high consistency and reliability of the data collected through the survey, affirming its suitability for analysis.

Table 4.4 Average Scores and Cronbach's Alpha for the Performance Indicators

ID	Indicators	Mean	Std. Deviation	Alpha (Item Deleted)
P1	User satisfaction	3.76	1.27	0.901
P2	Security	3.56	1.18	0.902
P3	Air Quality	4.34	0.82	0.905
P4	Thermal condition	4.52	0.71	0.916
P5	Cleanliness	3.96	1.14	0.901
P6	Acoustical Quality	4.16	1.00	0.920
P7	Lighting quality	4.62	0.64	0.911
P8	Amenities	3.44	0.99	0.899
P9	Service Interruptions	3.58	1.36	0.897
P10	Use of Energy	3.66	1.06	0.902
P11	Water usage	3.54	1.36	0.900

P12	Disabled Facilities	3.34	1.17	0.898
P13	Cycling provision	2.76	1.29	0.902
P14	Illness	2.70	1.33	0.906
P15	Building Condition	3.40	0.99	0.903
P16	GHG emissions	3.48	1.13	0.901
P17	Emergency Access	3.56	1.33	0.895
P18	Renewable Energy	3.54	1.09	0.897

Table 4.5 Cronbach's Alpha value Vs level of reliability

Cronbach's Alpha (α)	Internal Consistency
Above 0.9	Excellent
0.8 – 0.9	Good
0.7 – 0.8	Acceptable
0.6 – 0.7	Questionable
0.5 – 0.6	Poor
Less than 0.5	Unacceptable

4.2.3 Calculation of Weights using Fuzzy Analytic Hierarchy Process (FAHP)

In this study, KPIs are derived from Facility Management (FM) performance parameters using the innovative FAHP. FAHP builds upon the traditional AHP, as pioneered by Chang in synthetic decision-making analysis. While AHP is a well-established method, it does have limitations, especially when respondents are required to assign values within a rigid scale from 1 to 9, which can introduce uncertainty. FAHP addresses this challenge by introducing Fuzzy linguistic variables such as Very poor, poor, better, excellent, etc., making it more user-friendly and relevant for a broader audience. (Mosadeghi et al., 2015; Soroor et al., 2012).

This improvement is achieved by permitting the use of linguistic expressions and fuzzy numbers, including triangular or trapezoidal fuzzy numbers, to account for the inherent subjectivity and vagueness (in precision) in decision matrices. Pairwise comparisons, a fundamental aspect of AHP, are also integral to FAHP. However, in FAHP, these comparisons are conducted using fuzzy linguistic variables like equal importance and moderate importance, as illustrated in Figure 4.3, where triangle (1,1,2) represents "equal importance". Similarly all other triangle member ship values are presented in Table 4.6. These linguistic terms more realistically capture the degree of preference between criteria and alternatives compared to crisp numerical values.

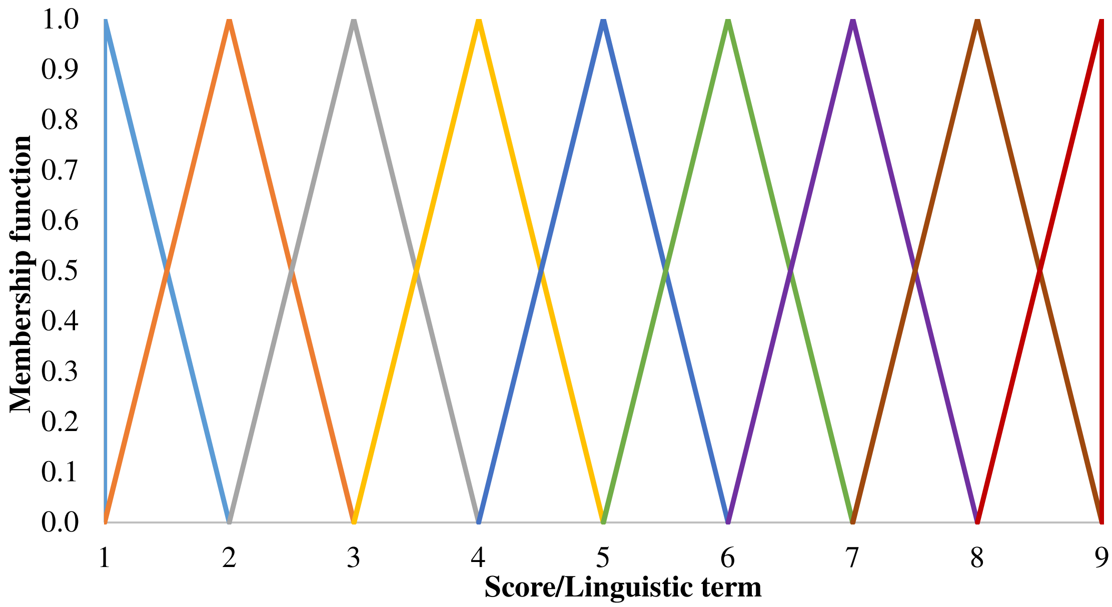


Figure 4.3 Triangular Membership Functions for Linguistic Terms

Table 4.6 Triangular Fuzzy number used for Linguistic terms (Kannan et al. 2015)

Linguistic terms	Triangular TFN	Reciprocal Number
Equal importance	(1,1,2)	(1/2,1,1)
Moderate importance	(2,3,4)	(1/4,1/3, 1/2)
Strong importance	(4,5,6)	(1/6,1/5,1/4)
Very strong importance	(6,7,8)	(1/8,1/7,1/6)
Extremely Strong importance	(8,9,9)	(1/9,1/9,1/8)
In-between values	(1,2,3)	(1/3,1/2,1)
	(3,4,5)	(1/5,1/4,1/3)
	(5,6,7)	(1/7,1/6,1/5)
	(7,8,9)	(1/9,1/8,1/7)

To consolidate the fuzzy pairwise comparison matrices, FAHP employs aggregation methods such as the geometric mean. These operations preserve the inherent fuzziness in the data, resulting in a comprehensive fuzzy priority vector. This vector provides normalized weights essential for prioritizing KPIs based on their significance. The selection of these KPIs is qualitative and draws from FM literature, playing a critical role in assessing building performance. Various evaluation methods, including benchmarking matrices, balanced scorecards, surveys and KPIs, support top-level management in making informed decisions. This approach ensures the systematic assessment and continuous improvement of building performance throughout its operational phase.

4.3 RESULTS AND DISCUSSIONS

The assessment of Key Performance Indicators (KPIs) for institutional buildings in this study provides valuable insights into improving building performance and user satisfaction. The approach integrates a broad set of indicators, incorporating existing literature and contextual considerations, yielding a comprehensive assessment framework. An important aspect is the inclusion of professionals with substantial expertise, some with over 15 years of experience, which enhances the reliability of the collected data. The high data consistency, demonstrated by a Cronbach's alpha exceeding 0.8, emphasizes the strength of the findings and instils confidence in the study's outcomes.

To determine the significance of the 18 KPIs, a comprehensive approach is employed, involving the collection of 50 pairwise comparisons from individual respondents through a detailed 9-scale questionnaire. These comparisons form the basis for constructing pairwise comparison matrices, each measuring 18 by 18 in size. The geometric means of these matrices are then calculated for each KPI. Subsequently, the calculated means undergo aggregation using fuzzy synthesis, resulting in fuzzified weight values for each KPI. To refine and make the results more interpretable, a defuzzification process is employed. This involves converting the fuzzified weight values into normalized weights for each parameter. Through this process, the final importance of the KPIs is determined based on their respective weight values.

Pairwise comparison matrix: The pair wise triangular fuzzy comparison matrix is developed as shown below:

$$\begin{bmatrix} 1 & x_2 & \cdots & \cdots & x_{18} \\ \frac{1}{x_2} & 1 & \cdots & \cdots & \cdots \\ \vdots & & & & \\ \vdots & \vdots & \vdots & \vdots & \cdots \\ \frac{1}{x_{18}} & \vdots & \vdots & \vdots & 1 \end{bmatrix}$$

Row-wise geometrical means are extracted and Fuzzy weights are calculated and the final normalized defuzzified weights are calculated as shown in Figure 4.4. The ranking of PIs is depicted in Table 4.7.

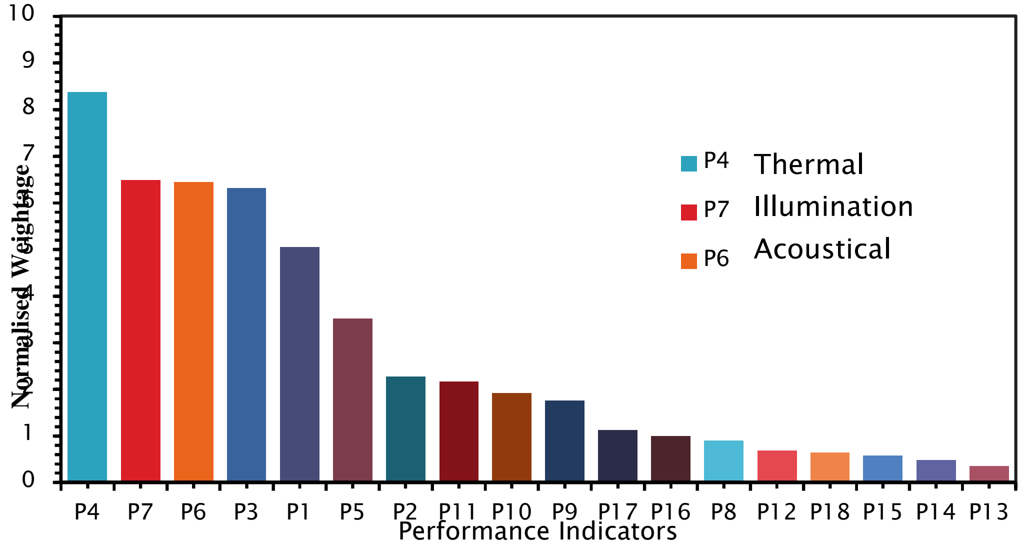


Figure 4.4 Normalised Weightage of PIs

Table 4.7 Ranking of KPIs

ID	KPIs	Rank	ID	KPIs	Rank
P4	Thermal condition	1	P9	Service Interruptions	10
P7	Lighting quality	2	P17	Emergency Access	11
P6	Acoustical Quality	3	P16	GHG emissions	12
P3	Air Quality	4	P8	Amenities	13
P1	User Satisfaction	5	P12	Disabled Facilities	14
P5	Cleanliness	6	P18	Renewable Energy	15
P2	Security	7	P15	Building Condition	16
P11	Water usage	8	P14	Illness	17
P10	Use of Energy	9	P13	Cycling provision	18

The comparison of relative significance among KPIs occurs through the application of FAHP norms, yielding the following results. Notably, among the 18 KPIs, Thermal, Illumination and Acoustical quality, emerge as the highest-ranking indicators. The descending order of ranking for the remaining parameters is as follows: Air Quality, User Satisfaction, Cleanliness, Security, Water usage, Use of Energy, Service Interruptions, Emergency Access, GHG emissions, Amenities, Disabled Facilities, Renewable Energy, Building Condition, Illness and Cycling provision. From Figure 4.4, it is evident that the thermal condition holds a normalized weightage of 8.37, Lighting quality follows with 6.48 and Acoustical quality closely follows with 6.44, signifying the greater importance of thermal condition compared to other parameters. In the Table 4.7, the relative rankings of the PIs are displayed as per the weightages obtained.

The findings have implications for design and Facility Management. The recommendation to prioritize Thermal Condition, Illumination and Acoustical quality in the initial design phase aligns with the global trend toward user-centric design principles. Additionally, the categorization of KPIs into high and low priority classes provides a practical tool for facility service personnel to promptly address critical indicators, promoting energy efficiency and enhancing user experiences. In summary, the study findings correspond with prior research (refer to Table 4.8) by highlighting the significance of Thermal condition, lighting quality, environmental factors, and cleanliness in evaluating institutional building performance. While specific rankings may vary, the overarching themes remain consistent with the broader body of research in this field.

Table 4.8 Previous studies and the KPIs

Previous Study	KPIs Identified
(Zaki et al., 2017); (Cheong & Lau, 2003)	P4,P3
(Piasecki et al., 2017); (Kiplagat et al., 2017)	P7, P5
(Zhong, 2020a); (M. S. Kim et al., 2017)	P6, P1

In conclusion, this study contributes to filling existing gaps in the research landscape and offers actionable insights for enhancing building performance and user satisfaction. By addressing these aspects, the study aligns with international discussions on sustainable building practices and user-centric design, ultimately enhancing the quality of institutional spaces on a global scale.

4.4 CONCLUSION

This study undertakes a comprehensive exploration to identify and evaluate KPIs for a holistic assessment of institutional building performance. These KPIs are derived from a blend of existing literature and local contextual conditions, employing a combination of objective and subjective methodologies. A crucial aspect of this approach involves the engagement of a diverse group of professionals, including individuals with more than 15 years of experience, ensuring the credibility and robustness of the findings. The study exhibits commendable data reliability, with a Cronbach's alpha value exceeding 0.8, underscoring the trustworthiness of the results.

The significance of this research becomes evident in its contribution to filling critical gaps within the current research landscape. The utilization of the FAHP enables us to ascertain the relative importance of KPIs, shedding light on the factors that wield the most influence over the overall comfort of building occupants. Notably, Thermal Condition, Illumination and Acoustical Quality emerge as the top-ranking parameters, surpassing their counterparts in significance. Further rankings of KPIs encompass Air Quality, User Satisfaction, Cleanliness, Security, Water Usage, Use of Energy, Service Interruptions, Emergency Access, GHG Emissions, Amenities, Disabled Facilities, Renewable Energy, Building Condition, Illness and Cycling Provision.

The implications of the findings are substantial, particularly in guiding design and Facility Management practices. It is recommended that Thermal Condition, Illumination and Acoustical Quality be accorded top priority during the initial design phase, both by designers and Facility Management teams. The classification of KPIs into high and low priority classes empowers facility service personnel to efficiently address high-priority indicators, resulting in reduced energy consumption and elevated service quality for end-users. This research, by addressing these aspects, aims to contribute to international dialogues on sustainable building practices and user-centric design, ultimately enhancing the quality of institutional spaces. The present study enables a new approach into institutional building KPIs, Future research should explore broader applications, employ advanced techniques and consider sustainability, allowing for more comprehensive building performance assessment in different contexts.

CHAPTER 5

DEVELOPING AN INTEGRATED COMFORT INDEX

This chapter deals with the second sub objective that evaluates the Combined Comfort Index (ICC) of institutional buildings, using the KPIs extracted from the first objective discussed in Chapter 4.

5.1 INTRODUCTION

For young adults aged 18 to 26 around the world, who primarily spend their time indoors within educational institutions, it is essential to create interior environments that inspire and support learning. During their undergraduate and graduate studies, students spend roughly 87% of their time inside buildings. Therefore, integrating elements that foster a stimulating atmosphere can significantly enhance their educational experiences and analytical thinking abilities (Dear et al., 2015; Thapa et al., 2018).

The construction sector plays a substantial role in global energy consumption, accounting for approximately 35% of the world's total energy usage, with this percentage continuing to rise at an annual rate of 8% (BEE, 2023). A significant portion of this energy, approximately 73%, is attributed to the operational phase of buildings, which includes all features aimed at providing maximum user comfort (BEE, 2017; Rawal et al., 2012; Rincon et al., 2013). Educational buildings, in particular, contribute significantly to this energy consumption as they strive to maintain thermal comfort for their occupants. According to the Energy use in commercial buildings (ECO-III) study, educational buildings globally consume 4,832 GWh of energy (Kumar, 2011).

The pursuit of thermal comfort in educational settings holds immense importance, directly impacting the learning process and students' motivation to engage in academic activities (Abeyrathna et al., 2023; M. C. Lee et al., 2012; Toyinbo et al., 2016; Ulla et al., 2015; Wargocki & Wyon, 2013; Z. Yang et al., 2013). Haverinen-Shaughnessy et al. found compelling correlations between favourable math and reading exam results and factors such as interior temperature, ventilation rate, and cleanliness of high-contact surfaces (Ulla et al., 2015). Similarly, Lee M.C. et al. observed strong links between voting behaviour and overall indoor environmental quality, especially concerning auditory components in university classes in Hong Kong (M. C. Lee et al., 2012). Toyinbo et al. revealed that non-recommended ventilation rates in school buildings are associated with poorer mathematics exam scores (Toyinbo et al., 2016). Yang et al. also conducted a study on the influence of classroom characteristics on student happiness and performance (Z. Yang et al., 2013). Additionally, Wargocki et al. reported that subpar indoor environmental quality could lead to a 30% decrease in learning performance (Wargocki & Wyon, 2013). These findings underscore the significance of creating a conducive indoor environment in educational institutions to enhance both academic achievements and student well-being.

According to a recent review conducted by Zomorodian et al., a total of 48 studies focusing on thermal comfort in educational buildings were published between 1969 and 2015 (Zomorodian et al., 2016). Among these studies, 25% focus on elementary and middle schools, covering the period from 1975 to 2016. Additionally, 34% of the studies are dedicated to secondary and high schools, while the remaining 41% focus on universities. Notably, recent field investigations carried out in primary and secondary schools reveal that children experience thermal comfort differently from adults due to their higher metabolism in various parts of the world (Almeida et al., 2016; Nam et al., 2015; Teli et al., 2014; Trebilcock et al., 2017; Z. Wang et al., 2017). The identified neutral comfort temperature is 23.1 °C for primary schools, 23.8 °C for secondary and high schools, and 25.1 °C for universities (Zomorodian et al., 2016).

Furthermore, researchers examine the acoustical characteristics of classrooms at different education levels and their impact on students' academic success worldwide. Yang and Bradley conducted speech tests on both elementary school pupils and adults, discovering that the intelligibility of speech for young children is affected by factors such as reverberation time and the signal-to-noise ratio (W. Yang & Bradley, 2009). Klatte et al. find that background noise has a more detrimental effect on children's speech perception and listening comprehension compared to adults (Klatte et al., 2010). In a study by Hodgson, classrooms at British Columbia University exhibit severe reverberation, low speech volumes (particularly at the rear of the rooms), and noisy ventilation systems. They also develop a questionnaire to assess the perception of the listening environment (Hodgson, 2002). Similarly, Zannin and Marcon identify inadequate acoustics in a Brazilian public school (Zannin & Marcon, 2007). These findings emphasize the importance of considering the specific environmental needs of educational spaces to create optimal learning conditions for students across different age groups worldwide.

Finally, but significantly, ensuring comfortable visual environments in classrooms is essential for effective learning and academic progress. Michael et al. conducted a study in Cyprus to assess the utilization of natural lighting in educational institutions and propose improvements to enhance visual comfort in classrooms (Michael & Heracleous, 2017). Similarly, Meresi develops a specialized light shelf and adjustable exterior shutters to meet the needs of students in south-facing classrooms in Athens (Meresi, 2016). In Iran, Korsavi et al. employ simulations and questionnaires to evaluate a typical high school's lighting conditions, revealing positive responses to sunlight acceptability (Korsavi et al., 2016). Lapisa et al. identify the optimal skylight-roof ratio, striking a balance between maximizing indoor illumination and minimizing energy consumption and thermal discomfort for occupants (Lapisa et al., 2020).

While previous literature predominantly focuses on individual factors influencing environmental comfort, there are few attempts to comprehensively assess the combined impact of multiple perspectives globally. To address this gap, new targeted questionnaires were developed to evaluate students' perceptions of acoustic and lighting comfort. Based on mean responses and measured data, six acoustical indices and four visual indexes are formulated. These indices then merge into a single index, considering three distinct characteristics: thermal-hygrometric, auditory, and lighting comfort conditions. Each aspect assigns specific single indices: a Predicted Mean Vote (PMV) Index for thermo-hygrometric settings, a Sound Index for acoustic comfort, and a Visual Index for lighting conditions. All indices are dimensionless and normalize on a scale of 0 to 1, where values close to 1 indicate favourable comfort conditions and values close to 0 indicate unfavourable ones. By correlating questionnaire responses with collected data, the comfort indices are computed. Notably, lighting, acoustics, and thermos-hygrometry are given equal weight in the evaluation process. A comprehensive combined comfort index proposes and calculates for each hostel room based on these weightings, aiming to benefit students worldwide.

Indian building construction varies widely based on region and tradition, typically using materials like brick, stone, and concrete, sometimes incorporating bamboo and mud. Architectural styles vary greatly, influenced by cultural and climatic factors. Traditional Indian architecture often emphasizes natural cooling techniques, such as courtyards and latticed screens, to combat the hot climate the case study building is located at NIT Warangal with google location latitude and longitudes of 17°59'00.7"N 79°32'09.2"E. The selected building is of reinforced concrete structure. India experiences diverse climates, ranging from tropical in the south to temperate and alpine in the north. The country has four main seasons: summer (March to June), monsoon (June to September), post-monsoon (October to November), and winter (December to February). Temperature and humidity levels vary significantly between regions and seasons, with northern India experiencing hot summers and cold winters, while southern India has a more consistent tropical climate with high humidity. The case study building is located at elevation of 266 meters (872.7 feet) above sea level, Warangal has a Tropical wet and dry or savanna climate (Classification: Aw). The district's yearly temperature is 29.65ºC (85.37ºF) and it is 3.68% higher than India's averages. User patterns in Indian buildings reflect cultural, social, and economic influences. In urban areas, apartment living is common, with families often residing in multi-story buildings. Rural areas often feature traditional single-family or mud houses. Indian households prioritize spaces for social gatherings and religious activities. Natural ventilation and lighting are prevalent, especially in older or traditional buildings, showcasing a harmony with the environment and cultural practices.

The National Building Code (NBC) of India (NBC, 2016) specifies a narrow temperature range of 23°C–26°C for summers and 21°C–23°C for winters, disregarding the vast geographical, climatic, ethnic, and cultural diversity of its population. Recent field studies in Indian buildings by Mishra and Ramgopal (Mishra & Ramgopal, 2015), Indraganti et al. (Indraganti et al., 2014), and Dhaka et al. (Dhaka et al., 2015; Dhaka & Mathur, 2017) in hot and humid, composite, and other climates respectively, reveal that Indian individuals exhibit a comfort temperature range much wider than that prescribed by the NBC. Manu et al. (Manu, et al., 2016) proposed the Indian Model of Adaptive Comfort (IMAC) based on data from five Indian climates: Ahmedabad (hot and dry), Bangalore (moderate), Chennai (warm and humid), Delhi (composite), and Shimla (cold). Similarly, a study by Kumar et al. (ASHRAE, 2008; Kumar et al., 2016) on the ASHRAE Standard 55 – 2013 graphical method for thermal comfort determination found that comfort boundaries for Indian subjects in the composite climate of Jaipur extend beyond those suggested by the standard. These studies indicate that Indian subjects are comfortable in a wider range of conditions than previously prescribed by the NBC. As a result, the adaptive thermal model suggested by Manu et al. (Manu, et al., 2016) was included in the Energy Conservation Building Code (ECBC) (Bureau of Energy Efficiency & USAID, 2008) of India. However, India's climatic and cultural diversity requires further investigation, particularly in the eastern part of India characterized by higher cloud cover, resulting in warm and humid, and cold and cloudy climates. Singh et al. (Singh et al., 2011) conducted adaptive comfort studies in three climatic conditions in the extreme north-eastern Indian states, and Singh et al., (2017) provided comfort conditions for office subjects in Tezpur and Shillong for the autumn months. Outside India, Fuller et al., (2009) discussed measures to improve comfort levels in high-altitude Himalayan houses in Nepal, revealing indoor conditions in traditional houses that were below international comfort standards.

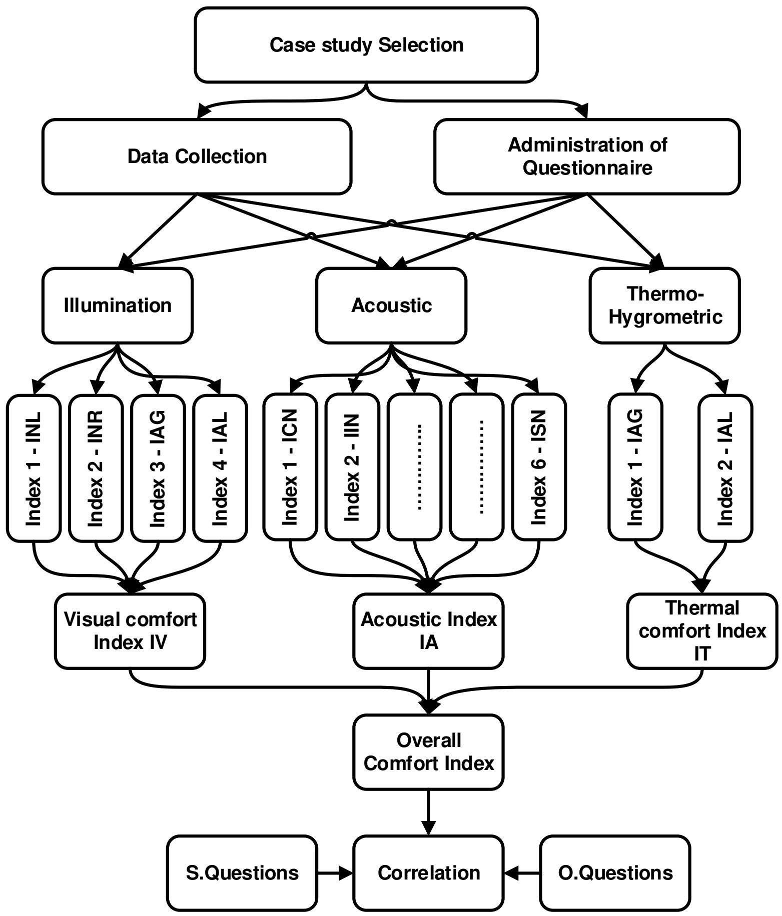


Figure 5.1 Flow chart of second sub objective

The primary objective of this study is to investigate the influence of the environment on occupant comfort, with a specific focus on thermal, acoustic, and lighting aspects. These key elements play a crucial role in determining overall comfort conditions and can be efficiently controlled through both active means, such as the incorporation of plants, and passive approaches, including advancements in the building envelope. The comprehension and fine-tuning of these factors can improve the learning environment, thereby positively affecting students' academic experiences. **Error! Reference source not found.** illustrates the flowchart for the second sub-objective.

5.2 METHODOLOGY

The methodology for developing a unified combined comfort index involves a series of steps:

1. Sample Selection: This study focuses on six hostel rooms situated at the National Institute of Technology Warangal (NITW) campus. The selection ensures the representation of various characteristics such as different volumes, occupancy levels, window surfaces, and exposures.
2. Data Collection: Data is collected during the year 2018. Researchers collect experimental measurements of thermal, lighting, and acoustical conditions in the selected hostel rooms. Instruments such as temperature sensors, humidity sensors, sound level meters, and illuminance meters are used for data gathering.
3. Questionnaire Development: A comprehensive questionnaire is designed to evaluate comfort levels in the hostel rooms. The questionnaire includes questions related to thermal comfort, acoustic comfort, and visual comfort, covering different aspects of comfort experienced by occupants.
4. Correlation Analysis: The collected experimental data are compared with responses from the questionnaire to evaluate subjective parameters closely related to the measured data. This analysis helps identify questions with the highest correlation to the experimental outcomes.
5. Individual Index Calculation: Based on the correlation analysis, distinct comfort indexes are developed for each parameter (thermal, acoustic, and lighting). Individual indexes are calculated using survey responses associated with relevant questions. These indexes are normalized on a scale of 0 to 1 to standardize the assessment of comfort conditions.
6. Weightage Assignment: Equal weights are assigned to individual comfort indexes based on prior research findings. This approach ensures an equitable contribution from all three parameters (thermal, acoustic, and lighting) to the overall comfort index.
7. New Combined Comfort Index (NCCI) Calculation: The final step involves calculating the NCCI for each hostel room. This index is derived by combining individual comfort indexes (thermal, acoustic, and lighting) using the assigned equal weights. The resulting NCCI serves as a comprehensive indicator of the overall comfort level for each room.

In summary, the research methodology involves a combination of sample selection, data collection, questionnaire development, correlation analysis, index calculation, and statistical analysis to assess and rate the combined comfort of the selected hostel rooms.

5.2.1 Available data & case study

The investigation comprised the examination of six hostel rooms situated on the premises of the National Institute of Technology Warangal (NITW) campus. The methodology's visual representation is captured by the flowchart in **Error! Reference source not found.**. These particular rooms are located within a hostel complex boasting a total capacity of 1,800 students (1.8k hostel/Ultra mega hostel) and are specifically designated as A3-13, B3-50, A7-12, A7-46, B7-20, and B7-48. The selection of these rooms was guided by factors such as the availability of students for active participation in the investigation and survey activities. A comprehensive consolidation of essential details concerning the hostel rooms, encompassing dimensions and occupancy particulars, is outlined in Table 5.1. Notably, this study maintained a dedicated focus on single sharing rooms to ensure coherence and uniformity within the analytical framework. Figure 5.2 depicts the arrangement of single and double sharing. Figure 5.3 and Figure 5.4 depict a typical floor plan, ariel view, and front view of the 1.8K hostel. The hostel rooms are studied in terms of thermo-hygrometrical, lighting, and acoustical conditions.

Table 5.1 Characteristics of Hostel rooms

Room type	Sharing	Length (m)	Width (m)	Height (m)	Floor area (m^2)	Volume (m^3)	Door surface (m^2)	window surface (m^2)
A	1	3.55	3.00	2.80	10.65	29.82	1.99	2.16
B	1	3.64	3.00	2.80	10.92	30.58	1.99	2.16
C	1	3.53	3.00	2.80	10.59	29.65	1.99	2.16
D	1	4.09	3.00	2.80	12.27	34.36	1.99	2.16
E	1	3.18	3.00	2.80	09.54	26.71	1.99	2.16
F	1	3.77	3.00	2.80	11.31	31.67	1.99	2.16
G	2	3.28	4.20	2.80	13.78	38.57	1.99	2.16
H	2	3.78	4.20	2.80	15.88	44.45	1.99	2.16
I	2	3.55	4.20	2.80	14.91	41.75	1.99	2.16
J	2	3.11	4.20	2.80	13.06	36.57	1.99	2.16
K	2	3.50	4.20	2.80	14.70	41.16	1.99	2.16
L	2	3.77	4.20	2.80	15.83	44.33	1.99	2.16

The measurements are taken at a height of 0.75 m from the floor to represent the students' usual sitting space, as shown in Figure 5.5. Experimental measurements of natural ventilated illumination and acoustical conditions are measured with various instruments. The list of instruments employed for data collection, along with their specifications, is presented in Table **5.2**.

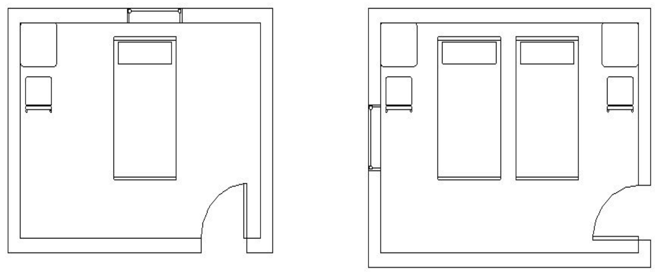
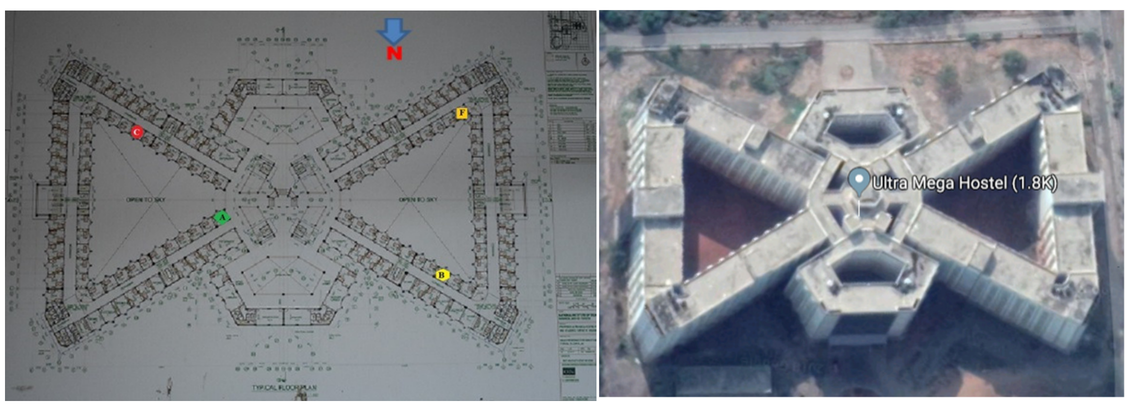


Figure 5.2 Typical Single and Double sharing arrangement



(a) (b)

Figure 5.3 Top view of the building a) Plan view of 7th floor b) Birds eye view

Figure 5.4 Front view of the 1.8K hostel

Figure 5.5 Illustrates the aggregation of factual data

Table 5.2 Comfort parameters range, accuracy and resolution

Parameter		Units	Range	Accuracy	Resolution	Instrument system
Air Temperature	Ti	°C	-50°C to +70°C (-58°F to + 158°F)	± 1°C	0.1°C	HTC-1, Digital Hygrometer Temperature Humidity Meter
Air Relative Humidity	Rh	%RH	10% RH to 99% RH	±5% RH	1%	
Sound	Si	dB	35 dB to 130 dB	1 dB	1dB	Digital Sound Level Meter
Illumination	Li	Lux	0 Lux to 200000 Lux	+ 3%	0.01 Lux	HTC Lux meter LX-103

5.2.2 Analysis of questionnaire data

The experimentally measured data is compared with responses obtained from a questionnaire, which includes specific questions and correspondent indexes listed in Table 5.3. The objective is to link each question to the corresponding measured value and analyses the subjective parameters closely associated with the experimental data. Figure 5.5 illustrates the process of experimental data collection.

5.2.3 The individual proposed indexes

Individual indexes are evaluated for each parameter under consideration, and these individual indexes are then combined to create a comprehensive single index that describes acoustic, lighting, and thermal-hygrometric comfort conditions. The calculation of individual indices takes into account various survey indexes from the questionnaire section. To assign weights to each index, the degree of correlation between perceived and measured values is considered. The index value is derived as the average of the answers to the questions, with a range from 0 to 10. Subsequently, a dimensionless single parameter index is computed by normalizing the value (ranging from 0 to 1) and dividing it by 10. This comprehensive index provides a holistic measure of overall comfort in the given environment.

Table 5.3 Acoustic, Lighting and Thermal questionnaires.

	No	Question	Index
Acoustic	1	Hostel mates making noise in the corridors	ICN- Corridor Noise Index
	2	Internal noise (fan, phone, etc.)	IIN- Internal Noise Index
	3	Noises that disturbs once in a day	IDN- Daily Noise Index
	4	Noises that disturbs occasionally	ION- Occasional Noise Index
	5	Do these noises disturbs you while taking rest	IRN- Rest Noise Index
	6	Do these noises disturbs you while you studying	ISN- Study Noise Index
Lighting	1	Amount of light entering through the windows	INL- Natural Light Index
	2	Experience discomfort due light reflecting from outside	INR- Reflection Light Index
	3	Inside the room, dark patches and too bright locations created by window	IAG- Lighting Annoying Glares Index
	4	How frequently you use artificial lighting in room	IAL- Artificial Light Index
Thermal	1	The heat entering through windows from natural source (sun) in winter	INH- Natural Heat Index
	2	The heat shield by the windows and wall (summer)	IIH- Internal Heat Index

5.2.3.1 Acoustic index AI:

The Acoustic Index (AI) is calculated based on the formula 5.1 provided below.

$$AI = \frac{0.1*(10-ICN)+0.1*IIN+0.4*(10-IDN)+0.2*(10-ION)+0.1*(10-IRN+0.1*(10-ISN)}{10} \quad (5.1)$$

Where ICN- Corridor Noise Index; *IIN*- Internal Noise Index; *IDN*- Daily Noise Index; *ION*- Occasional Noise Index; *IRN*- Rest Noise Index; *ISN*- Study Noise Index.

The weightage assigned to each sub-index is proportional to its correlation between the perceived value with that of experimental data, with the question most closely correlated receiving the highest weightage. It is important to mention that an increase in mean votes for ICN, IDN, ION, IRN, and ISN is associated with reduced acoustic comfort, thus the average considers a complement of 10. The formula for AI, VI and TI are developed by summation of all subindex values varies from 0 to 10 from the secondary questioners. Normalised to 0 to 1 by dividing with 10.

5.2.3.2 Visual Comfort Index VI:

The Illumination Index (VI) is computed according to the formula 5.2 presented below:

$$VI = \frac{0.46*INL+0.01*INR+0.03*(10-IAG)+0.5*(10-IAL)}{10} \quad (5.2)$$

Where INL- Natural Light Index; *INR*- Reflection Light Index; *IAG*- Lighting Annoying Glares Index; *IAL*- Artificial Light Index.

The weightage assigned to each sub-index is proportional to its correlation between the perceived value with that of experimental data, with the question most closely correlated receiving the highest weightage. Negative values are utilized in the calculations by subtracting the votes from 10, as an increase in mean votes for the indices IAG and IAL indicates reduced visual comfort.

5.2.3.3 Thermal comfort index TI:

The thermal comfort level can be evaluated using the Predicted Mean Vote (PMV), which will vary between -3 and +3. A dimensionless index, IPMV, ranging from 0 to 1, is derived from PMV using the equation 5.3 shown below, considering the linear relationship illustrated in Figure 5.6.

$$IPMV = |(|PMV| + 1) - (|PMV| * 4/3)| \tag{5.3}$$

When PMV equals -3 or +3, IPMV becomes 0, and it reaches a maximum value of 1 when PMV is 0. For intermediate PMV values, the IPMV varies linearly from 0 to 1.

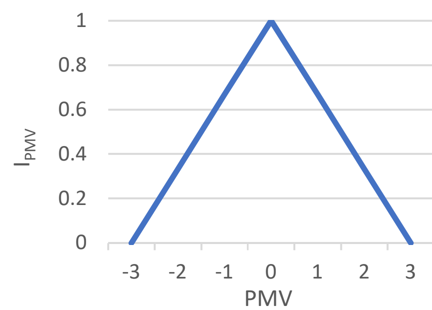


Figure 5.6 PMV Vs IPMV

5.2.4 The combined comfort index CCI:

To calculate the overall comfort index, we combine the weighted average values of the individual comfort indices. Each individual comfort index is given an equal weight, which is normalized to a range of 0 to 1. This equal weighting is applied because these parameters are ranked as top indicators among the 18 Performance Indicators. However, a limitation of this approach is that it does not account for potential variations in importance among these three KPIs, which would require a separate survey to estimate the individual weightages. The formula for determining the new combined comfort index, referred to as CCI, is given in equation 5.4 as shown below:

$$CCI = \frac{1}{3} * AI + \frac{1}{3} * VI + \frac{1}{3} * TI \tag{5.4}$$

Where AI represents the comfort index for acoustic conditions, VI for visual conditions, and TI for thermal conditions. This comprehensive index, CCI, provides a holistic measure of overall comfort, considering the combined impact of acoustic, visual, and thermal factors on the environment.

5.3 RESULTS AND DISCUSSIONS

In 2018, a year's worth of data was collected for all the selected parameters. Here, the maximum and minimum values of outdoor temperature and humidity are presented in Figure 5.7 and Figure 5.8, respectively. Figure 5.9 illustrates the indoor measured values for temperature, Figure 5.10 for humidity, Figure 5.11 for illumination, and Figure 5.12 for acoustic parameters. For a better understanding, the day variations of the selected parameters in hostel and classroom settings, measured at various floors and locations within the rooms, are presented individually in Figure 5.13, Figure 5.14, Figure 5.15, Figure 5.16, Figure 5.20, Figure 5.21, and Figure 5.22. Additionally, the mean values of the observed data are presented in Figure 5.25 for temperature, Figure 5.26 for humidity, Figure 5.24 for illumination, and Figure 5.23 for acoustic parameters. Data was collected over a period of seven days, focusing on thermal, lighting, and acoustical conditions. Throughout this brief autumn month, the indoor temperature fluctuates within a narrow range, with the minimum observed at 30.1°C (room B7-18), closely aligned with the outdoor temperature of 31.70°C (Thapa et al., 2018). The maximum indoor temperature of 30.56°C was recorded in room A7-12. Interestingly, the temperature differences among the rooms are minimal, and they generally maintain similar temperatures. Acoustic findings indicate that sound levels in all rooms exceeded 60dB, with the maximum recorded at 71.91 dB (room A7-46), potentially due to higher occupancy in that room.

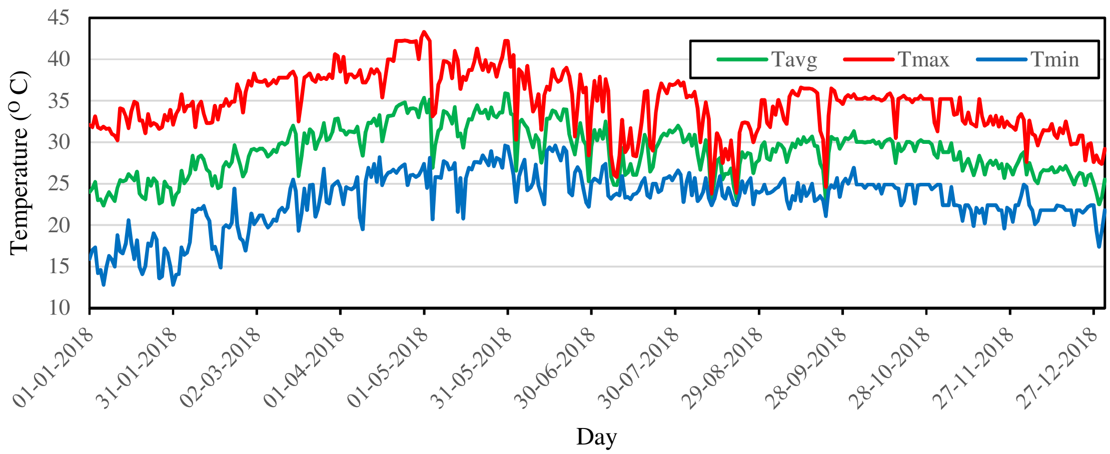


Figure 5.7 Measured Out door temperature

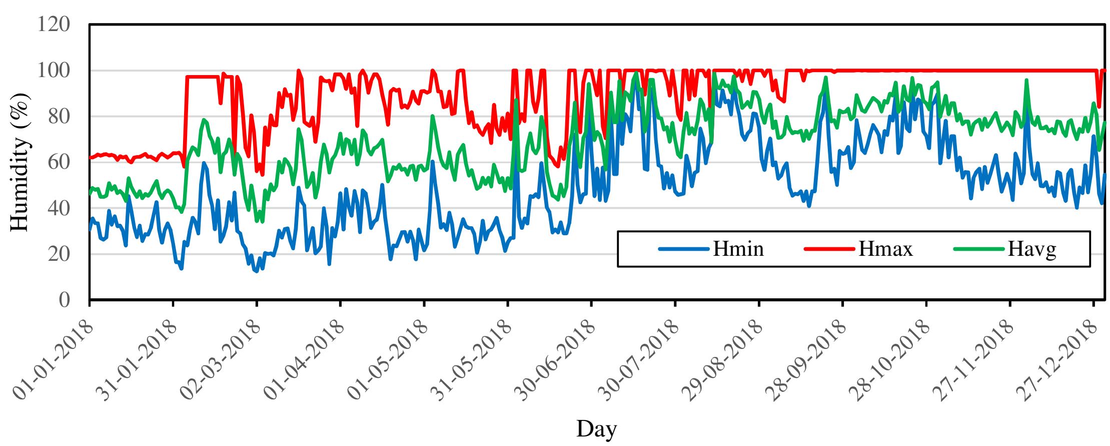


Figure 5.8 Measured Out door Humidity

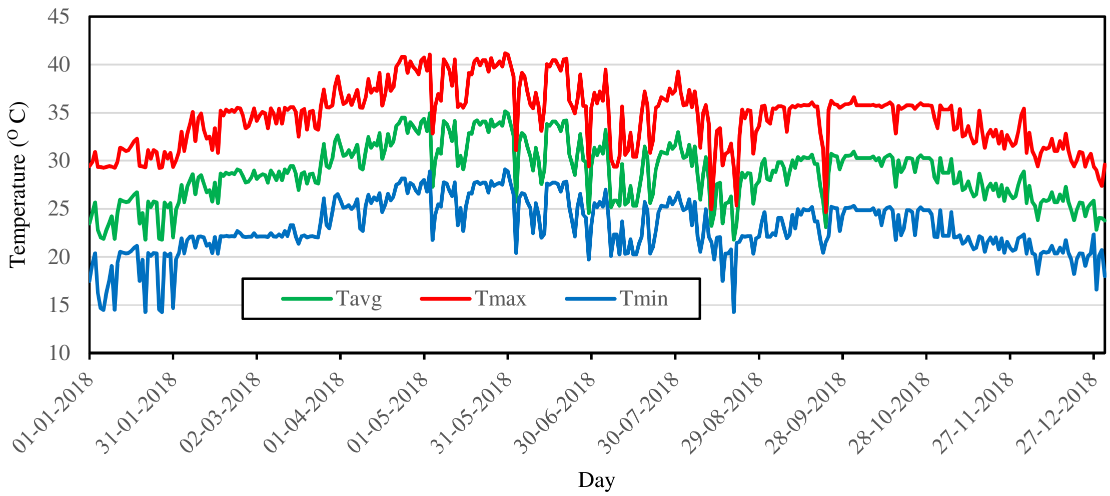


Figure 5.9 Measured Indoor temperature

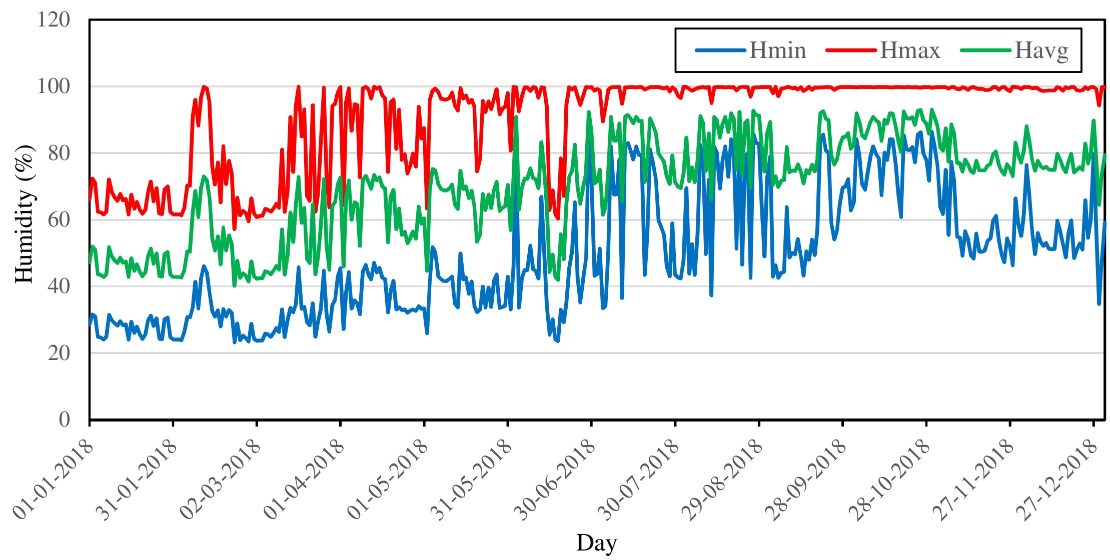


Figure 5.10 Indoor Humidity

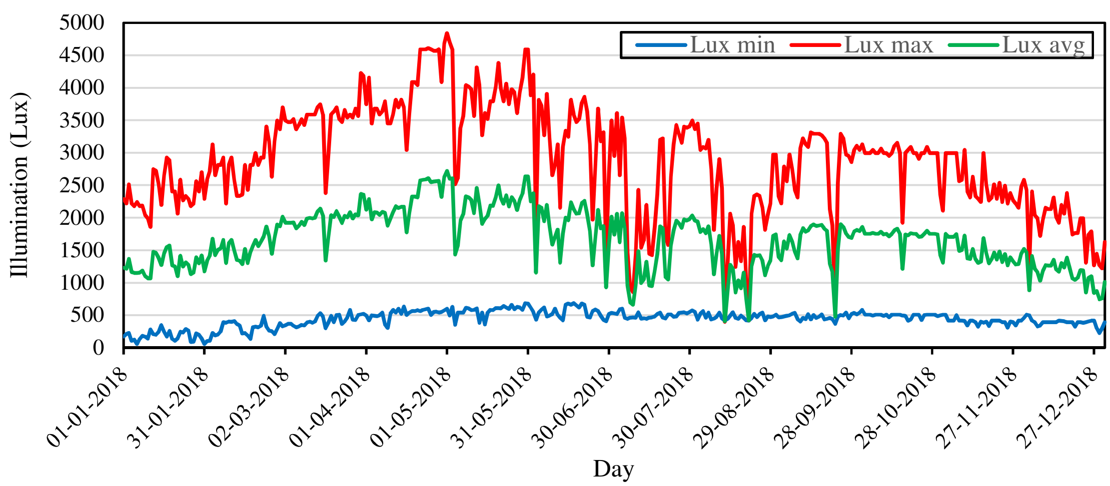


Figure 5.11 Indoor Illumination values

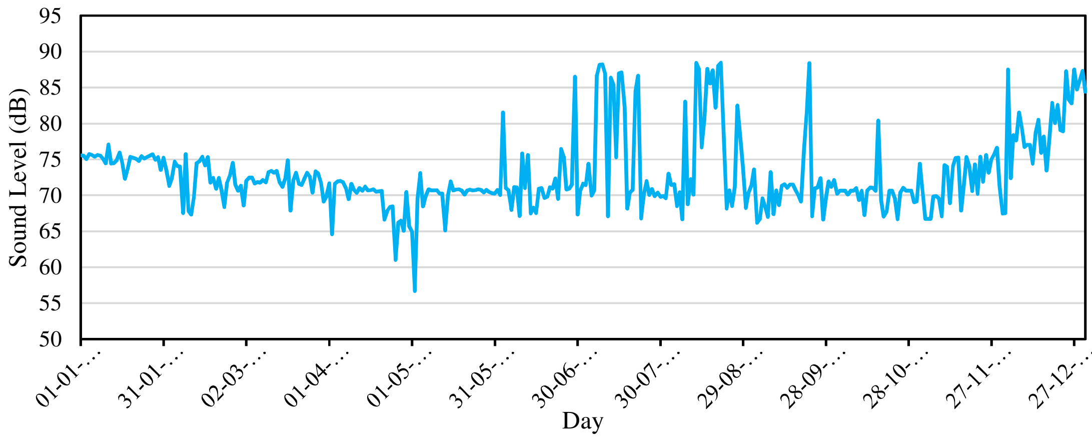


Figure 5.12 Indoor acoustic values

Daylight Intensity Analysis in Hostel Rooms:

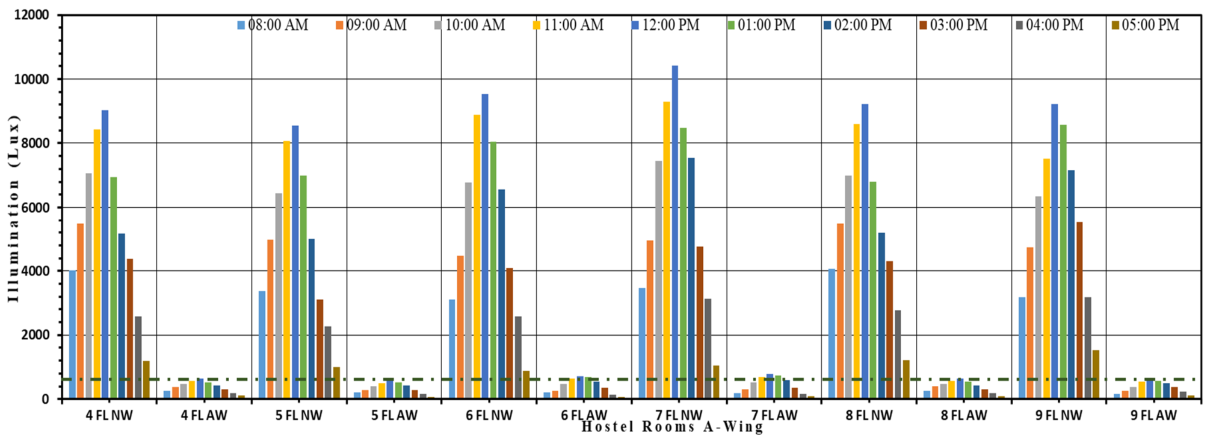


Figure 5.13 Illumination levels over a day (Hostel Rooms - A wing).

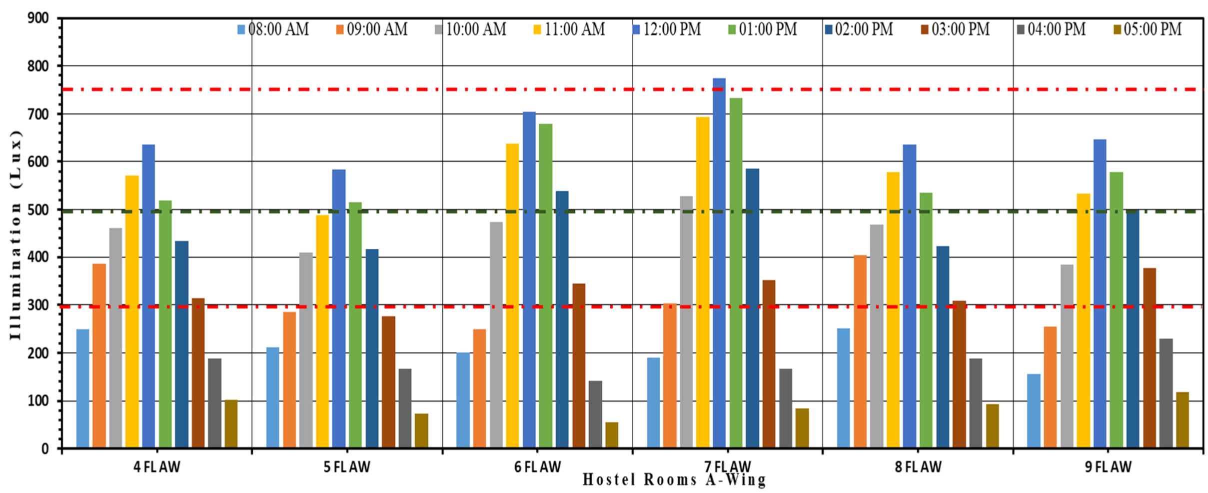


Figure 5.14 Illumination levels over a day (Hostel Rooms - A wing).

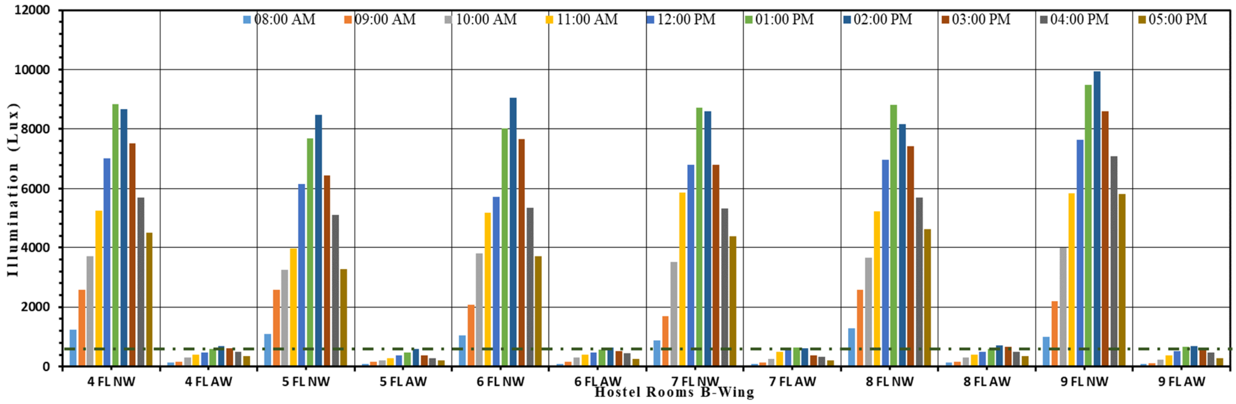


Figure 5.15 Illumination levels over a day (Hostel Rooms - B wing).

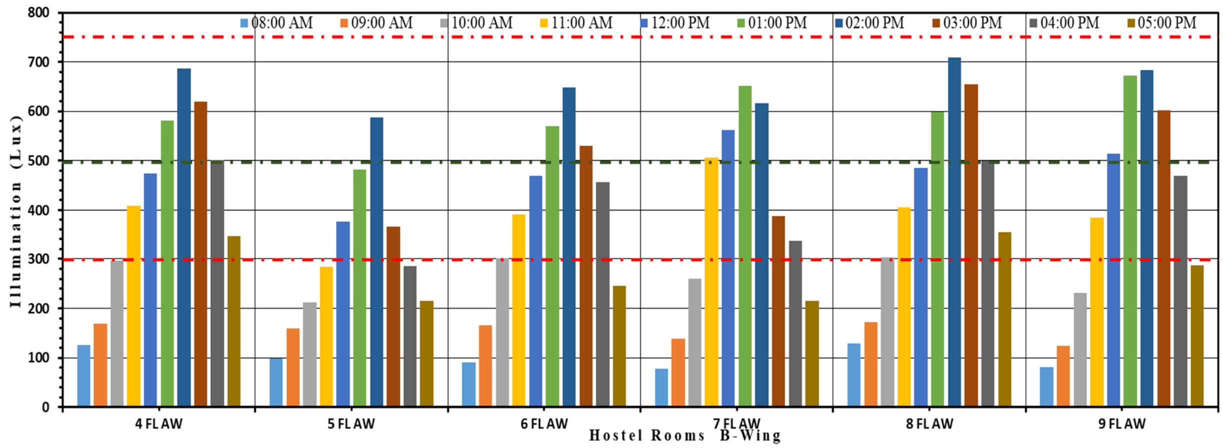


Figure 5.16 Illumination levels over a day (Hostel Rooms - B wing).

Daylight Intensity Analysis in Class Rooms

The department of civil engineering at NIT Warangal is located with latitude and longitude of 17°58'58.6"N 79°31'51.3"E. the aerial view is shown in Figure 5.17. The vegetation covers near the classrooms are different creating somewhat different indoor lighting conditions for each classroom. Three classrooms are selected named C1 (M.Tech-STR classroom), C2 (M.Tech-CTM classroom) and C3 (M.Tech-RSGS classroom). The entrance view of Department of civil engineering division and the classroom arrangement is shown in Figure 5.18. These classrooms are located in the 2nd floor of the Civil Engineering Department. The positions of doors and windows in the classrooms are same in the second floor for all the rooms. The seating arrangement inside the classrooms are shown in Figure 5.19.

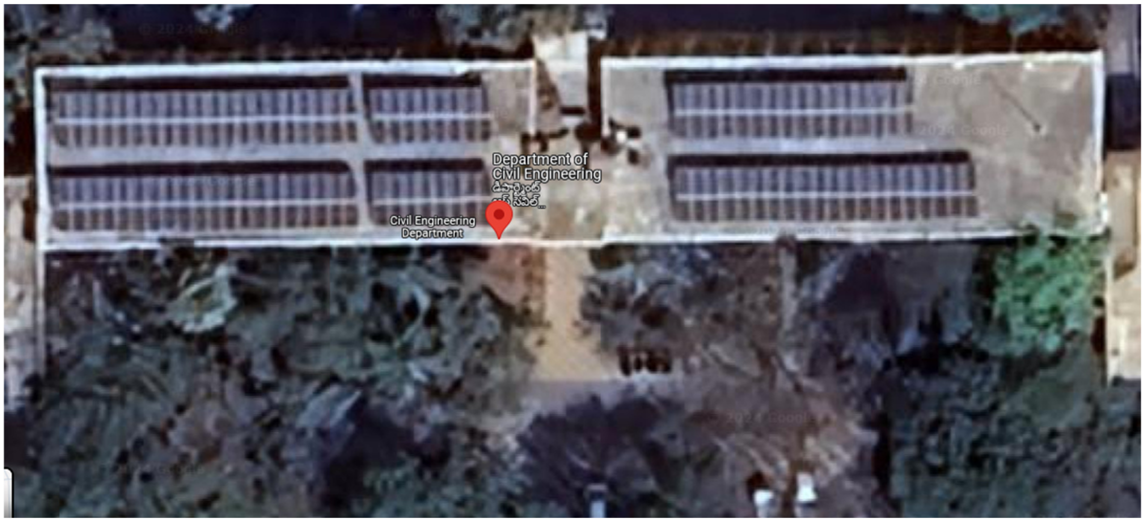


Figure 5.17 Aerial view of Department of Civil Engineering

Figure 5.18 Entrance of the Civil Engineering Department and location of classrooms in the floors

Figure 5.19 Seating arrangement inside the classroom

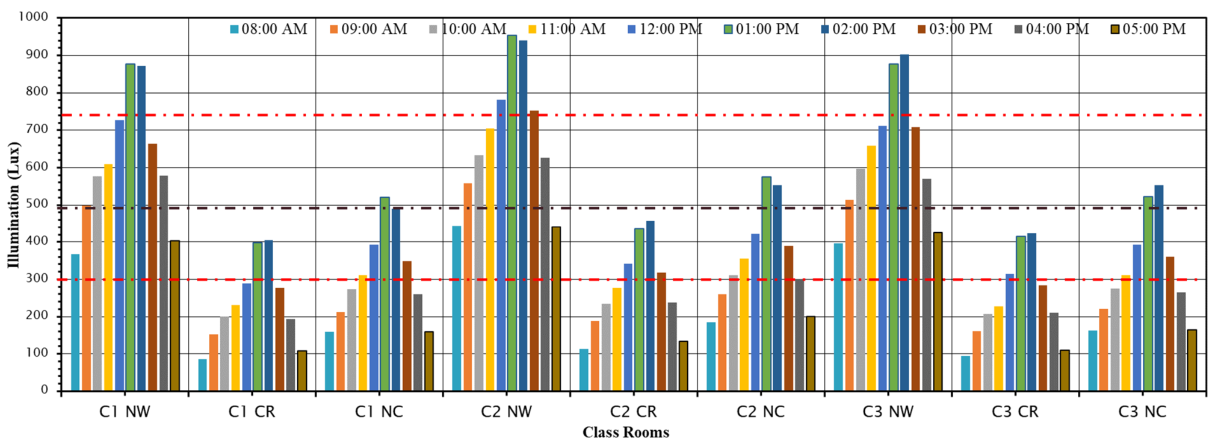


Figure 5.20 Illumination levels over a day (Class Rooms).

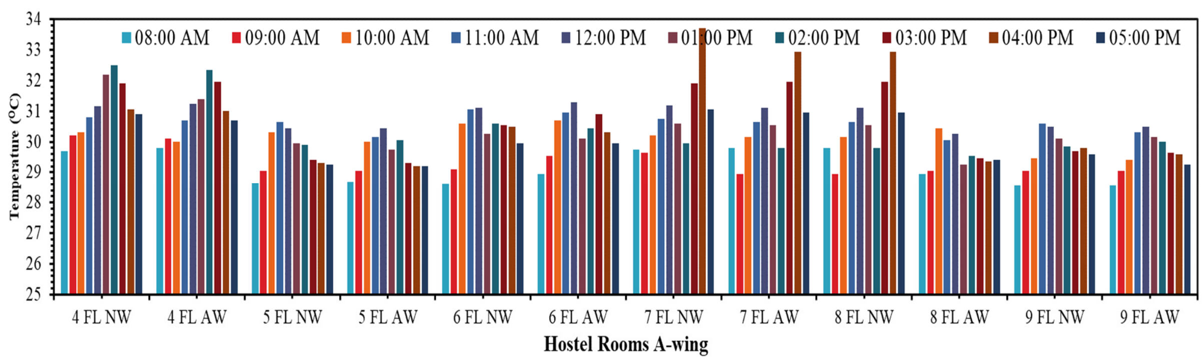


Figure 5.21 Temperature variation (Hostel room – A wing)

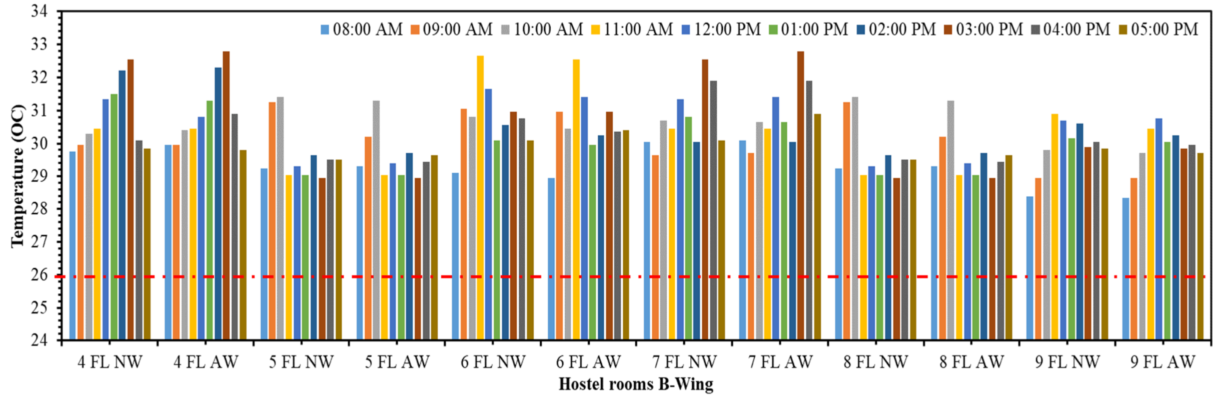


Figure 5.22 Temperature variation (Hostel room – B wing)

Six Hostel Rooms selected for the study. A3-13, B3-50, A7-12, A7-46, B7-20, and B7-48 are referred as R1, R2, R3, R4, R5 and R6 respectively.

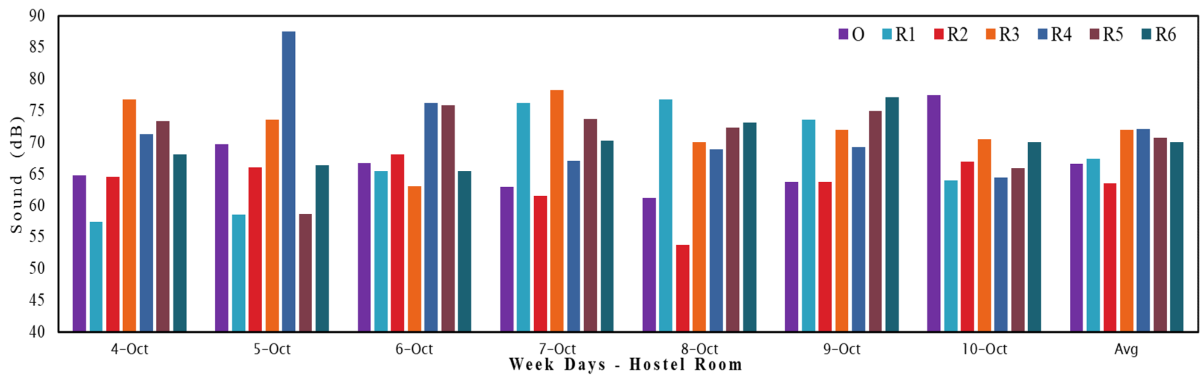


Figure 5.23 Weekly acoustical observations

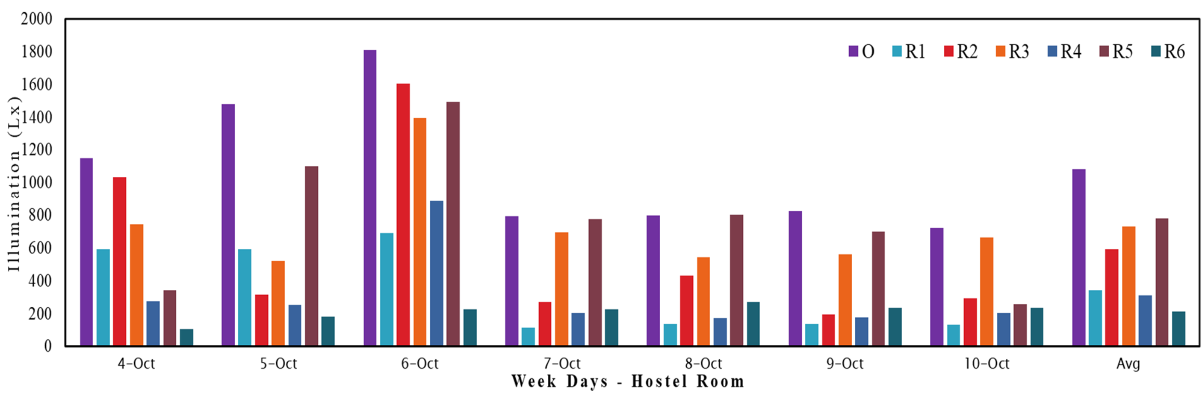


Figure 5.24 Weekly illumination observations

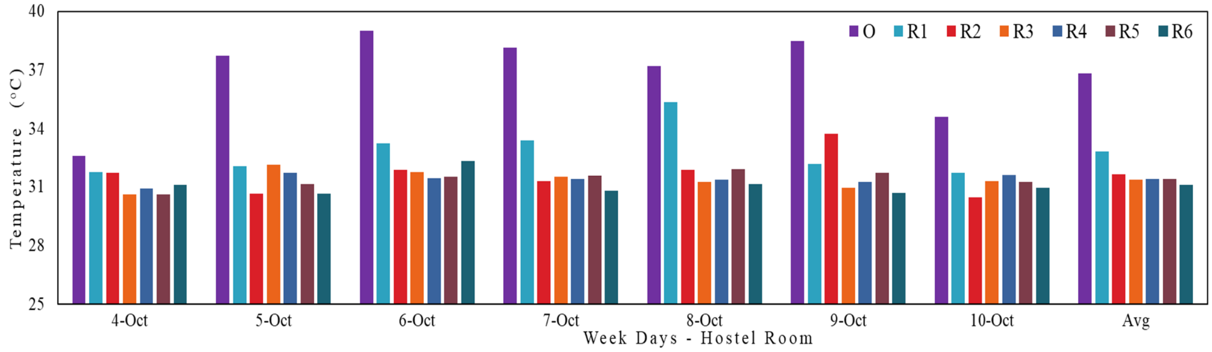


Figure 5.25 Weekly Temperature variations

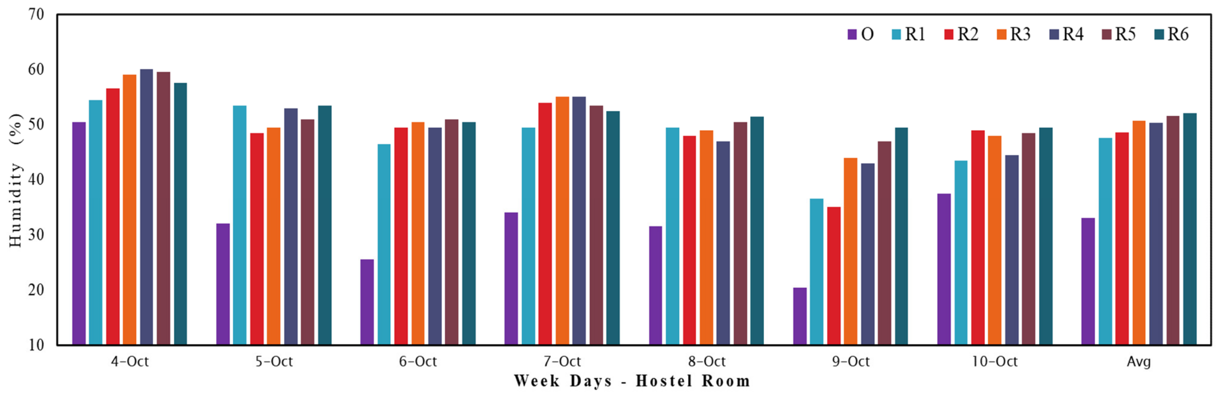
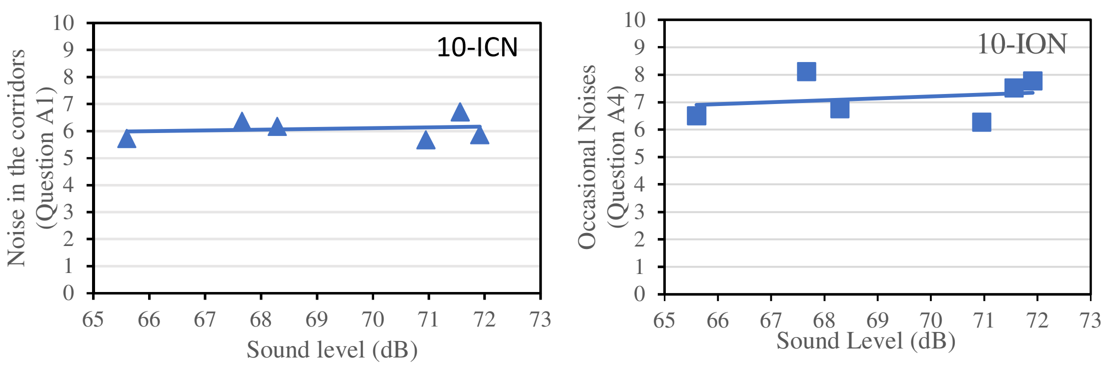


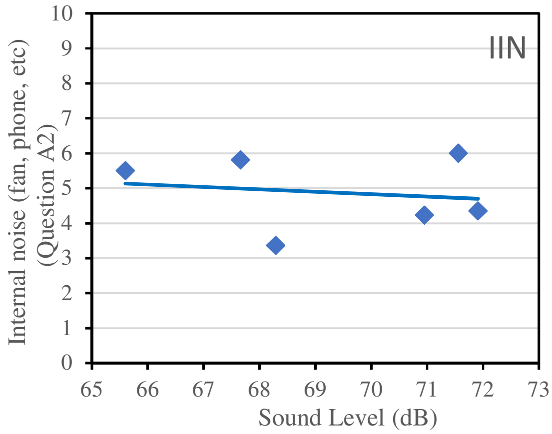
Figure 5.26 Weekly Humidity variations

5.3.1 Acoustic index AI:

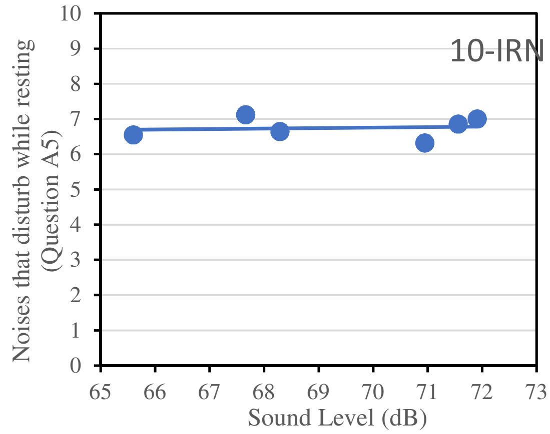
The weightages for all the sub-indices of acoustical parameter are calculated based on the amount of correlation with the perceived values. ICN is given a weight of 10%, IIN receives 10% weight, and IDN receives the highest weight at 40%. ION is assigned a weight of 20%, while both IRN and ISN receive a weight of 10% each. The weights are mentioned in brackets for each sub-indices of the correlation between measured data and certain answers are depicted in Figure 5.27.



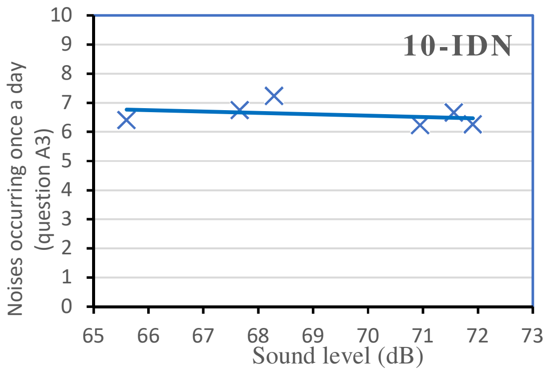
(a) 10-ICN (wt. 0.10) **(b) 10-ION (wt. 0.20)**



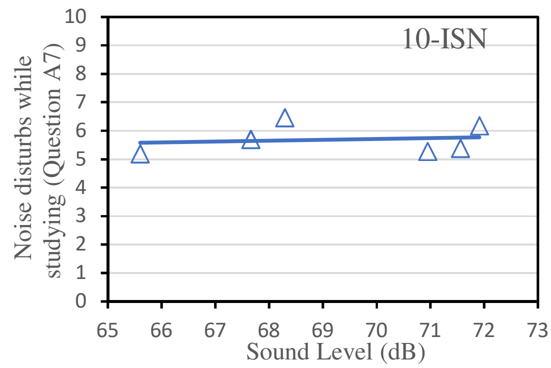
(c) IIN (wt. 0.10)



(d) 10-IRN (wt. 0.10)



(e) 10-IDN (wt. 0.40)

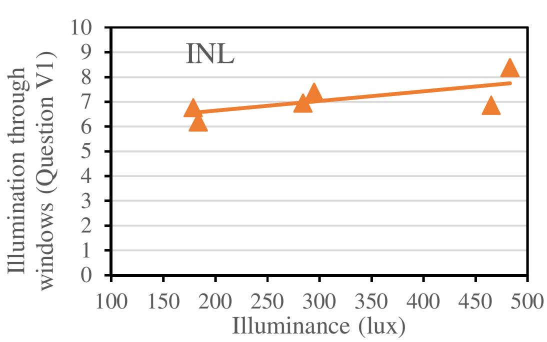


(f) 10-ISN (wt. 0.10)

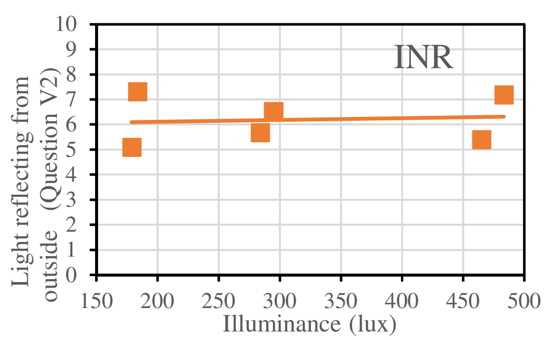
Figure 5.27 Weightages of sub-indices of acoustical parameter

5.3.2 Visual comfort index IV:

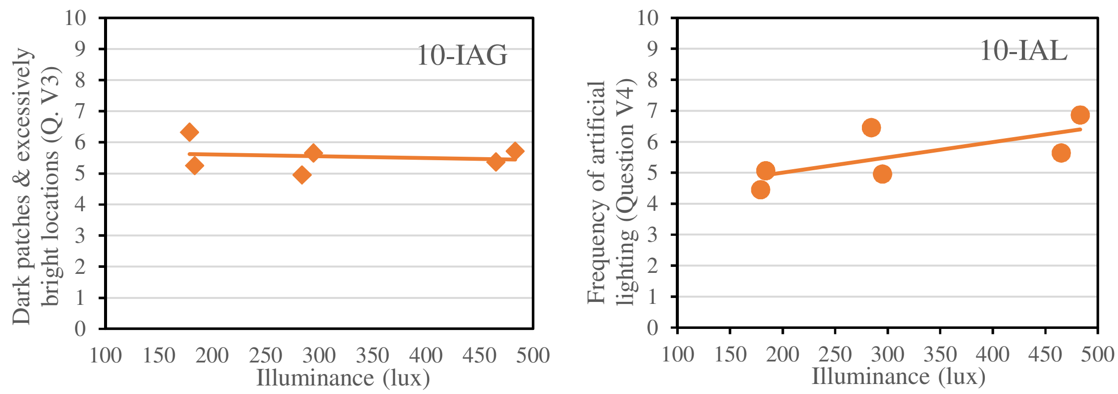
INL is assigned 46% of the weightage, INR receives 1%, IAG receives 3%, and IAL is given the highest weight at 50%. In Figure 5.7, correlations between subjective and experimental illumination results for different aspects; (a) Illumination through windows, (b) Light reflecting from outside, (c) Dark patches and excessively bright locations, and (d) Frequency of artificial lighting are presented Figure 5.28. The weights are shown in brackets.



(a) INL (wt. 0.46)



(b) INR (wt. 0.01)



(c) 10-IAG (wt. 0.03) **(d) 10-IAL (wt. 0.50)**

Figure 5.28 Comparison between subjective and experimental Illumination results

The evaluated individual sub-indexes for acoustical, illumination and thermal parameters in each of the selected rooms are presented in Figure 5.29, Figure 5.30 and Figure 5.31 respectively.

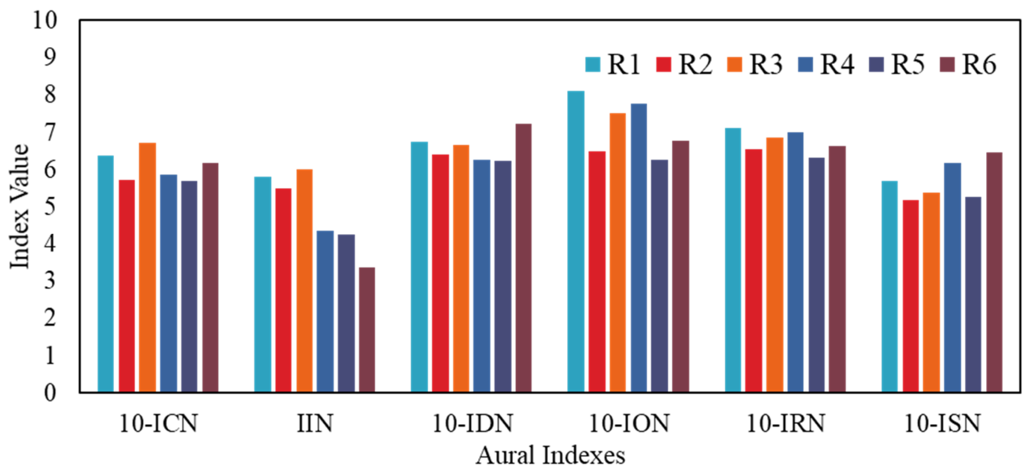


Figure 5.29 Sub-indices of Acoustical parameter

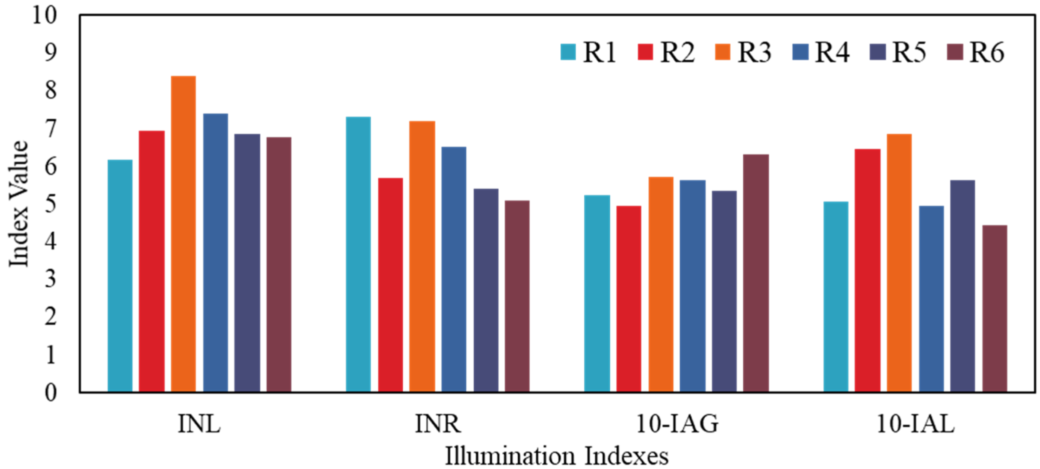


Figure 5.30 Sub-indices of Illumination parameter

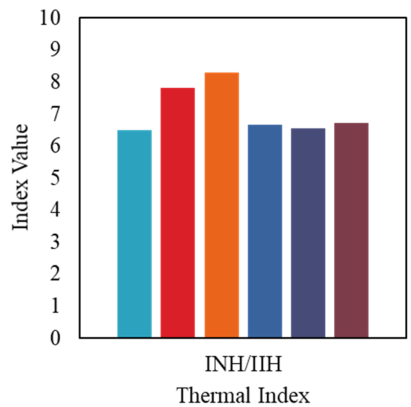


Figure 5.31 Thermal index variations

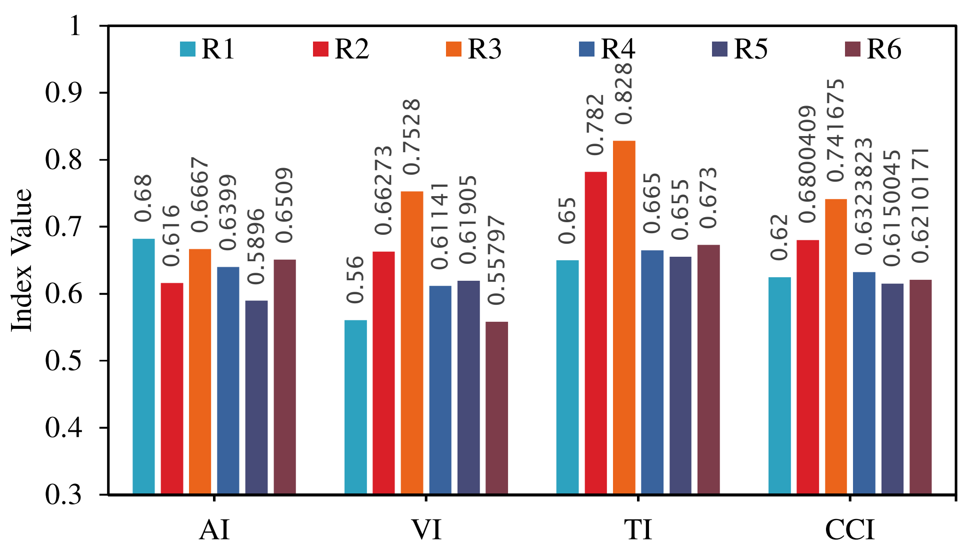


Figure 5.32 Individual parametric and combined comfort index variations

Table 5.4 ICC values Vs Grade of the building

CCI value	Grade
1	Best performance
>=0.65	Comfortable
0.45 – 0.65	Neutral comfort
<=0.45	Uncomfortable

The Acoustical, illumination and thermal index are computed using the developed equations 5.1, 5.2 and 5.3 respectively. Subsequently, the CCI is calculated by assigning equal weightage to these parameters as mentioned in equation 5.4. The variations of individual parametric indexes and the overall combined comfort among all these selected rooms are depicted in Figure 5.32. The new combined comfort index is measured on a scale from 0 to 1, where 0 represents the worst comfort and 1 indicates the best comfort. A value greater than 0.65 is considered comfortable, while values between 0.45 and 0.65 are classified as neutral. Any value below 0.45 is categorized as uncomfortable as shown in Table 5.4. The CCI value Vs Grade is formulated following Khatri et al., (2011) with little variations from the suggested values. With overall CCI of the building = 0.65, the building is graded as comfortable. R3, Illumination is good at east side rooms at higher floor. R1, AI is good at East side lower floor room might be with open area. R3, Best thermal index, exposed to sunlight for a shorter duration.

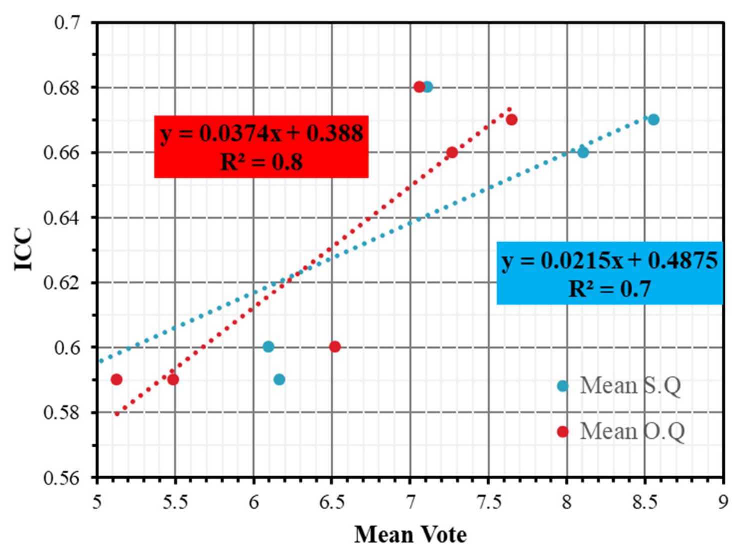


Figure 5.33 Correlations among the ICC Vs Mean S.Q & Mean O.Q

Correlating the Comfort Combined Index (CCI) with mean votes from occupants on thermal, acoustic, and lighting aspects. Calculated as the arithmetic average of the three votes. Mean votes for specific questions (Mean S.Q) (mean votes of Acoustic: Q2, Lightning: Q1 and Thermal: Q1). Mean votes for overall comfort questions are categorized as Mean values of Overall Questions (Mean O.Q). Highlighting a strong correlation between mean votes and ICC across a range of comfort conditions through Mean S.Q and Mean O.Q as shown in Figure 5.33.

5.4 CONCLUSION

The National Building Code (NBC) of India prescribes a narrow temperature range of 23°C–26°C for summers and 21°C–23°C for winters, disregarding the vast geographical, climatic, ethnic, and cultural diversity of its population. Recent field studies in Indian buildings reveal that Indian individuals exhibit a comfort temperature range much wider than that prescribed by the NBC. Manu et al. proposed the Indian Model of Adaptive Comfort (IMAC) based on data from five Indian climates. Similarly, a study by Kumar et al. found that comfort boundaries for Indian subjects in the composite climate of Jaipur extend beyond those suggested by the standard. These studies indicate that Indian subjects are comfortable in a wider range of conditions than previously prescribed by the NBC. As a result, the inclusion of adaptive thermal comfort models, such as IMAC, in the Energy Conservation Building Code (ECBC) of India is a step towards aligning building regulations with the actual comfort needs of occupants in diverse Indian climates.

Regarding room comfort, Rooms R3 and R2 demonstrate significantly higher comfort levels based on the Combined Comfort Index. The east side higher-level floors and west side lower-level floors provide a more comfortable experience. Acoustically, Room R1 outperforms all other rooms with an AI (Acoustic Index) of 0.68, but it has a relatively lower visual comfort index (VI) of 0.56. Room R5, with an AI of 0.59, stands at a neutral comfort level. Lower-level east side rooms perform better, possibly due to more open areas and vegetation. In terms of visual comfort, R3 has the highest value (VI=0.75), while R6 has the lowest value (VI=0.55), placing it at a neutral performance level. Assessing the overall building comfort by applying the Combined Comfort Index to the hostel building yields a rating of 0.65 out of 1, indicating that the building is considered comfortable based on the evaluation. A significant correlation is identified between the mean votes assigned to the rooms and the CCI (Combined Comfort Index), established for both S.Q and O.Q metrics. The obtained R-square values from this analysis are substantial, registering 0.7 and 0.8, respectively. This consistency underscores the efficacy of the composite thermal, acoustic, and visual comfort indicator formulation.

In conclusion, the studies on adaptive thermal comfort in India underscore the importance of revisiting and updating building regulations like the ECBC and NBC to reflect the diverse comfort needs of occupants in different climatic regions. By incorporating adaptive comfort principles into building design and energy conservation practices, India can move towards more sustainable and comfortable built environments that meet the needs of its diverse population.

CHAPTER 6

FORMULATING ENERGY CONSERVATION STRATEGIES

This chapter addresses the third sub-objective, where two pivotal aspects take centre stage. The first aspect involves selecting the optimal design alternative by integrating Building Information Modelling (BIM) and Visual Programming Language (VPL) tools during the early stages of construction. The second objective is centred around a streamlined energy analysis approach, which evaluates the impact of building orientation, envelope design and Window-to-Wall Ratio (WWR). Energy savings are primarily influenced by factors such as solar heat gain and local variables, including social lifestyle considerations. This dual approach aims to provide a comprehensive understanding of sustainable design practices and to guide designers toward more flexible and environmentally conscious choices.

6.1 INTRODUCTION

6.1.1 Integrating Multi Criteria Decision Method (MCDM) and Building Information Modelling (BIM) in the Building Planning Stage

Early decisions wield substantial influence on the entire lifecycle of a project, a universal truth that applies to endeavours as diverse as constructing a simple residence, a thermal power plant, or a dam. The progression of a construction project unfolds across multiple distinct phases, including the conceptual, schematic, production, bidding and construction stages. Within the sphere of residential structure design, the conceptual phase stands as a critical juncture, notably when it comes to finalizing the floor plan. Here, designers may grapple with a range of options, each susceptible to influence from an array of factors (Chintis, 2019; Valdes George, 2022). Achieving an optimal floor plan design involves adherence to the 'principles of building planning,' a concept outlined by the American Institute of Architects, emphasizing the systematic and efficient arrangement of building elements and units to maximize available space, area and facilities. This facet of architectural planning intersects with the 12 standard criteria often found in the literature, referencing works by Ahuja and Mahajan (Ahuja, 2007; Mahajan, 2016). These criteria may at times present conflicting considerations when selecting a floor plan layout, aiming to fulfil a multitude of requirements. To address this intricate challenge, a MCDM approach emerges as a valuable tool for resolving the task of establishing a floor plan layout in alignment with the overarching principle of planning. MCDM stands for Multi-Criteria Decision Making. It is a field of study that deals with making decisions in the presence of multiple, often conflicting, criteria or objectives. MCDM methods help decision-makers evaluate and select the best alternative or course of action from a set of options based on a range of criteria or factors. These methods aim to provide a systematic and structured approach to decision-making, especially in complex and uncertain environments. Surprisingly, an examination of existing literature reveals a paucity of prior study that fully delves into this specific nexus, marking an intriguing area for further exploration.

The literature review highlighted the relatively limited attention given to the integrated MCDM-BIM approach and the persistent need to explore its effectiveness (Tan et al., 2021). To foster effective synergy between these two crucial components, a seamless medium for data exchange is imperative. Employing computational design tools represents a promising avenue for achieving this objective. At its core, Computational Design (CD) involves applying computational strategies to the design process, enhancing problem-solving by encoding design decisions in a computer language.

Notably, the application of CD is predominantly associated with architects within the Architecture, Engineering and Construction (AEC) industry. Therefore, the primary aim of this study is to introduce a methodology that bridges MCDM and BIM processes for building design planning, underpinned by the principles of building planning. The proposed methodology is subsequently validated through the analysis of two case studies, demonstrating its practical application in real-world scenarios.

The concept of building planning can be defined as the organized arrangement of various components or parts within a structure to create a functional and cohesive form (Mahajan, 2016). The primary goal of building planning is to position all building elements at the appropriate levels according to their functional requirements, thereby maximizing the use of available space. Building planning adheres to twelve fundamental principles as outlined by Ahuja (2007), which include:

1. **Aspect:** Aspect involves positioning rooms in a way that occupants can fully experience natural elements such as sunlight, airflow and scenic views. While a good view is desirable, design should not be solely dictated by this factor.

2. **Prospect:** In building planning, prospect refers to the desired view from certain parts of the house. It is influenced by the surroundings of the site, such as gardens or dumps. The layout should consider doors and windows to optimize prospect, but not at the

expense of a good overall layout. For example, projecting windows or a blind bay face with side window openings can maintain privacy while enhancing views.

3. **Furniture Requirements:** Each room, whether it's a living room, kitchen, office, or laboratory, has unique furniture needs that should be considered during planning.

4. **Roominess:** The efficient use of room dimensions to create a sense of space without compromising the plan is essential. Rectangular rooms tend to be more functional than square ones, with an ideal length-to-width ratio of 1.2 to 1.5.

5. **Grouping:** Grouping involves organizing rooms according to their functions and proximity to one another. Proper grouping minimizes disruptions and ensures smooth transitions between different areas.

6. **Circulation:** Circulation pertains to the internal connections between rooms on the same floor or between different levels. It involves both horizontal circulation (e.g., corridors) and vertical circulation (e.g., stairs). Circulation paths should be efficient and well-lit.

7. **Sanitation:** Building sanitation encompasses the provision of sanitary facilities, lighting and ventilation. Adequate lighting and ventilation should be maintained throughout the structure to ensure proper hygiene.

8. **Elegance:** The overall aesthetic and arrangement of a building are critical for creating an elegant appearance. The choice of the construction site significantly influences the building's elegance.

9. **Privacy:** Privacy is an important consideration in building design. Every room should offer a level of seclusion, which can be achieved through thoughtful entry placement, door and window positioning and internal design elements.

10. **Flexibility:** Flexibility involves designing rooms that can serve multiple purposes, which is particularly relevant in economically driven construction, where versatility is essential.

11. **Economy:** Economic considerations play a substantial role in building planning. Adjustments to the design may be necessary to align with resource and financial

constraints, but these should not compromise the structure's required strength and durability.

12. **Orientation:** Proper orientation aims to align the building layout to maximize comfort in natural elements. This involves optimizing the direction of the building to enhance resident comfort and environmental advantages.

These principles collectively guide the art and science of building planning, ensuring structures are functional, aesthetically pleasing and responsive to the needs of their users.

In this streamlined methodology, the initial project data, scope and building requirements are first collected and thoroughly understood. Subsequently, a range of design alternatives is crafted using Revit's Design Options feature, allowing for equitable evaluation by stakeholders to identify the optimal choice. Criteria for evaluating these alternatives are derived from building planning principles and their relative importance is calculated through AHP, often with the guidance of an experienced architect. A questionnaire is constructed in Dynamo, aligning with the chosen criteria and experts assign scores to each question. These scores are then exported to MS Excel for the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) analysis. The best alternative is determined based on these scores and results are visualized and saved within Revit. In cases where further modifications are made, the analysis can be reiterated to update the results. Once the final selection is confirmed, the chosen alternative is designated as 'primary' for subsequent detailed development. The flowchart illustrating the first aspect of the third objective, the integration of BIM with MCDM during the project's initial phase is depicted in Figure 6.1

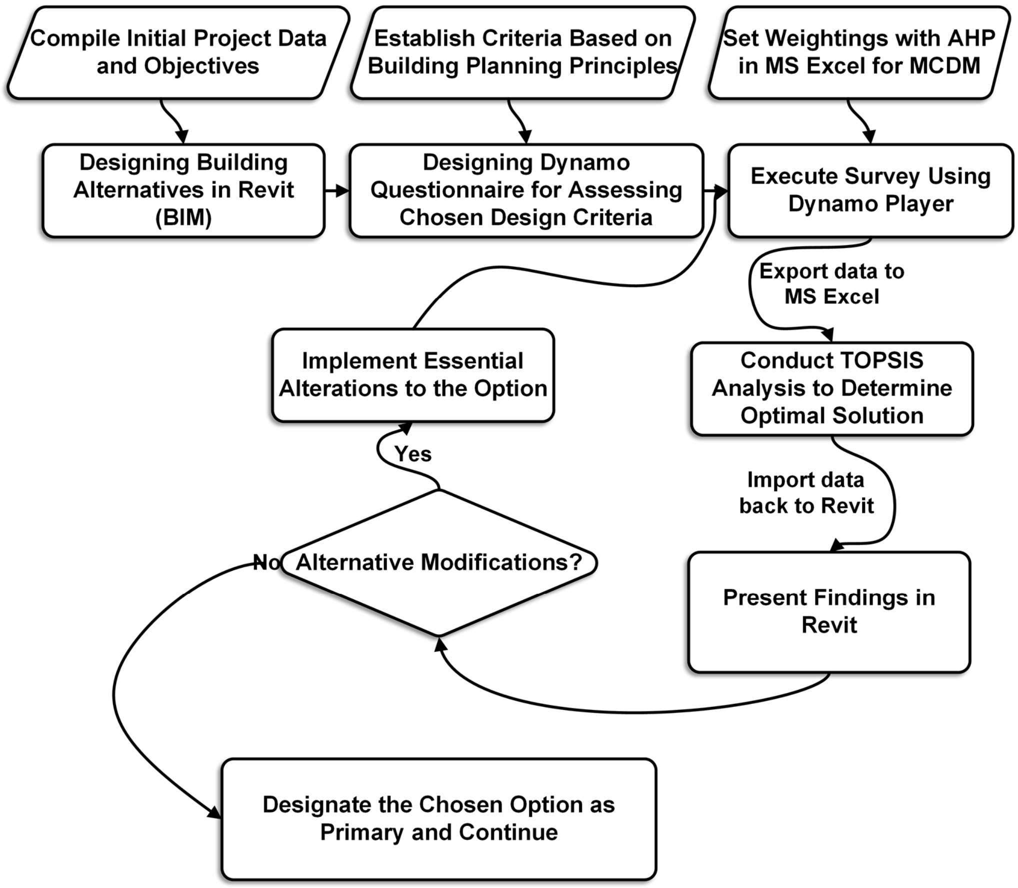


Figure 6.1 Flowchart of MCDM and BIM Integration in the Building Planning Stage

6.1.2 Integrated Energy Conservation Strategies: Blending Envelopes, Orientation and Window-to-Wall Ratio (WWR)

The construction industry's growing emphasis on energy efficiency has become a global priority, resonating throughout the AEC sector. Energy efficiency plays a crucial role in addressing a range of global concerns, including environmental impact, life-cycle costs of projects, carbon footprint reduction, challenges related to global climate change and the broader pursuit of sustainability. With the world's population expanding at an exponential rate and energy demand continually on the rise, it has become imperative to reduce the energy consumption of buildings by enhancing their energy efficiency. To achieve a sustainable future, it is paramount to implement clean energy solutions and conservation measures.

Buildings currently represent a significant portion of global energy consumption, accounting for approximately 40% of the world's primary energy production and contributing to roughly 30% of carbon dioxide emissions. While the incorporation of insulation materials in building envelopes can significantly reduce energy demand, it is worth noting that many builders, especially in regions with comparatively lower energy performance, do not integrate such materials. The intricate variations in global climate across different regions and seasons are well-established. Some areas endure scorching heat, while others contend with extreme cold. Many countries possess unique climate characteristics, such as dry continental climates with cold and relatively rainy winters, or hot and sun-soaked summers. Despite extensive global studies into the energy behaviour of buildings concerning these climate variations, there is a noticeable shortage of literature addressing specific regional contexts.

6.1.2.1 Building Information Modelling (BIM) Overview

BIM is defined as "a digital representation of the physical and functional characteristics of a facility." It offers a substantial potential for life-cycle modelling and the management of buildings and building systems (NBIMS, 2015; VA BIM STANDARD, 2017). While BIM policies have advanced significantly in serving the needs of Architectural, Engineering, Construction, Owner and Operator (AECOO) trades, its application has been primarily limited to large-scale commercial or residential projects. Small-scale residential sectors have often been overlooked in this context. BIM can be broadly categorized into two areas: one focuses on modelling and the other pertains to analysis, including energy simulations, quantity take-offs, environmental impacts and data communication among stakeholders (Eastman et al., 2011). BIM, as a multidimensional tool, can be further classified into various dimensions: 3D-BIM for modelling, 4D-BIM for adding a time dimension to simulate activity sequences, 5D-BIM for incorporating cost elements in construction estimation, 6D-BIM for achieving sustainability through thermal and Global Warming Potential (GWP) simulations and 7D-BIM for comprehensive building performance management and operation and maintenance (O&M) purposes (Redmond, et.at., 2012).

There are several reputable BIM software tools commonly used for residential purposes, such as VisionREZ, Vertex BD, Envisioneer, ARCHICAD 19 Solo, SoftPlan, Chief Architect, Vectorworks, Revit, StrucSoft Solutions, FreshBrix, BuilderTREND and BIM Pipeline. Each of these tools has its own strengths and weaknesses. The choice of the best BIM software depends on the specific project requirements and complexity (Eastman et al., 2011; Fabris, 2010; Garcia et al., 2018; GRAPHISOFT, 2016; Green, 2016; Lucas, 2017; Merschbrock & Munkvold, 2014; Yoders, 2011). Designers and builders select suitable and cost-effective BIM software and often incorporate various add-ins to facilitate their desired analyses. For instance, Autodesk Insight 360 can be integrated into Revit for energy and lighting analysis, offering extended options and capabilities (Autodesk, 2017).

6.1.2.2 Energy analysis/simulation software tools and Building Information Modelling (BIM)

Ample energy analysis software has been created by different organizations for energy optimization of the building virtually, where some are compatible with BIM for integration and some are independent. As per a web-based information by Building Energy Simulation Tools - Directory (BEST-D), there are around 196 energy simulation tools available and it is very difficult to select a reliable tool. This directory was formerly hosted by the US department of energy and currently it is handled by the International Building Performance Simulation Association (IBPSA) (IBPSA USA, 2017). These building performance simulation software tools are of various types, ranging from whole building simulators, building system calibrators and energy auditors to ensure detailed analysis for specific energy conservation and energy fault detection purposes (Lu, et.al., 2017). In general, these tools are in three ways (Stergard et al., 2016).

1. Applications with integrated simulation engine (e.g. Energy Plus, ESP-r, IES-VE, IDA ICE);
2. Software that docks to a certain engine (e.g. Design builder, eQuest, RIUSKA, Sefaira);
3. Plugins for other software enabling certain performance analysis (e.g. DIVA for Rhino, Honeybee, Autodesk Green Building Studio).

Auto desk Revit is used as BIM software for the present study. Revit is one of the top-rated software and pretends as BIM tool, as has been revealed in a survey conducted by National Building Specification (NBS) in their annual reports (NBS, 2015, 2017, 2018). For analysis the Green building studio add-on to Revit, Insight 360 is used.

The core objective of this study is to reduce the annual energy demand of multifamily dwellings based on weather data and specific building attributes. This reduction is achieved through the utilization of BIM and energy simulation software. To attain this goal, a case study is conducted, focusing on a reference building serving as a representative model for multifamily houses. The study encompasses a total of energy simulation analyses, exploring combinations that consider various local materials for walls, floors and roofs. This evaluation aims to compare electricity consumption with a benchmark building.

Upon analysing and comparing the simulation results, the most energy-efficient option is identified. Further, this option is subjected to variations in building orientation and assessments of increasing the glazing area. The flowchart illustrating the second aspect of the third objective, which pertains to integrated energy conservation strategies, is presented in Figure 6.2

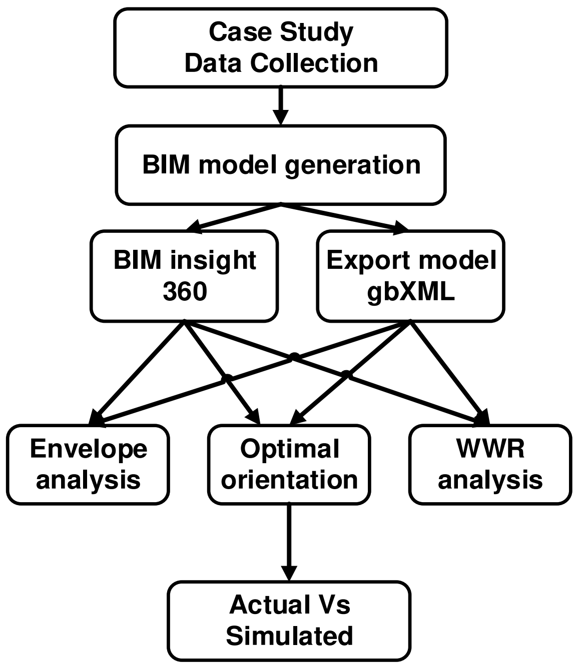


Figure 6.2 Flowchart of Integrated Energy Conservation Strategies for the Second Aspect of the Third Objective

6.2 METHODOLOGY

6.2.1 Unifying Multi Criteria Decision Method (MCDM) and Building Information Modelling (BIM) in Building Planning

This first aspect of the third sub-objective outlines a systematic approach for the integration of BIM with MCDM during the initial stages of construction projects.

1. **Initial Data Gathering:** It commences by meticulously collecting fundamental project details, including the scope of work, involving an in-depth exploration of the building's

functional requirements and a comprehensive analysis of site conditions. This initial step lays the foundation for informed decision-making.

2. **Design Alternatives Creation:** Subsequently, various design alternatives are developed, recognizing the existence of multiple options for any given project. Ensuring that all stakeholders have an equal opportunity to visualize these alternatives during the project's initial stages is crucial for selecting the optimal choice. The versatile 'Design Options' feature in Revit software is harnessed for this purpose. After creating the design alternatives, assessment criteria are selected based on the principles of building planning. Weights for these criteria are determined using the AHP, guided by the expertise of an experienced architect who assists in performing pairwise comparisons of the criteria.

3. **Questionnaire Development:** The next stage involves the creation of a questionnaire, seamlessly integrated into a Dynamo script. This questionnaire aligns with the chosen criteria and forms the foundation for ranking the design alternatives. Experts are invited to provide scores, typically on a scale of 1 to 100, for each questionnaire item. These scores are systematically collected and then exported to MS Excel, preparing for the subsequent TOPSIS analysis.

4. **Optimal Alternative Selection:** Using the TOPSIS analysis, the most suitable design alternative is determined, taking into account the accumulated scores. The rankings of these alternative design options can be reintegrated into the Revit environment using Dynamo, where they can be visually represented in various chart formats. The results are carefully stored as draft views for reference and further analysis.

5. **Iterative Refinement:** This process remains flexible and responsive. If further adjustments or refinements are necessary, the entire process can be repeated. This iterative approach allows revisiting and updating results as needed. Once the final decision is reached, the chosen alternative is formally designated as the 'primary' option, marking the transition to the next phase where further detailed development and execution await.

6.2.1.1 Concise Insights into Utilized Tools and Techniques

1 Autodesk Revit

Revit software is a versatile tool commonly utilized by architecture, engineering and construction teams to craft high-quality buildings and infrastructure. Developed by the team at Parametric Technology Corporation (PTC), a well-known United States-based company celebrated for its widely-used FEM program, Mathcad, Revit software empowers users with the capability to:

1. Create parametrically accurate, precise and easily modifiable models of forms, structures and systems.
2. Efficiently manage and update documentation, enabling real-time adjustments to plans, elevations, schedules and sections as projects progress.
3. Provide interdisciplinary teams with specialized toolsets and a unified project environment for seamless collaboration.

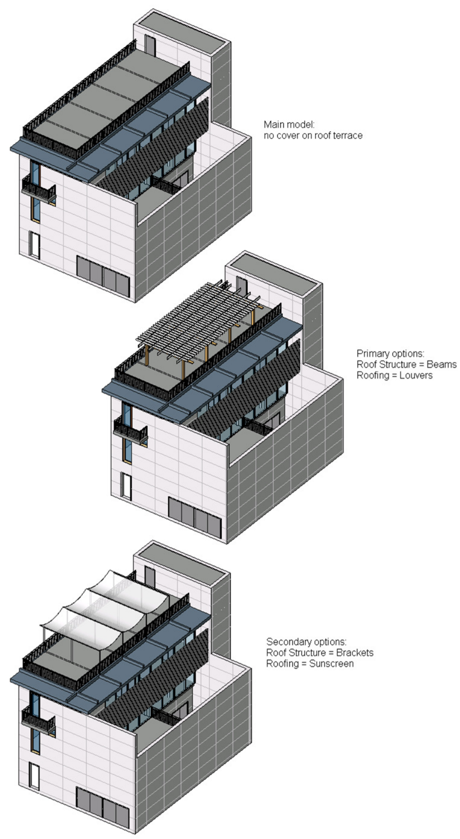


Figure 6.3 Example for Design options (Source: Autodesk, 2018)

Furthermore, the Design Options functionality enables teams to develop, evaluate and refine building components and spaces within a single project file. Design options can span a spectrum of complexity, allowing for the exploration of various entry designs or roof structural systems. As projects advance, design options often evolve into more focused and streamlined alternatives. An example of a design option in selecting various roof coverings is shown in Figure 6.3.

2 Dynamo

Dynamo, an open-source visual programming language, is developed by designers and construction experts to enhance Revit's capabilities. It allows users to input code and build algorithms through nodes. Dynamo extends BIM functionalities in Revit, enabling complex geometry modelling, task automation, error reduction and data export to various formats. Its user-friendly interface and extensive scripting libraries expedite the design process. The structure of nodes in Dynamo is depicted in Figure 6.4

Regarding the structure of Dynamo nodes, they encompass five core components:

1. Name
2. Main Body
3. Ports (In and Out)
4. Lacing Icon
5. Default Value.

These elements collectively shape the functionality of nodes, making Dynamo a versatile and efficient tool.

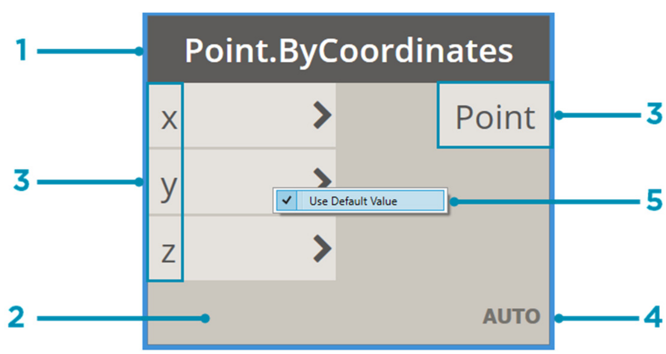


Figure 6.4 Structure of nodes in Dynamo (Dynamo BIM, 2019)

3 The Analytic Hierarchy Process (AHP)

It is a mathematical and psychology-based approach designed to facilitate the organization and evaluation of complex decisions. Originating in the 1970s and refined over time, it was developed by Thomas L. Saaty. AHP consists of three essential components: the central objective or problem to be addressed, the array of feasible options and the criteria against which these alternatives will be assessed. AHP provides a robust framework for arriving at well-founded decisions by establishing the criteria, exploring alternative options and aligning these elements with the overarching goal. The fundamental scale for comparative purposes, as indicated by Saaty in 1987, is outlined in Table 6.1.

Table 6.1 The foundational scale, as described by Saaty (Saaty, 1987)

Intensity of Importance on an absolute scale	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

1. Model Development: The initial phase involves defining the problem, establishing a model and identifying the alternatives for comparison. For illustrative purposes, It is considered selecting the best project from three options. The criteria for evaluation denoted as X1, X2, X3 and X4, are chosen. The model is depicted in Figure 6.5.

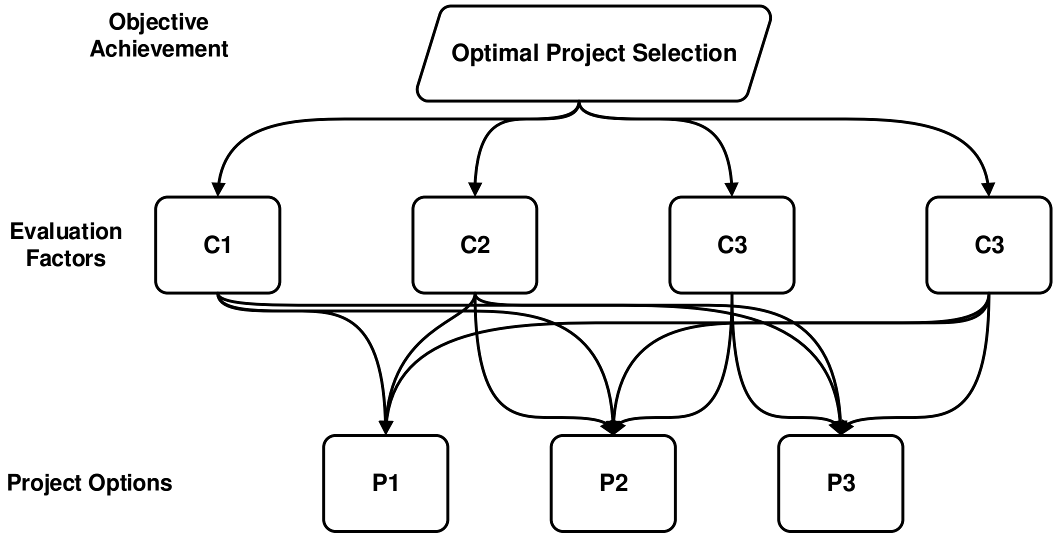


Figure 6.5 Model Visualization

2. Pairwise Comparisons: Conduct Pairwise Comparisons Using the Established Fundamental Scale. An illustration of a pairwise comparison matrix is presented in Table 6.2. The subsequent step involves validating the consistency of the pairwise comparison matrix through the following procedure. Here, $[C_N]$ denotes the geometric mean of each row within the pairwise comparison matrix.

$[C_1]= (1* 1/7* 1/5* 1/3)^{1/4} = 0.31239$

$[C_2]= (7* 1* 2* 3)^{1/4} = 2.5457$

$[C_3]= (5* 1/2* 1* 3)^{1/4} = 1.6549$

$[C_4]= (3* 1/3* 1/3* 1)^{1/4} = 0.75984$

Sum $(S) = \sum[C_N]= 5.2728$

Table 6.2 Matrix for Pairwise Comparisons

	C1	C2	C3	C4
C1	1	1/7	1/5	1/3
C2	7	1	2	3
C3	5	1/2	1	3
C4	3	1/3	1/3	1

The weightage of $[C_N]$ (incorporated in A2 matrix) is denoted as $WCn = [C_N] / (S)$.

where $S=\sum[C_N]$.

W_{C1}= 0.059246

W_{C2}= 0.4828

W_{C3}= 0.31385

W_{C4}= 0.144

3. Assessing Consistency: AHP offers the advantage of evaluating the consistency of the obtained weightages by computing the consistency ratio. To do so, perform the following calculation:

$$\text{Matrix, A3 = A1 x A2} = \begin{bmatrix} 1 & \frac{1}{7} & \frac{1}{5} & \frac{1}{3} \\ 7 & 1 & 2 & 3 \\ 5 & \frac{1}{2} & 1 & 3 \\ 3 & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix} \times \begin{bmatrix} 0.059246 \\ 0.4828 \\ 0.31385 \\ 0.1441 \end{bmatrix} = \begin{bmatrix} 0.23902 \\ 1.9575 \\ 1.2838 \\ 0.58739 \end{bmatrix}$$

$$A4 = \frac{A3}{A2} = \begin{bmatrix} 0.23902 \\ 1.9575 \\ 1.2838 \\ 0.58739 \end{bmatrix} / \begin{bmatrix} 0.059246 \\ 0.4828 \\ 0.31385 \\ 0.1441 \end{bmatrix} = \begin{bmatrix} 4.0344 \\ 4.0545 \\ 4.0905 \\ 4.0762 \end{bmatrix}$$

The consistency index, denoted as CI, is expressed through the following equation:

$$\text{Consistency Index, CI} = \frac{\lambda_{\max} - n}{n-1} \tag{6.1}$$

Where $\lambda_{\max}$ represents average of values in A4 matrix and ‘n’ represents number of criteria.

For the given case, $\lambda_{\max}$ = 4.0639 and n =4.

Hence, Consistency Index, CI $= \frac{4.0639-4}{4-1}$ = 0.0213

Following the computation of CI, the subsequent step is to calculate the Consistency Ratio, denoted as CR, as per the equation.

$$CR = \frac{\text{Consistency Index}}{\text{Random Index}} \tag{6.2}$$

The Random Index, RI, is determined as the average of CI values from various sizes of comparison matrices. Table 6.3 provides the RI values corresponding to different n values.

Table 6.3 Random Index (Saaty, 1987)

Attributes	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

Hence, CR = $\frac{0.0213}{0.89}$ = 0.02393.

To ensure the adequacy of pairwise comparisons, the consistency ratio should be below 0.1. In the present case, the value is indeed less than 0.1, confirming that the weightages derived in the A2 matrix are acceptable.

4 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is a multi-criteria decision-making method developed in the 1980s. This approach identifies the alternative that minimizes the Euclidean distance from the ideal solution while maximizing the distance from the negative ideal solution. The theoretical framework and step-by-step procedure are as follows:

Step 1: Assignment of Scores: Scores are assigned for alternatives based on various criteria considered. Alternatives denoted as a = 1, 2, 3, … n. Criteria are labelled as i = 1, 2, 3, … m. Form the decision matrix, D = (x_{ai}).

Step 2: Normalization of Performance Scores: The selected criteria may be measured in different units and the assigned scores might vary in scale or range. Therefore, it is essential to normalize the matrix for subsequent calculations. This is achieved by dividing the scores by the square root of the sum of each squared element in a column (criterion), as expressed in the following equation:

$$r_{ai} = \frac{x_{ai}}{\sqrt{\sum_{a=1}^{n} x_{ai}^2}} \tag{6.3}$$

Where $a = 1,2,\ldots,n$ alternatives and $i = 1,2,\ldots,m$ criteria.

Step 3: Calculation of the Weighted Normalized Decision Matrix: The normalized scores must be weighted by the calculated weights for each criterion. These weights can be determined using various techniques, such as AHP. If the criteria weights are denoted as W_{xi} and the normalized scores as r_{ai}, then the resulting weighted scores, v_{ai}, are determined by the following equation.

$$V_{ai} = W_{xi} * r_{ai} \tag{6.4}$$

Step 4: Calculation of Distances from Ideal and Anti-Ideal Points: The weighted normalized scores obtained in the previous step are employed to assess each alternative concerning the virtual ideal and anti-ideal alternatives.

- Creation of the virtual ideal alternative (vn+): This is achieved by considering the best scores for each criterion.
    - Max(v_{ai}) if the criterion i is to be maximized.
    - Min(v_{ai}) if the criterion i is to be minimized.
- Formation of the virtual anti-ideal alternative (vn-): This is established using the worst scores for each criterion.
    - Max(v_{ai}) if the criterion i is to be minimized.
    - Min(v_{ai}) if the criterion i is to be maximized.

The Euclidean distance from the ideal point (Sn+) and the anti-ideal points (Sn-) for each alternative must be calculated. The formula for the distance from the ideal point (Sn+) is presented in the following equation.

$$S_n^+ = \sqrt{\sum \left(v_i^b - v_{ai}\right)^2} \tag{6.5}$$

Where $a = 1,2, \dots, m$ and $i = 1,2 \dots n$

Step 5: Closeness Ratio: Calculation of Closeness Ratio for Each Alternative The closeness ratio can be computed using the equation 6.6. The closeness ratio falls within the range of 0 to 1, with the alternative possessing the highest value being considered the best among the options.

$$P_i = \frac{S_n^-}{S_n^+ + S_n^-} \tag{6.6}$$

6.2.2 Optimizing Energy Efficiency: Harmonizing Building Envelopes, Orientation, and Window-to-Wall Ratio (WWR)

The second aspect of the third sub-objective is organized into several stages to address the integration of BIM, building orientation, envelope variations and WWR to reduce energy demand in multifamily dwellings and a hostel building located in Afghanistan and India respectively. These stages are meticulously designed to collectively address the study objectives:

1. **Literature Review:** The study initiative commences with an in-depth literature review spanning diverse domains. In the BIM domain, the exploration encompasses the body of knowledge, historical development, frameworks and practical use cases. In the building energy domain, the review scrutinizes key factors that contribute to energy-efficient buildings. Particular emphasis is placed on understanding the pivotal role of building orientation in shaping energy consumption.
2. **Energy Analysis and Predictions:** This stage dives into the core of the study, focusing on energy analysis and predictions through the lens of building integration with BIM. The primary aim is to gain insights into how BIM tools can be harnessed to enhance energy efficiency and reduce overall energy demand.
3. **Case Study Selection and Building Reconstruction:** A real-world multifamily residential building and a hostel building are carefully chosen as representative case studies. Detailed information about these structures is meticulously collected and subsequently reconstructed through the use of 2D AutoCAD and 3D BIM models created with Autodesk Revit. Furthermore, various energy calculation tools and software are employed to assess the selected case studies. The selection of well-documented buildings with accessible data simplifies the development of simulation alternatives.
4. **Comparative Energy Demand Analysis:** In this stage, the calculated energy demand derived from simulations is rigorously compared with actual energy consumption data, including electricity and gas bills. This comparative analysis is instrumental in evaluating the performance of different building orientations, envelope variations and window-to-wall ratios in the context of energy simulation software.

The overarching study goal is to harness the capabilities of Revit and Green Building Studio BIM tools to significantly reduce the annual energy demand of multifamily dwellings in

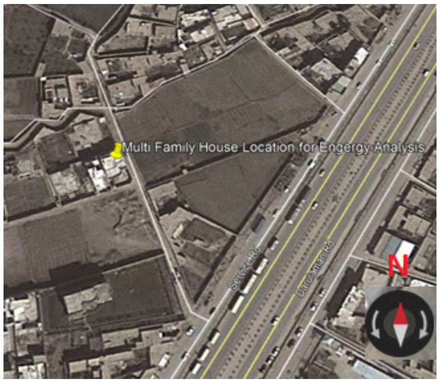
Afghanistan and a hostel building at NITW. This reduction is achieved by optimizing construction materials, glazing areas, building orientation and WWRs to leverage natural energy sources, ultimately reducing the reliance on artificial heating and cooling systems.

6.2.2.1 Orientation

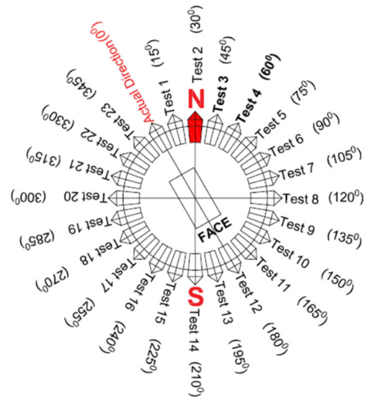
A multi-family residential house, which is located at Darulaman road, 7 district, Kabul, Afghanistan, 34°28'42.3"N 69°07'41.2"E latitude and longitude is used as case study (see Figure 6.6 (a)). It is a 4–storied (Basement, G+2) residential building, basement floor consists of family gathering area along with 2 rooms for multipurpose. Ground and first floor have typical floor plans consisting of a drawing room, dining room, kitchen and common bathroom with w/c (water closet), stairway to access the basement and first floor, 2 bedrooms with attached bathrooms. The second floor (pent house) consists of a half-open terrace while the rest is covered with stairway, kitchen, bathroom with water closet and bedroom. The selected house belongs to the relatives of one of the co-authors of the paper, which made it easy to collet related information to rebuild the model in Revit and get all the relevant documents (energy bills) for validation.

A series of analyses are made with different orientations starting from actual alignment of the building which is 30^{o} anti-clock wise from the north direction and considered as 0^{o}. Analysis refers to the use of a BIM tool for modelling along with energy simulation software (Insight 360, GB studio) to understand the effect of orientation on energy estimates. The building entrance or facing is towards south direction (taken as Test 12 (180^{o}) orientation), and the north direction, which is taken as 30^{o} reference gives data for analysis Test 2 analysis. Test 3 analysis is for 45^{o} angle, an increment of 15^{o} gives a total of 24 sets of analysis (23 + 1 actual direction of the building). The complete orientation tests are shown in Figure 6.6 (b) along with the sun path motion for actual orientation in Figure 6.6 (c).

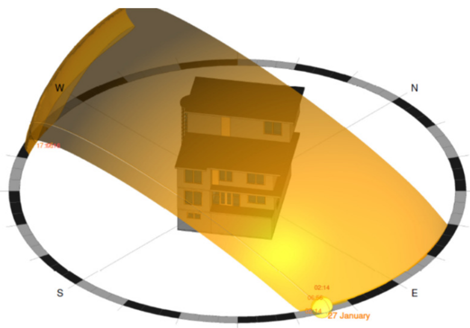
The Model is created in Revit by taking actual measurements of the building and rooms. The building drawings and site plans are not preserved by the owners and this compelled the use of physical measurements. The model is generated and exported to Green building studio using Green Building XML (gbXML) service. The recent BIM tool (Revit) has both the green building studio-Insight 360 and design builder as add-on. The interoperability issues in generating the gbXML by importing and exporting can be minimised. Figure 6.7 and Figure 6.8 shows floor plans and elevations and Figure 6.9 shows the 3D Revit rendered model.



(a) Location – satellite image

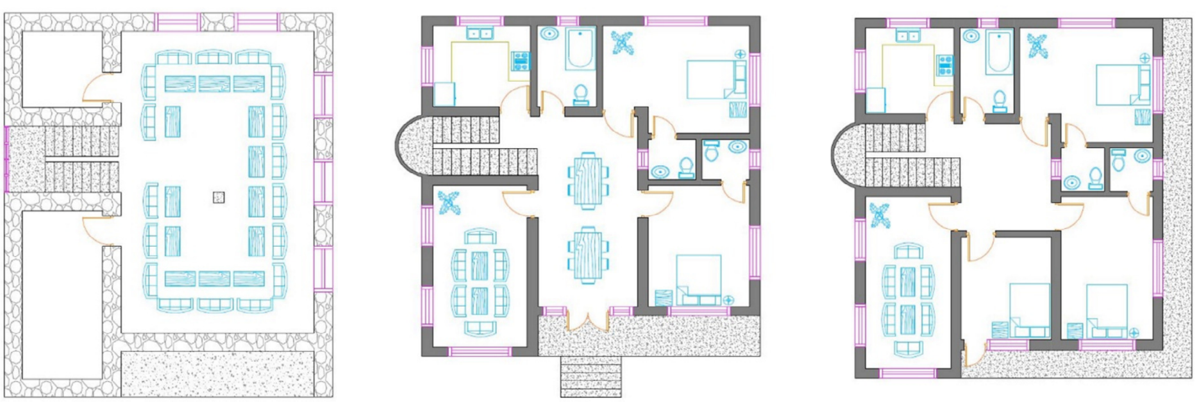


(b) Test orientations



(c) The actual base case of the building along with sun path

Figure 6.6 Location of the Building and test orientations (Co-ordinates from Google maps 34°28'42.3"N 69°07'41.2"E)

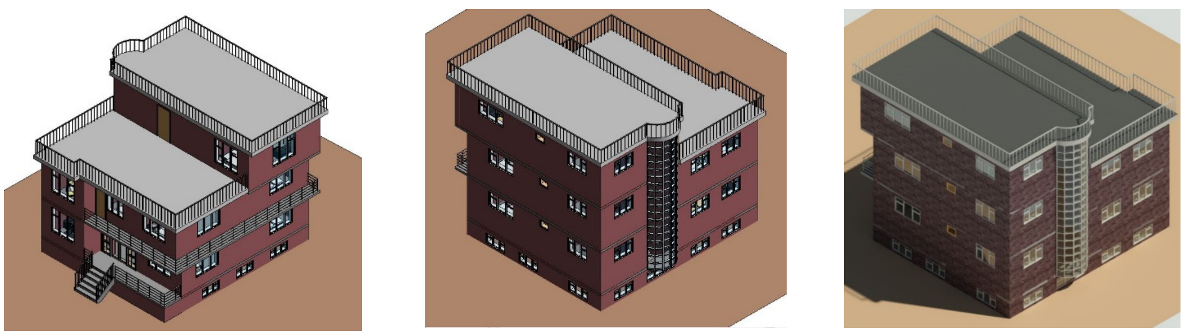


(a) (b) (c)

Figure 6.7 Plan and Elevation of the case study building (a) Basement plan, (b) Ground Floor plan (c) First floor plan

(d) (e) (f)

Figure 6.8 Plan and Elevation of the case study building (d) Terrace floor plan (e), (f) Front (south facing) & back elevation



South-east corner view North-west corner view Rendered image

Figure 6.9 3D model of the selected building and rendered image

Once the building model is generated in Revit, it can be taken to simulation run to GBS using exported gbXML file or it can use Insight 360 plugin. Figure 6.10 shows the simulated energy results for the actual direction of the building. In GBS, it is necessary to give the relevant project information like the type of facility, location of the building and utility details. The present electricity rates are taken from the Afghanistan electricity board and average price values are adopted for Kabul city (https://main.dabs.af/KabulElectricitytariff). Afn 7.25/kWh is used for electricity cost while fuel cost is Afn 150.7/thm (Therm). The GBS takes the nearby weather station and relevant information from various leading data engines like DOE 2.2, Energy Plus, etc., for simulation purposes. Once the base run simulation is performed, the design alternative tab is accessible, where various building parameters such as orientation, material, shading devices, etc., can be changed for more simulation runs. All the test scenarios are added by changing only the direction of the building and once all the alternative runs are added as shown in Figure 6.11, they are then run for simulation performance evaluations. The output result of the base run is presented in Figure 6.12.

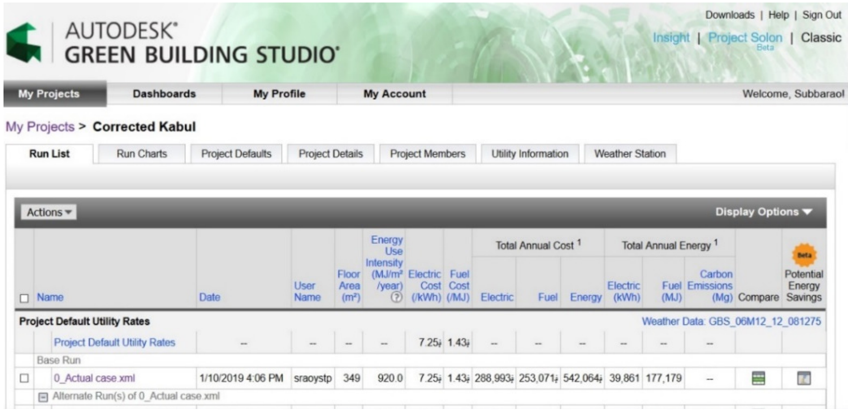


Figure 6.10 Base run simulation energy results in GBS

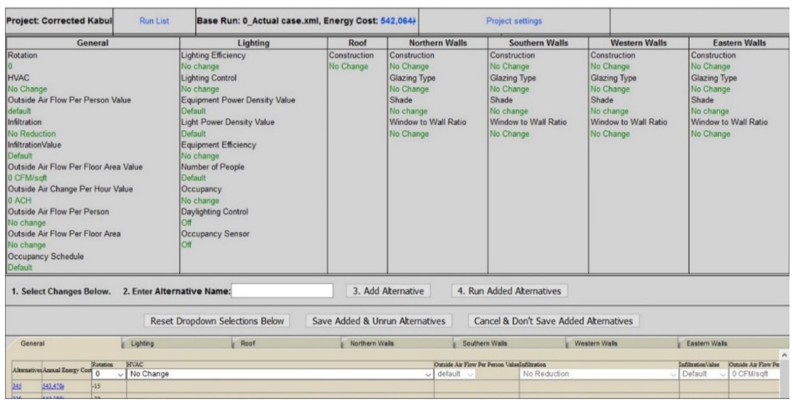


Figure 6.11 Alteration of various Project parameters

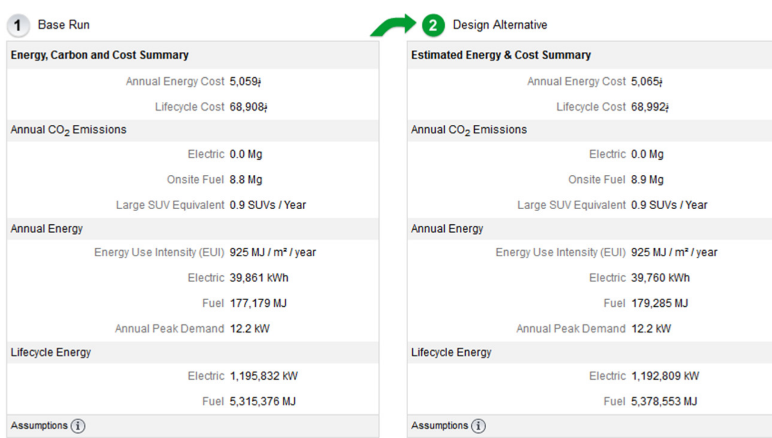


Figure 6.12 Typical output result of energy simulation (actual and alternative design)

6.2.2.2 Envelop Variations

To evaluate energy demand variations among various envelope materials, locally available materials typically used in residential buildings in Afghanistan are examined. This encompasses 6 wall types, 4 floor types and 4 roof types. The selection of construction materials for the building's external envelope is based on prevalent practices in the Afghan residential sector, as depicted in Table 6.4. Ninety six combinations are formed for the energy analysis are shown in Table 6.5

Table 6.4 Details of the selected materials for envelope variations

Type	Name	Material			Thickness (mm)		
		ES	C	IS	ES	C	IS
			Wall Types				
W1	Fire brick masonry	CP	Fire brick	CP	20	350	20
W2	Fire brick masonry	CP	Fire brick	CP	20	220	20
W3	Adobe brick masonry	GP	Adobe brick	MP	20	350	20
W4	CMU block masonry	CP	CMU block	CP	20	200	20
W5	Fire brick masonry	LP	Fire brick	LP	20	220	20
W6	Fire brick masonry	CP	Fire brick	GP	20	220	20
			Floor Types				
F1	RCC with carpet	CMC	RCC	CP	60	120	10
F2	RCC with Tile	CMT	RCC	CP	50	120	10
F3	Fire brick	CMC	Fire brick	GP	60	110	20
F4	Mud Floor	MPC	Mud+Timber	--	40	130	--
			Roof Types				
R1	RCC roof	WCM	RCC	CP	74	150	10
R2	RCC roof	CMT	RCC	CP	50	150	10
R3	Brick roof	WCM	Fire Brick	GP	74	110	20
R4	Mud roof	MPP	Mud+Timber	--	31	130	--

Acronyms used in the **Table 6.4**

ES	Exterior side	**CMU**	Concrete masonry unit	**GP**	Gypsum Plaster
C	Core	**LP**	Lime plaster	**MP**	Mud plaster
IS	Interior side	**CMC**	Cement mortar + carpet	**WCM**	Water proof + Cement mortar
CP	Cement Plaster	**MPC**	Mud plaster + Carpet	**MPP**	Mud plaster + plastic sheet

Table 6.5 Details of the selected combinations of material

Comb. No.	Wall Type	Roof Type	Floor Type
C1	W1	R1	F1
C2	W1	R1	F2
C3	W1	R1	F3
C4	W1	R1	F4
C5	W1	R2	F1
C6	W1	R2	F2
C7	W1	R2	F3
C8	W1	R2	F4
C9	W1	R3	F1
C10	W1	R3	F2
C11	W1	R3	F3
--	--	--	--
--	--	--	--
--	--	--	--
C96	W6	R4	F4

6.2.2.3 Window-to-Wall Ratio (WWR)

Beside other feature and benefits, Revit allows the users to perform accurate material takeoffs and provides different schedules for different components of a building. This feature leads to saving time and energy for manual quantity takeoffs and cost estimation of buildings. in the current study this feature of rivet is used to find out the total area of exterior façade of each level separately and based on that and percentage of WWR, windows glazing area of each level for 10%, 20%, 30%, 40%, 50% and 60% WWR is calculated. Then 6 new models with new windows are created accordingly. Also, the same method is used to figure out the WWR of the actual existing building to find out the percentage of its glazing area. Finally, 6 new models are simulated and energy demand results including the actual model are compared to find out the glazing area variation impact from an energy consumption point of view. The following tables show the total area of exterior walls extracted from rivet and their relevant glazing areas which are calculated in excel spreadsheets accordingly.

6.3 RESULTS AND DISCUSSION

6.3.1 Multi Criteria Decision Method (MCDM) and Building Information Modelling (BIM)

This study entails creating various design alternatives and selecting the best design options. Two case study buildings are chosen to obtain this. Case study project 1 (8.9172773o Latitude and 76.6369787o Longitude) is currently in the design phase, with only the ground floor finalised and various design alternatives considered. Case study project 2 (8.9159834o Latitude and 76.6378281o Longitude) is a G+1 building with the requirement of an additional bedroom on the first floor, for which different design alternatives are considered.

Case Study Project 1&2 base details are givne in Table 6.6. Figure 6.13 depicts the location (satellite image) for (a) Case Study 1 and (b) Case Study 2. Following an examination of the site layout, topography and client requirements, three different design alternatives are created within a single ".rvt" file using Revit's Design options feature. In that order, the options are dubbed Model 1, Model 2 and Model 3. The setbacks from the plot line are determined in accordance with the Kerala Municipal Building Rules (KMBR) (Government of Kerala, 2019).

Table 6.6 Base details regarding case studies 1 & 2

	Case study 1	Case study 2
Type of building	Residential house (Single storey)	Residential house (G+1)
Location	Karicode, Kerala	Karicode, Kerala
Coordinates	8.9172773 ^{o} Latitude & 76.6369787 ^{o} Longitude	8.9159834^{o}Latitude & 76.6378281^{o} Longitude
Client	Asif Alam	Nizam
Budgeted cost	2.4 Million Rupees	
Area of plot	283.22 m^2	323.74851 m^2 (108.89 m^2 existed)

(a) **(b)**

Figure 6.13 Location – satellite image (a) Case study 1 (b) Case study 2

As a result, the following constraints are shared by all three proposed plans: 3 m front setback, 1 m side offset, and 1.5 m rear end. 147 m^2 total floor area (140 m^2). Three proposed models are developed using the aforementioned constraints. Figure 6.14 depicts the floor plans of Model 1, Model 2, and Model 3 of the case study 1. Whereas case study 2 is in the construction stage and the three design options considered are as Option 1, Option 2 and Option 3 are shown in Figure 6.15.

Figure 6.14 Design options of Case study 1 - Ground Floor plan of Model 1, Model 2 and Model 3.

Figure 6.15 Design options of Case study 2 - First floor plan of Option 1, Option 2 and Option 3

With the assistance of an expert, four of the twelve building planning principles are chosen to best fit the existing case study as aspect, prospect, grouping, and flexibility. The experts have ten years of combined experience in architecture and planning. The weights are calculated and the consistency ratio is calculated. If the consistency ratio is less than 0.1, the weight obtained may be acceptable. After a few trials, the weights are fixed because the consistency ratio obtained is 0.0381, which is within the acceptable range. The weights obtained for the selected criteria are 0.55, 0.23, 0.13 and 0.09 for Aspect, Prospect, Grouping and Flexibility respectively.

As part of the Dynamo script, a questionnaire is created for each of the three developed alternatives to assign a score based on selected criteria. Figure 6.16 depicts the Dynamo script for Case Study 1.

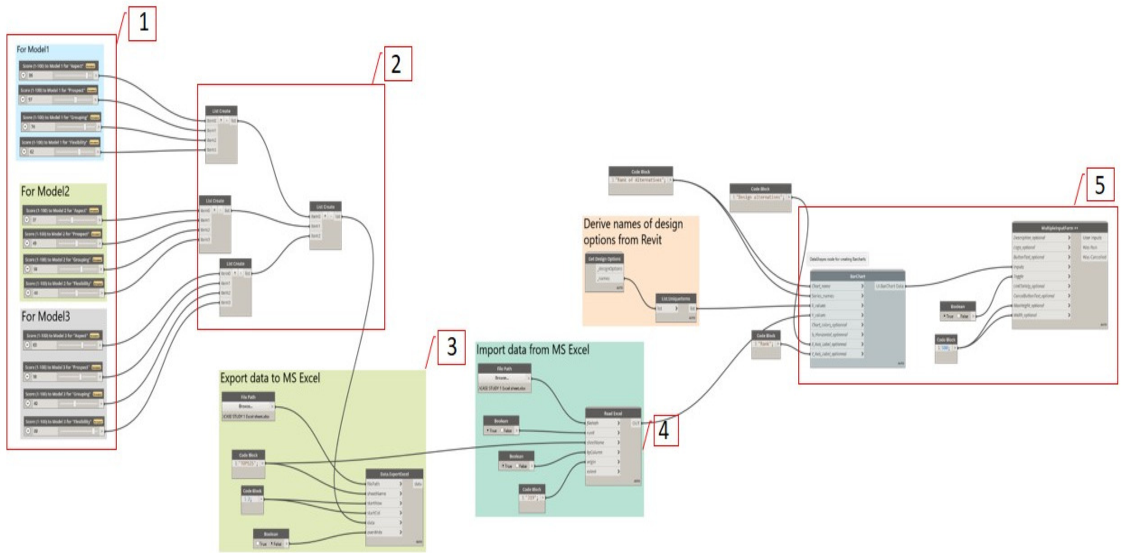


Figure 6.16 Dynamo script for case study 1

This Dynamo script is designed to efficiently collect expert scores through the Dynamo player. The process involves a set of nodes:

1. **Data Collection**: A set of nodes gathers scores from experts using Dynamo player.
2. **Matrix Conversion**: These nodes convert individual numerical scores into a matrix for computation in MS Excel.
3. **Data Export**: Another set of nodes exports the data into specified cells in an MS Excel file. This data is crucial for the subsequent TOPSIS analysis, ultimately resulting in a detailed ranking in a specified order.
4. **Ranking Transfer**: Following the completion of the ranking process, this node transfers the ranking data back to Revit.
5. **Result Visualization**: Using nodes from the 'Data Shapes' package, the script generates a Bar chart displaying alternative names on the x-axis and their respective rankings on the y-axis.

Throughout the script development, number sliders containing scores are labelled as 'inputs' to display them effectively in Dynamo player. Leveraging the advantages of BIM, precise visualizations facilitate the comparison of alternatives. For instance, the view from the entrance of all three options (see Figure 6.17, Figure 6.18 and Figure 6.19) can be precisely produced using the ‘camera view’ option. This helps in comparing alternatives when privacy is considered.

Figure 6.17 Model 1 View from entrance

Figure 6.18 Model 2 View from entrance

Figure 6.19 Model 3 View from entrance

Additionally, it enables visualization through doors and windows, offering a perspective (prospect) on the exterior. Experts are provided with comprehensive information using these visualization options to aid in scoring. The questionnaire is then executed in 'Dynamo Player' to obtain scores, as illustrated in Figure 6.20 and Figure 6.21.

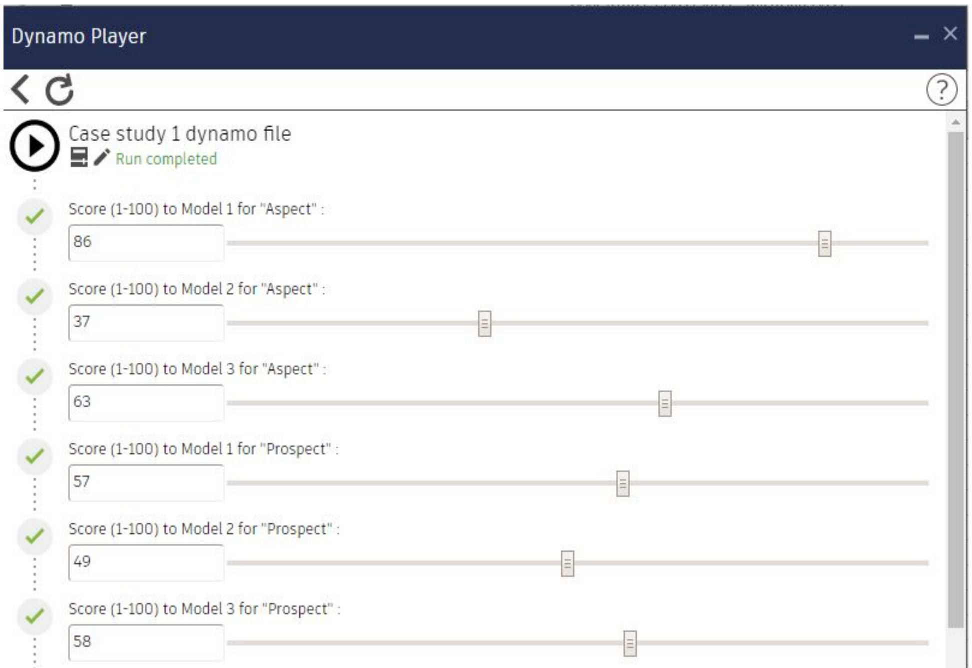


Figure 6.20 Allotment of scores to alternatives (cont'd in fig. 6.21)

Figure 6.21 Allotment of scores to alternatives

6.3.1.1 Choosing the Optimal Alternative with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

After entering the scores and running the program in Dynamo Player, the data exports to predefined cells in MS Excel and the analysis carried using TOPSIS. The MS Excel sheet, as shown in Figure 6.22, needs to have the required formulas assigned to carry out the computation. It is concluded from this figure that the script runs successfully.

	A	B	C	D	E	F	G	H	I	J
1			Aspect	Prospect	Grouping	Flexibility				
2		Wxn	0.546	0.233	0.131	0.089		**TOPSIS for Case study 1**		
3		*Model1*	86	57	74	62				
4		*Model2*	37	49	58	44				
5		*Model3*	63	58	40	89				
6										
7										
8			Calculation of Normalized matrix ɼai							
9			Aspect	Prospect	Grouping	Flexibility				
10		Wxn	0.546	0.233	0.131	0.089				
11		*Model1*	0.762107	0.600365986	0.72423827	0.529682417				
12		*Model2*	0.327883	0.516104093	0.56764621	0.375903651				
13		*Model3*	0.558288	0.610898722	0.39148015	0.760350566				
14										
15										
16			Calculate weighted normalized matrix Vai							
17			Aspect	Prospect	Grouping	Flexibility	Si+	Si-	Pi	Rank
18		Wxn	0.546	0.233	0.131	0.089				
19		*Model1*	0.41611	0.139885275	0.09487521	0.047141735	0.020676	0.242245	0.921362	1
20		*Model2*	0.179024	0.120252254	0.07436165	0.033455425	0.241432	0.023078	0.087247	3
21		*Model3*	0.304825	0.142339402	0.0512839	0.0676712	0.119518	0.132229	0.525244	2
22										
23			Calculate ideal best and ideal worst value							
24		*V+*	0.41611	0.142339402	0.09487521	0.0676712				
25		*V-*	0.179024	0.120252254	0.0512839	0.033455425				

Figure 6.22 Computation of rank using TOPSIS of Case study 1

Similarly, three different layouts are proposed for case study project 2 as Option 1, Option 2 and Option 3 with the best one chosen. The floor plans for Options 1, 2 and 3 are shown in Figure 6 (b). By relocating the bedroom to the northwest, Option 1 increased its size by 14.07 m^2. Option 2 includes an additional room and toilet on the ground floor, next to bedroom #1. This makes structural and other detailing easier. Furthermore, the proposed common hall can be used for a variety of purposes, making it a more versatile option. Option 3 adds a new toilet room to the north-east side. This adds 13.193 m^2 to the available floor space.

The weights assigned to the four building planning principles of aspect, prospect, flexibility and elegance are 0.55, 0.23, 0.14 and 0.08, respectively. The questionnaire is built as part of the Dynamo script for the evaluation of three alternatives in Dynamo Player, as shown in Figure 6.23. Dynamo Player is used to assign scores to all of the options. The Dynamo player's collected scores are processed in an Excel spreadsheet using the TOPSIS method and the final ranking of the alternative options is extracted.

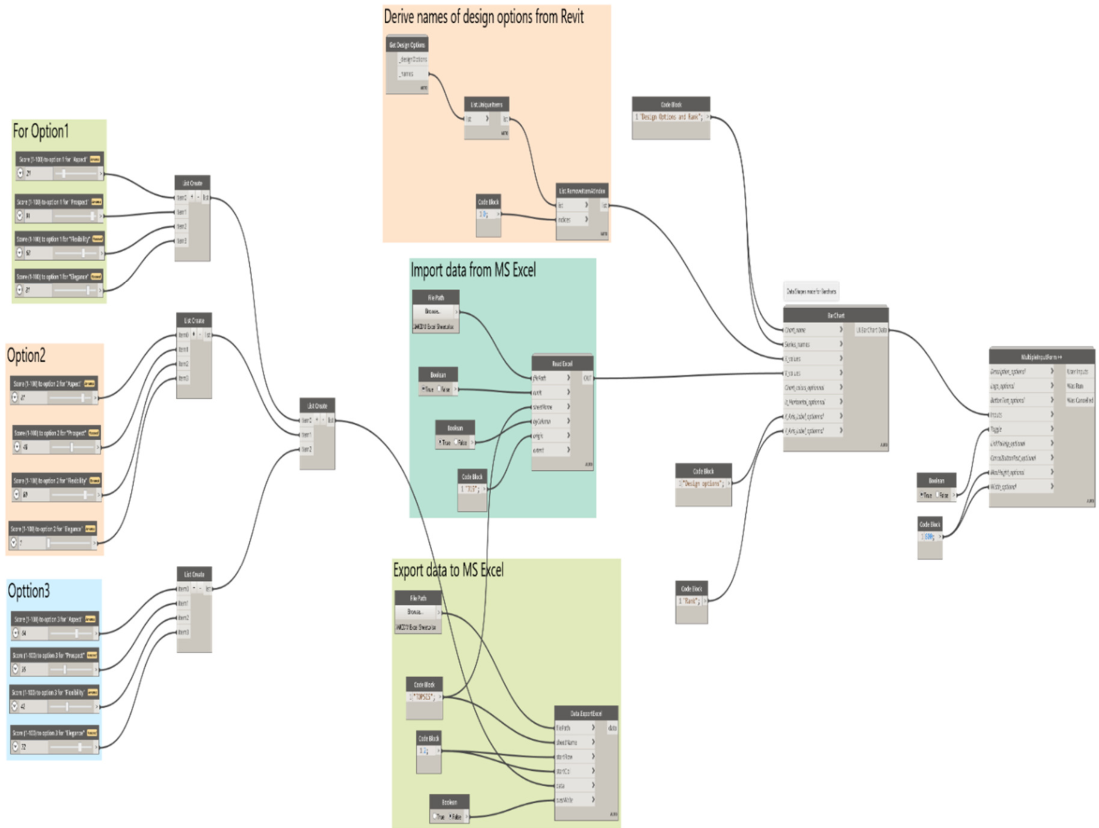


Figure 6.23 Dynamo script for case study 2

Once the script is made, the questionnaire is then executed in Dynamo Player to obtain scores, as illustrated in Figure 6.24 and Figure 6.25. Dynamo player is used to collect the scores and to export that data to a predefined MS Excel sheet. As mentioned earlier, the data is exported to MS Excel which is preprogramed to carry out the analysis using the TOPSIS method. The image of the MS Excel sheet in which TOPSIS is carried out is shown in Figure 6.26.

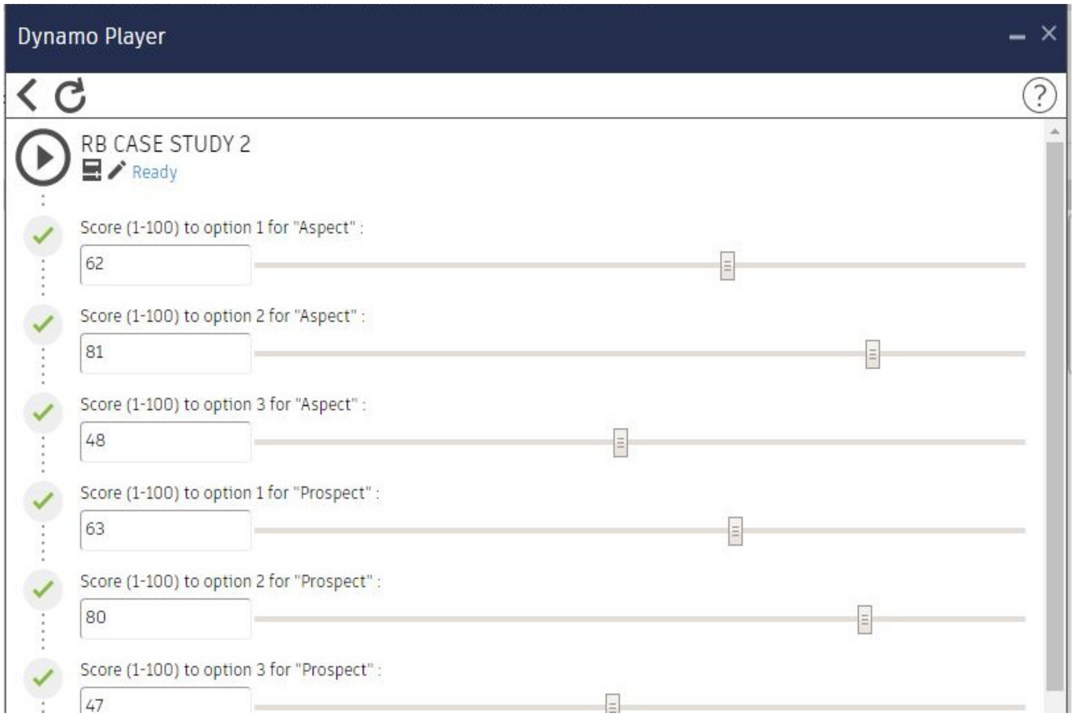


Figure 6.24 Assigning of scores using Dynamo player (cont'd in fig. 6.25)

Figure 6.25 Assigning of scores using Dynamo player

TOPSIS PERFORMED FOR CASE SUDY 2

	Aspect	Prospect	Flexibility	Elegance
Weightage	0.545	0.233	0.138	0.084
Option1	62	63	60	60
Option2	81	80	82	87
Option3	48	47	36	39

Calculation of Normalized matrix r'ai

	Aspect	Prospect	Flexibility	Elegance
Weightage	0.545	0.233	0.138	0.084
Option1	0.5499662	0.56173923	0.55660639	0.532623641
Option2	0.71850423	0.713319657	0.7606954	0.77230428
Option3	0.425780284	0.419075298	0.33396383	0.346205367

Calculation of weighted normalized matrix Vai

	Aspect	Prospect	Flexibility	Elegance	Si+	Si-	Pi	Rank
Weightage	0.545	0.233	0.138	0.084				
Option1	0.299731579	0.13088524	0.07681168	0.044740386	0.104321	0.082915	0.442836	2
Option2	0.391584805	0.16620348	0.10497596	0.06487356	0	0.186817	1	1
Option3	0.232050255	0.097644544	0.04608701	0.029081251	0.186817	0	0	3

Calculate ideal best and ideal worst value

V+	0.391584805	0.16620348	0.10497596	0.06487356
V-	0.232050255	0.097644544	0.04608701	0.029081251

Figure 6.26 Ranking of alternatives using TOPSIS case study 2

Case Study 1

The Dynamo script includes a segment designed to import necessary data from MS Excel back to Revit, presented in the form of a Bar chart utilizing the Data Shapes node. In this study, Model 1 emerged as the best alternative among the three options. The output is showcased as a pop-up window in Revit upon successful script execution, as illustrated in Figure 6.27. It can be saved in Revit, along with the date and time of recording, as depicted in Figure 6.28. The outcome is shared with the client and the proposed alternative is chosen for subsequent detailed development.

TOPSIS offers a notable advantage by providing information about the potential for improvement in each alternative. This is particularly valuable in the context of a floor plan layout, where even minor adjustments can enhance both aesthetics and functional requirements, holding significant importance. By closely analysing Figure 6.22, valuable insights can be gleaned for each alternative. It becomes possible to identify the best and worst-performing alternatives concerning each criterion, enabling further refinement through revisions if necessary as shown in Table 6.7.

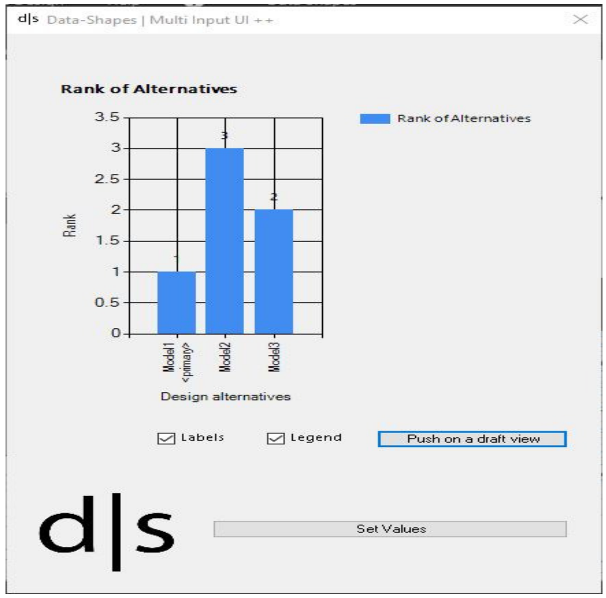


Figure 6.27 Ranking of alternatives for case study 1

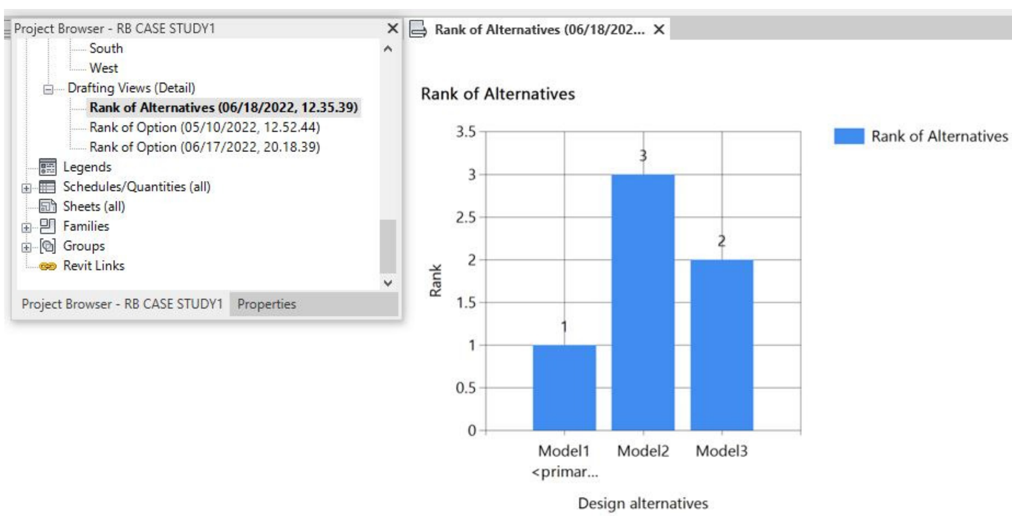


Figure 6.28 Draft view of ranking

Table 6.7 Best and worst alternative w.r.t criteria

Alternative/Criteria	Aspect	Prospect	Grouping	Flexibility
Best alternative	Model 1 Option 2	Model 3 Option 2	Model 1 Option 2	Model 3 Option 2
Worst alternative	Model 2 Option 3	Model 2 Option 3	Model 3 Option 3	Model 2 Option 3

Case Study 2

In the second case study, option 2 is ranked first, followed by option 1 and option 3 is ranked second and third, respectively. The script is successfully run and the output is shown in Figure **6.29**. The client is informed of the outcome and agreed to proceed with it. The two case studies indicate that the proposed methodology is successful in selecting the optimal floor plan when multiple criteria are required to be considered.

The principles of building planning take into account all factors when determining a floor plan and thus provide proper guidance in arriving at the best solution. In addition, the "Design Option" in Revit aided in the conduct of this study and served as an important component of the methodology framework. Integration of MCDM and BIM aids in working with large amounts of data when computation must be automated and decisions must be made quickly but accurately and reasonably. The study work demonstrated that it is possible to combine MCDM and BIM for optimal building planning. Another important conclusion from this study is that the computational design tool can be extremely useful when data transfer between Revit and other platforms is required. According to the study of Abrishami et al. (Abrishami et al., 2021), the use of computational design during the early conceptual stage is extremely beneficial.

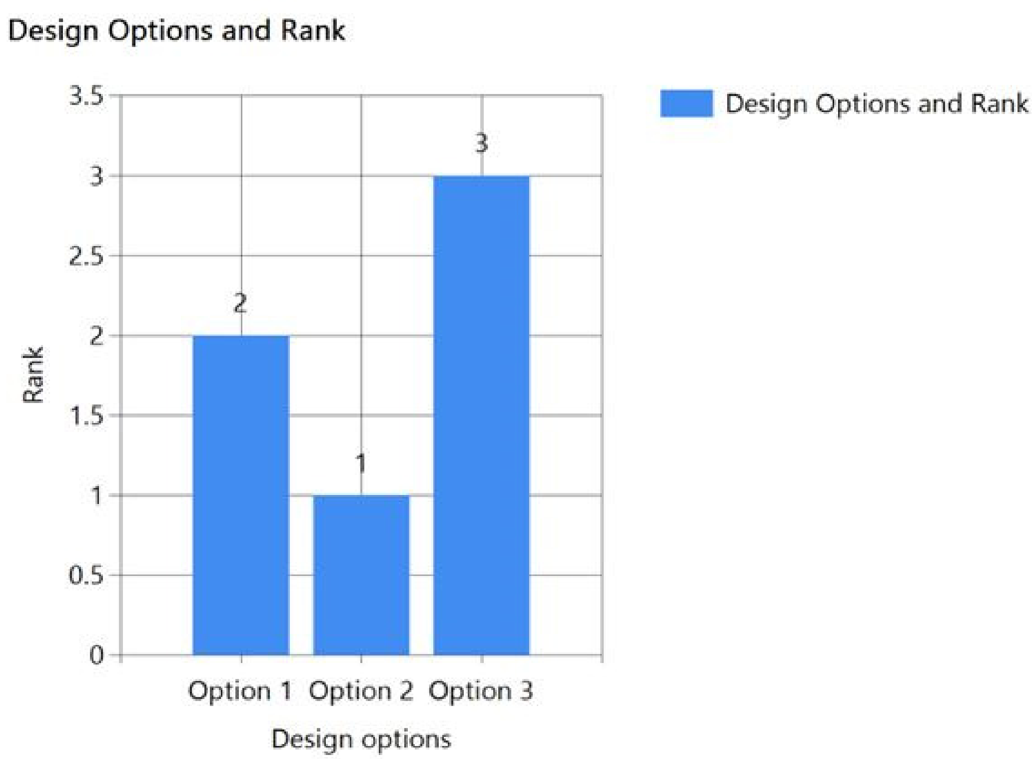


Figure 6.29 Ranking of alternatives for Case study 2

Students, researchers and practitioners are polled via questionnaire. A question is asked about integrating BIM and computational design to overcome challenges during the early design stage and in designing complicated shapes. Notably, 32% of respondents express a level of uncertainty regarding the integration, indicating a cautious or reserved stance. In contrast, a modest 2.6% explicitly reject the idea, presenting a minority perspective. However, the survey's most significant revelation comes from the sizable majority of 65.4% who resoundingly endorse the significance of incorporating computational methods. This majority consensus strongly affirms the belief that computational approaches are instrumental in addressing the complexities inherent in modelling future buildings. The emphasis here is not merely on complexity but on the demand for precision and accuracy, implying a recognition of the potential of computational tools to meet high standards in the architectural and design realm.

Discussion

Based on the analysis of the two case studies, it is evident that the proposed methodology successfully identified the optimal floor plan when dealing with multiple criteria. The principles of building planning, which encompass a comprehensive consideration of various factors, proved effective in guiding the selection of the optimal solution. Additionally, the utilization of the Design Option feature in Revit played a crucial role in the methodology, contributing significantly to the overall framework. Furthermore, it is recommended that all BIM software incorporate features enabling the execution of such computations and interpretations for MCDM. This would open up more study opportunities within the software. Taking Dynamo, a CD platform, into consideration, designers are actively introducing new packages that support data visualization, including table formats, even before exporting to MS Excel. An example is the Data Shapes package, which offers nodes for tables and various chart forms such as spline or line charts. Figure 6.30 illustrates Data Shapes nodes for data visualization and export, while **Error! Reference source not found.** and **Error! Reference source not found.** show examples of a Spline chart and a Line chart, respectively, created using Data Shapes nodes. This enhancement in functionality enhances the capabilities of Dynamo and contributes to more robust data analysis and interpretation in the realm of building design and planning.

The amalgamation of MCDM and BIM proves highly beneficial when handling extensive data requiring automated computation and swift, yet accurate and rational decision-making. The present study demonstrates the feasibility of incorporating MCDM and BIM for optimal building planning. An additional noteworthy insight from this study is the advantageous role computational design tools play in facilitating data transfer between Revit and other platforms. However, insights from a study by (Abrishami et al., 2021) emphasize the application of computational design, particularly Generative Design (GD), during the early conceptual stage.

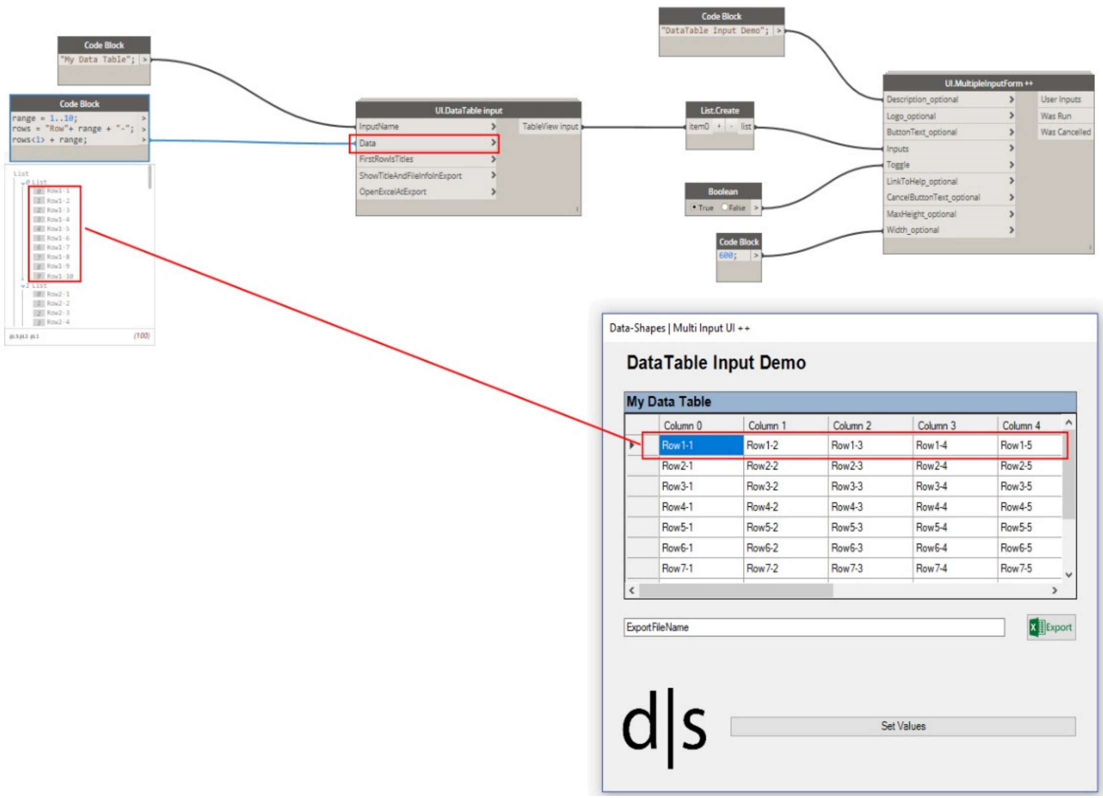


Figure 6.30 Data Shapes nodes for data visualization and export

Surveying students, researchers and practitioners revealed that 65.4% believed in integrating BIM and Generative Design to address challenges in the early design phase, attesting to the substantial benefits of computational methods in modelling future buildings with intricate designs demanding accuracy and precision.

Generative Design (GD), an advancement in CD, is gaining prominence, albeit at a gradual pace within the AEC industry. A critical examination of contemporary approaches to GD development within BIM was undertaken by Wei Ma and colleagues in 2021 (Ma; et al., 2021). The review involved an analysis of methodological relationships, skill prerequisites, and the overall improvement of GD-BIM development. The study suggests that designers should possess proficiency in both VPL and Textual Programming Languages (TPL) for effective GD problem-solving. The proposed skill learning path recommends starting with VPL (e.g., Dynamo for Revit, Grasshopper for Rhino) for those without programming skills, progressing to TPL to create custom nodes for specific tasks. This path bifurcates into two directions: enhancing GD-BIM development ability and programming skills in VPL or leveraging TPL and Rosetta (a generative design tool) to improve efficiency. It is emphasized that deliberate acquisition and refinement of VPL and TPL abilities can enhance GD-BIM development gradually, impacting capacity and effectiveness across various phases and degrees of development.

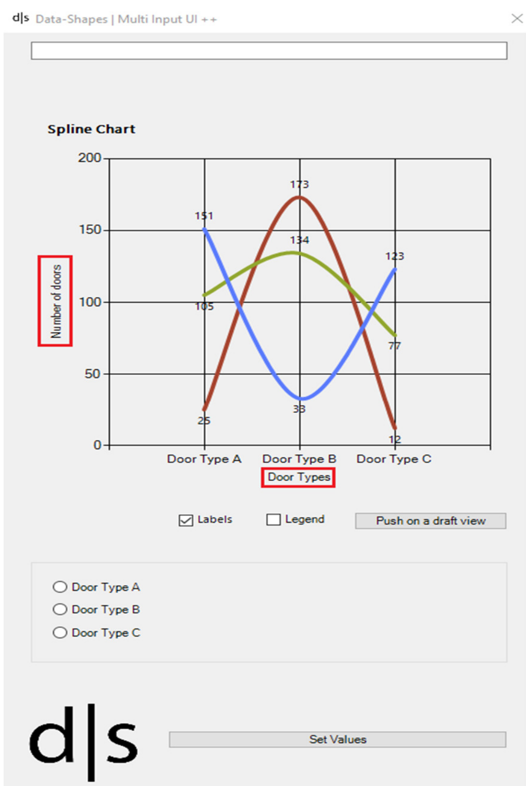


Figure 6.31 Spline chart using Data Shapes node

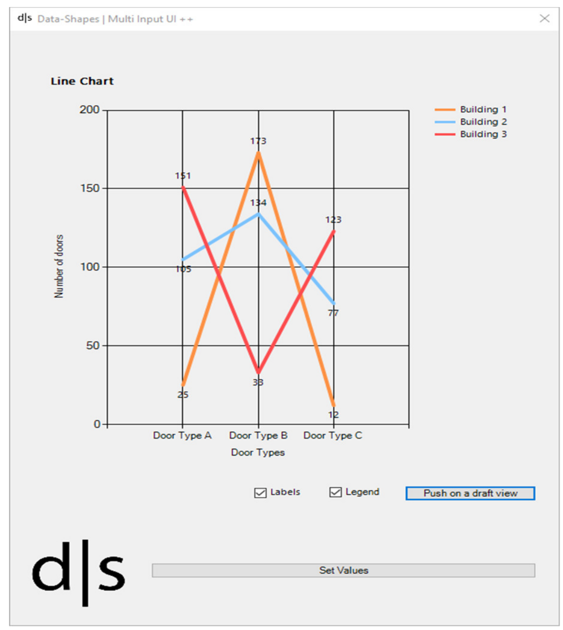
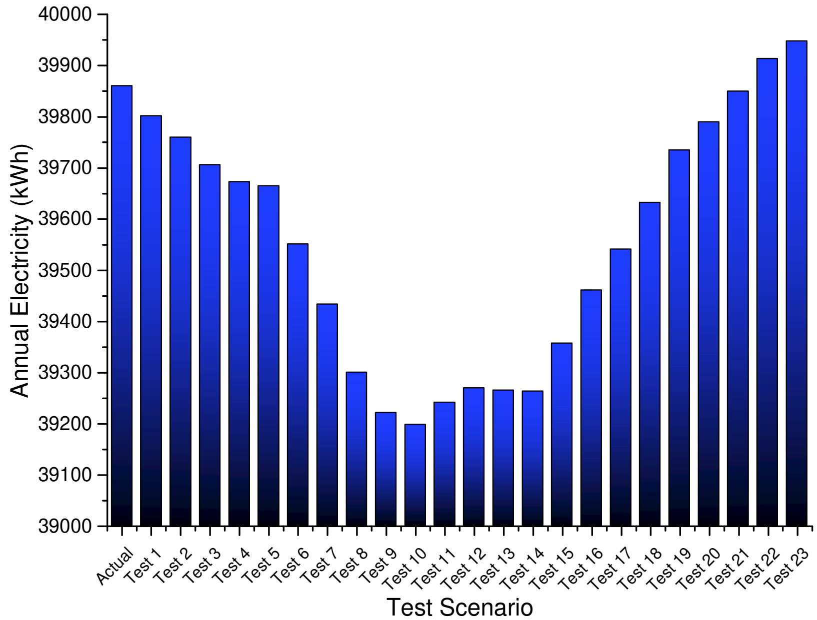


Figure 6.32 Line chart using Data Shapes node

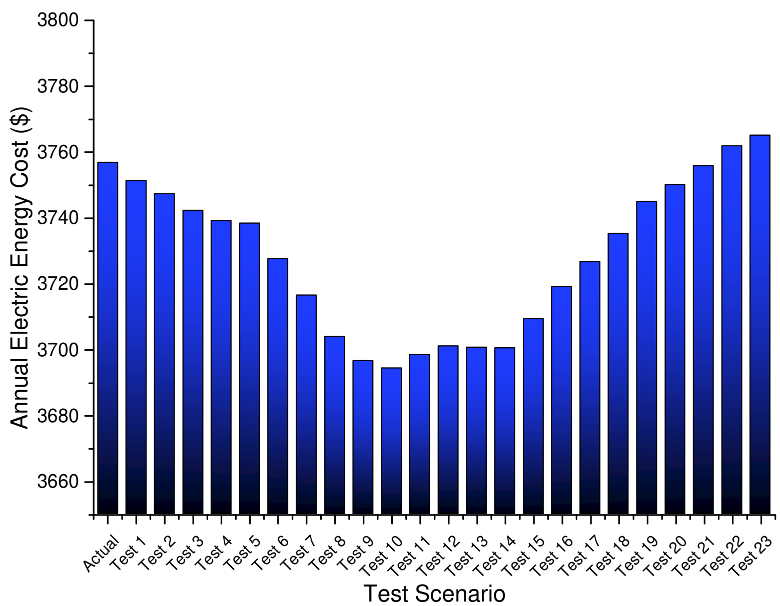
6.3.2. Energy conservation Strategies

6.3.2.1 Orientations

Afghanistan is located in both the northern and eastern hemisphere; to get the most benefit from solar energy; the buildings should face south. The amount of electricity energy needed depends on the amount of solar energy perception by the building elements and their exposure to sun light for better ventilation in winters and nominal ventilation in summer seasons. Therefore, the building is rotated clockwise 15 degrees each time to perform energy simulations. The actual entrance face of the building is southwards and is created as base case (the back face is 30 degrees counter-clockwise) as shown in Figure 6.6 (b).



(a)



(b)

Figure 6.33 (a) Simulated annual Electric (kWh) (b) Annual Electric Energy Cost Vs Building orientations

The simulated results are analysed to extract the relationship between the direction of the building and the energy consumption of a multi-family residential building. **Error! Reference source not found.** describes the annual electric energy and cost estimates for all the test scenarios considering life cycle of the building. Whereas **Error! Reference source not found.** describes the annual energy (includes both electric and fuel) consumptions and cost estimates considering life cycle span. There are certain assumptions that GBS takes into account such as the total life span of a building being 30 years and 6.1% as cost discount factor. Transmission losses are not accounted for in the simulation. The annual and life cycle energy and costs along with different orientations are discussed. Further, the facing of the building at each orientation is compared with the actual south face of the building.

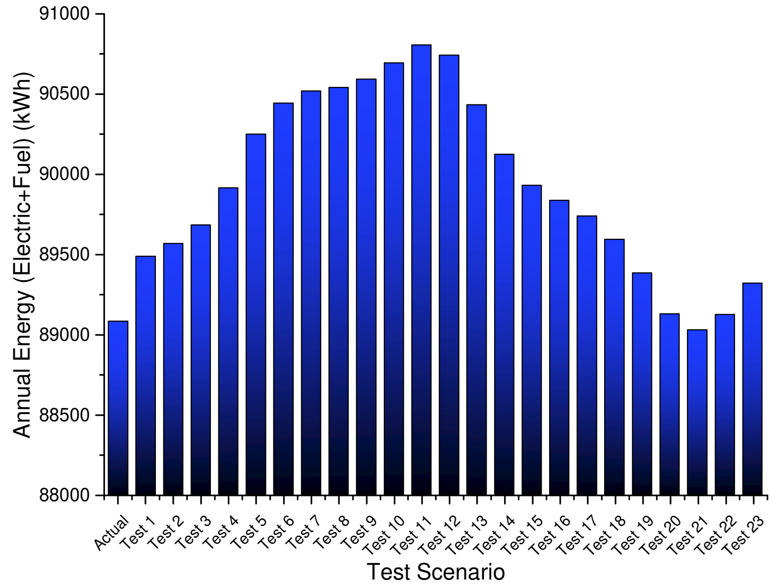
1. Analysis of Test Scenarios

I. Actual Case - Base Case: This test is for the actual orientation of the building, where the building faces south. As shown in Figure 6.6 (b), the back face is towards North and is 30-degree anti-clock wise to the north as taken in Actual case test (referred as 0 degree). The drawing hall and southeast corner bedrooms are front facing. The annual and Life Cycle (LC) electric energy consumptions are simulated as 39,861 kWh and 1,195,832 kWh respectively.

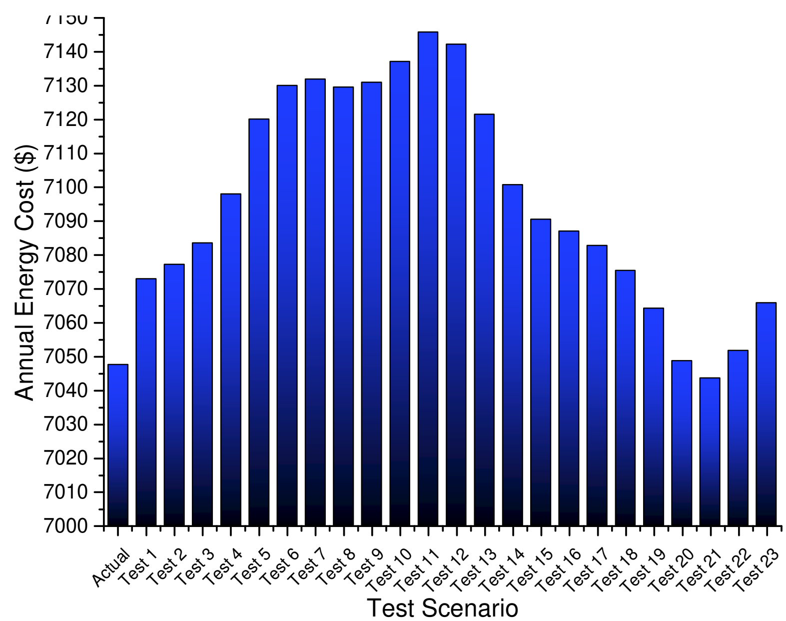
II. Test 2 (30^{o}): The orientation of the building is such that the face of the building is exactly towards the south and both the side faces and its openings are exposed to sunlight. The design alternative tab in GBS is employed by selecting +30^{o} rotation, which rotates the building model by 30^{o} clockwise. The simulation results in electrical energy consumption of 39,760 kWh and 1,192,809 kWh annually and LC respectively.

III. Test 4 (60^{o}): All the bed rooms and their windows face east direction sunlight till mid-day. The face of the building gets the sunlight from the noon session. The results generated by GBS for this orientation of annual and LC electricity are 39,673 kWh and 1,190,190 kWh respectively.

IV. Test 6 (90^{o}): in this orientation, both the front and right side face (bed room side walls and windows) of the building receive a good amount of solar energy in winter and a minimal amount in summer. The simulated annual and LC electric energy values are 39,551 kWh and 118,6531 kWh respectively.



(a)



(b)

Figure 6.34 Annual Energy estimates (a) Total Energy (Electric and Fuel) (kWh) (b) Total Energy cost ($)

V. Test 10 (150 ^{o}): Both the right face and back face of the building are exposed to sun light, where all the bedrooms and kitchen are exposed on the two sides. At this orientation of the building, the simulated values of electric energy consumption are the lowest, which in turn consumes low electricity for both cooling and heating purposes. The simulated values of electricity are 39,198 kWh & 1,175,948 kWh for both the annual and LC respectively.

VI. Test 14 (210 ^{o}): In this building orientation, the back face, right and front faces are interfering with availability of sunlight in winter and minimal exposure to the sun during summer seasons. The electric energy estimates of annual and life cycles are 39,263 kWh and 1,177,891 kWh, respectively.

VII. Test 18 (270 ^{o}): The back face and the stair side face are getting good sunlight. The electric energy simulation estimates are as follows: 39,632 kWh and 1,188,946 kWh for annual and LC respectively.

VIII. Test 20 (300 ^{o}): The electric energy estimates for this orientation of the building energy are 39790 kWh and 1193693 kWh for both annual and LC respectively. Only the front and back faces of the building are being exposed to direct sunlight. Especially in winter, the stair side face is getting a good amount of solar energy, but only one single bed is situated on this face to get benefit out of it.

IX. Test 22 (330 ^{o}): The front and right side faces (stair face) are gaining a good amount of sunlight in winter. The simulated values of electric energy are 39,914 kWh annually and 1,197,417 kWh in a life cycle.

Including the actual building orientation and 23 numbers of test scenarios covered one complete 360-degree rotation to identify the best orientation, which consumes minimal energy. This study considered only electricity. This is because a typical Afghan family uses abundantly available firewood and coal for heating purposes in winter. Gas is used mainly for cooking purposes only. An attempt is made to project the annual and life cycle electricity and fuel energy along with costs. It is common practice in Afghanistan for the electricity board to cut power in summer during the daytime and in winter at night for about 12 hrs. The currency of Afghanistan is Afghani (Afn) symbolled as (؋). For the cost estimates, 1 Afn = 0.013 USD is used. The annual electric energy estimates are plotted in Fig. 8 and as can be seen, the best orientations are between Test 8 to Test 14 with a minimum annual electricity consumption estimate at Test 10 orientation of 39,198 kWh with a total difference from maximum to minimum of

(39,948 kWh– 39,198 kWh) being 750 kWh, as identified from Fig. 8. The life cycle electricity consumption estimates can be observed from **Error! Reference source not found.**, with a minimum of 1,175,948 kWh to a maximum of 1,198,442 kWh with a difference of 22494 kWh.

2. Discussion

On carrying out a detailed study of the selected case study over its orientation, it is made possible to generate the data to address the target methodology. In this study, the BIM-Revit model is used along with GBS in attaining energy simulations for various orientations. It is evident that the solar sun path and the exposure of the building envelope to it plays a major role in providing a good amount of solar gain naturally. It is clear from the study the orientation of the building plays a major role in energy consumption. The relation between them depends on the type of building, the envelops, occupant life style, financial status of the resident, amount of opening area and local climate. The behaviour and financial status of the residents cannot be controlled or modelled.

There are two ways of projecting the results: 1) considering only the electric energy estimates (see **Error! Reference source not found.**) combining both the electric and fuel estimates (see **Error! Reference source not found.**). The two ways of projecting the results are due to the large variations of the resident's financial status and lifestyle as well as discontinuity on the power supply.

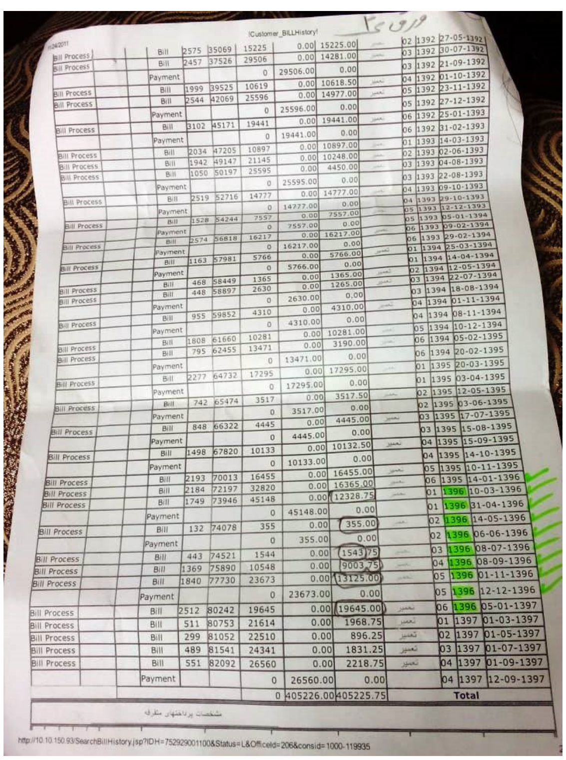
I. Extraction from Electric Energy Estimates: The lowest annual electric energy cost estimate of $3,694 at a rotation of orientation of +150 (Test 10) from the actual case (base case) is highlighted by the highest cost of $3,765 at an orientation of +345 (Test 23) from the base case, with a difference $71. Similarly, for the life cycle estimates (30 years span) the difference of electric energy cost from the best orientation ($110,833) to the poorest orientation ($112,953) is compared with a difference of cost of $2,120. It is observed from the electric energy analysis that there is a significant influence of the orientation of the building.

II. From Total Energy Estimates: The lowest annual energy cost estimate of $7,044 at a rotation of orientation of +315 (Test 21) from the actual case (base case) is highlighted by the highest cost of $7,146 at an orientation of +165 (Test 11) from the base case, with a difference of cost of $102. Similarly, for the life cycle estimates (30 years span) the difference of electric energy cost from the best orientation ($ 95,934) to the poorest orientation ($97,327) is compared with a difference of cost of $1,393. It is observed there is not much influence of the different orientations for the 30-year life cycle energy analysis.

When you compare only electric energy estimates Test 10 is the best orientation and Test 23 worst. On the other hand, when you compare total energy (both electric and fuel) Test 21 is the best orientation and test 11 is the worst. This variation can be visualised from **Error! Reference source not found.** and **Error! Reference source not found.**. It is observed at building on-site, that people use firewood for heating purposes, not fuel or electricity.

3. Validating simulated electric energy

The simulated energy results are compared with actual electricity bills. The actual orientation of the building is modelled as test scenario “Actual”. The real energy consumption of the buildings considered as valid data for auditing purpose of the simulated data by energy simulation tools (Jensen, 1995; Laine & Karola, 2007). The simulated annual electricity of the real building orientation is 39,861 kWh, whereas the actual annual consumption of the electricity from the previous records (source: Afghanistan electricity board/Electricity bills) is 10,229 kWh for the year 2017-2018. The actual electricity bills are shown in Figure 6.35 of the House situated at Kabul Province, Kabul city, Darul Aman road, Afghanistan – 1004.



Customer_BILLHistory

Bill Process	Bill	2575	35069	15225	0.00	15225.00	02	1392	27-05-1392
Bill Process	Bill	2457	37526	29506	0.00	14281.00	03	1392	30-07-1392
	Payment			0	29506.00	0.00	03	1392	21-09-1392
Bill Process	Bill	1999	39525	10619	0.00	10618.50	04	1392	01-10-1392
Bill Process	Bill	2544	42069	25596	0.00	14977.00	05	1392	23-11-1392
	Payment			0	25596.00	0.00	05	1392	27-12-1392
Bill Process	Bill	3102	45171	19441	0.00	19441.00	06	1392	25-01-1393
	Payment			0	19441.00	0.00	06	1392	31-02-1393
Bill Process	Bill	2034	47205	10897	0.00	10897.00	01	1393	14-03-1393
Bill Process	Bill	1942	49147	21145	0.00	10248.00	02	1393	02-06-1393
Bill Process	Bill	1050	50197	25595	0.00	4450.00	03	1393	04-08-1393
	Payment			0	25595.00	0.00	03	1393	22-08-1393
Bill Process	Bill	2519	52716	14777	0.00	14777.00	04	1393	09-10-1393
	Payment			0	14777.00	0.00	04	1393	29-10-1393
Bill Process	Bill	1528	54244	7557	0.00	7557.00	05	1393	12-12-1393
	Payment			0	7557.00	0.00	05	1393	05-01-1394
Bill Process	Bill	2574	56818	16217	0.00	16217.00	06	1393	09-02-1394
	Payment			0	16217.00	0.00	06	1393	29-02-1394
Bill Process	Bill	1163	57981	5766	0.00	5766.00	01	1394	25-03-1394
	Payment			0	5766.00	0.00	01	1394	14-04-1394
Bill Process	Bill	468	58449	1365	0.00	1365.00	02	1394	12-05-1394
Bill Process	Bill	448	58897	2630	0.00	1265.00	03	1394	22-07-1394
	Payment			0	2630.00	0.00	03	1394	18-08-1394
Bill Process	Bill	955	59852	4310	0.00	4310.00	04	1394	01-11-1394
	Payment			0	4310.00	0.00	04	1394	08-11-1394
Bill Process	Bill	1808	61660	10281	0.00	10281.00	05	1394	10-12-1394
Bill Process	Bill	795	62455	13471	0.00	3190.00	06	1394	05-02-1395
	Payment			0	13471.00	0.00	06	1394	20-02-1395
Bill Process	Bill	2277	64732	17295	0.00	17295.00	01	1395	20-03-1395
	Payment			0	17295.00	0.00	01	1395	03-04-1395
Bill Process	Bill	742	65474	3517	0.00	3517.50	02	1395	12-05-1395
	Payment			0	3517.00	0.00	02	1395	03-06-1395
Bill Process	Bill	848	66322	4445	0.00	4445.00	03	1395	17-07-1395
	Payment			0	4445.00	0.00	03	1395	15-08-1395
Bill Process	Bill	1498	67820	10133	0.00	10132.50	04	1395	15-09-1395
	Payment			0	10133.00	0.00	04	1395	14-10-1395
Bill Process	Bill	2193	70013	16455	0.00	16455.00	05	1395	10-11-1395
Bill Process	Bill	2184	72197	32820	0.00	16365.00	06	1395	14-01-1396
Bill Process	Bill	1749	73946	45148	0.00	12328.75	01	1396	10-03-1396
	Payment			0	45148.00	0.00	01	1396	31-04-1396
Bill Process	Bill	132	74078	355	0.00	355.00	02	1396	14-05-1396
	Payment			0	355.00	0.00	02	1396	06-06-1396
Bill Process	Bill	443	74521	1544	0.00	1543.75	03	1396	08-07-1396
Bill Process	Bill	1369	75890	10548	0.00	9003.75	04	1396	08-09-1396
Bill Process	Bill	1840	77730	23673	0.00	13125.00	05	1396	01-11-1396
	Payment			0	23673.00	0.00	05	1396	12-12-1396
Bill Process	Bill	2512	80242	19645	0.00	19645.00	06	1396	05-01-1397
Bill Process	Bill	511	80753	21614	0.00	1968.75	01	1397	01-03-1397
Bill Process	Bill	299	81052	22510	0.00	896.25	02	1397	01-05-1397
Bill Process	Bill	489	81541	24341	0.00	1831.25	03	1397	01-07-1397
Bill Process	Bill	551	82092	26560	0.00	2218.75	04	1397	01-09-1397
	Payment			0	26560.00	0.00	04	1397	12-09-1397
				0	405226.00	405225.75	Total		

مشخصات پرداختهای متفرقه

http://10.10.150.93/SearchBillHistory.jsp?IDH=752929001100&Status=L&OfficeId=206&consid=1000-119935

د افغانستان برښنا شرکت
چمن حضوری
کابل افغانستان
شماره تماس: ۱۴۴

نمبر بل	02201709208357
دوره میتر خوانی	03
تاریخ صدوربل	۱۳۹۶-۰۷-۰۸
تاریخ مکلفیت تحویل پول	۱۳۹۶-۰۸-۰۷

نمبر میتر	102904A
تعرفه	تعمیر
ضریب میتر	1
فاز	1
نمبر حساب / نمبر حساب سابقه	100100570 / 060804893
نمبر اشتراک	127393
جنکشن	جنکشن-۶
ترانسفارمر	Sanatoryam
نمبر صندوق	F1 Box 5
کود مسیر	10/01/JS6/101632/06 50/1

تفصیلات	دوره	قرائت
درجه حالیه	31-06-1396	74521
درجه گذشته	01-05-1396	74078

صرفیه ۴۴۳ کیلووات ساعت برای ۶۰ روز

صرفیه برق	قیمت	مبلغ به افغانی
0-200 کیلووات ساعت	2.50	500.00
201-400 کیلووات ساعت	3.75	750.00
401-700 کیلووات ساعت	6.25	268.75

مجموعه مصارف	1518
کمیشن بانکی	15
مصارف خدمات	0
مصارف فرمانیه	10
ضایعات ترانسفارمر / جریمه	0
مصارف متفرقه	0
مجموعه مصارف متفرقه	25
مبلغ بل	1543
مالیه	0
مبلغ قابل پرداخت	1543.7
باقیات گذشته	0.2
مبلغ قابل تادیه	1544

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بانکداری اسلامی در کشور!

(a) (b)

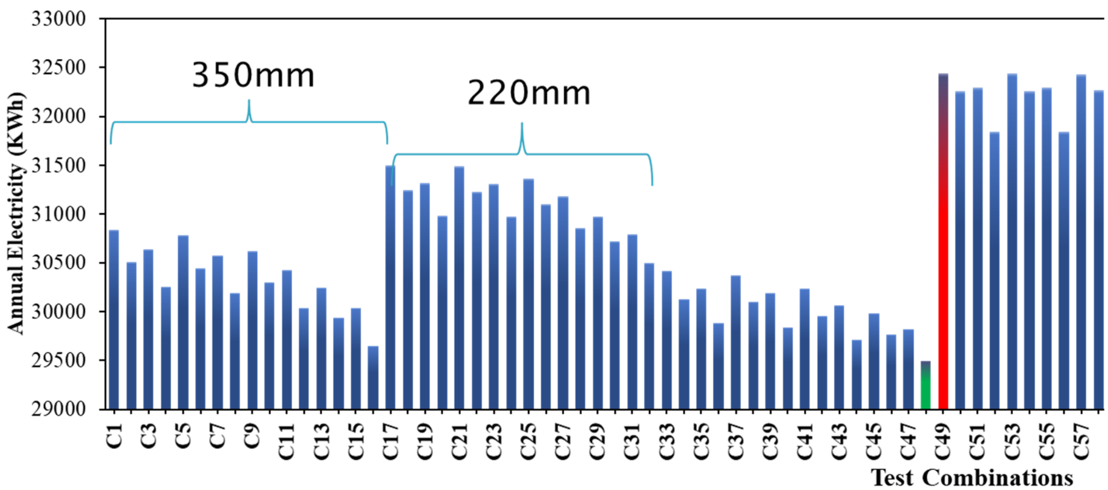
Figure 6.35 Actual electricity bills, (a) Sheet no.2 of summary sheet for 10years. (b) 2 month interval of Eb bill for 23rd July – 22nd Sep 2017

The Eb (Electricity board) bills are in Afghani language and in the Hijri calendar year format. For the validation, the authors used the English calendar and tabulated in Excel sheets as supplementary data. The simulated values of electricity using GBS is 3.9 times greater than the actual bill values. This is because of an electricity power cut of 12 hrs per day on peak consumption time (i.e. in summers – day time and in winters in night times). This made the people relay on alternative energy sources like wood and coal. The green building studio is not modelled to take care of all these issues.

An approximation approach is used to fit the real situation of the local issues. The annual electricity estimate is 39,861 kWh. On considering the above effect of a power cut on peak time and 12 hours usage, the above value is multiplied with a factor of 0.25 (0.5-0.25). If data assumes consumption for only 12 hours, then the simulated values are for 24 hrs – 1* 39,861 kWh. For 12 hours of supply, 0.5 is subtracted from multiplier 1 (new multiplier = 1 – 0.5 = 0.5), again 0.25 is deducted to the new multiplier due to the power cut at peak times, so the final multiplier of 0.25 (Final multiplier = 1 – 0.5 – 0.25 = 0.25) is used to suit the actual situation of the building. The revised simulated value of electricity is 9,965.25 kWh (0.25*39,861). The actual electricity values are very close to the revised simulated values. The actual values are 2.65% greater than the revised simulated values. The allowable percentage error between the simulated and the actual data must be ± 15% only then the software tool used for the simulation is reliable (Maamari et al., 2006; Reeves et al., 2012). In this case study the simulated values are not in a comparable range due to big local error, which cannot be modelled in GBS. Hence, the simulated values are revised by an approximation and then compared to the error (2.65%) which is within the permissible limit. There are many errors that are out of focus, these being: 1) The actual orientation of the building is difficult to measure and model, 2) The number of people living in the building varies from month to month as also their financial stature (income, profession, country of origin). 3) There are many assumed factors in GBS such as the real building elements, heat transfer factors (U-values), which may be differed from assumed values.

6.3.2.2 Envelop Variations

A thorough examination is conducted on ninety-six distinct combinations of local Afghan construction materials for the residential building envelope. As the result of the energy analysis experiments, it is found that a combination of Case 48 (with an annual energy demand of 29,496 kWh) emerges as the most energy-efficient configuration, showcasing optimal energy performance. The C48 combination is of Adobe brick masonry (W3), mud roof (R4) and mud floor (F4). In contrast, Case 49 (with an annual energy demand of 32,440 kWh) represents the least favourable scenario, indicating the highest energy consumption among the configurations under scrutiny. (Savings of 2,944 kWh). The C49 combination is of CMU block masonry (W4), RCC roof (R1) and RCC floor (F1) Figure 6.36 shows the complete result of the experiment for all combinations. Further, it is identified from the analysis there is a reduction of firebrick thickness from 350mm to 220mm, resulting in the increase of energy demand by 754kWh.



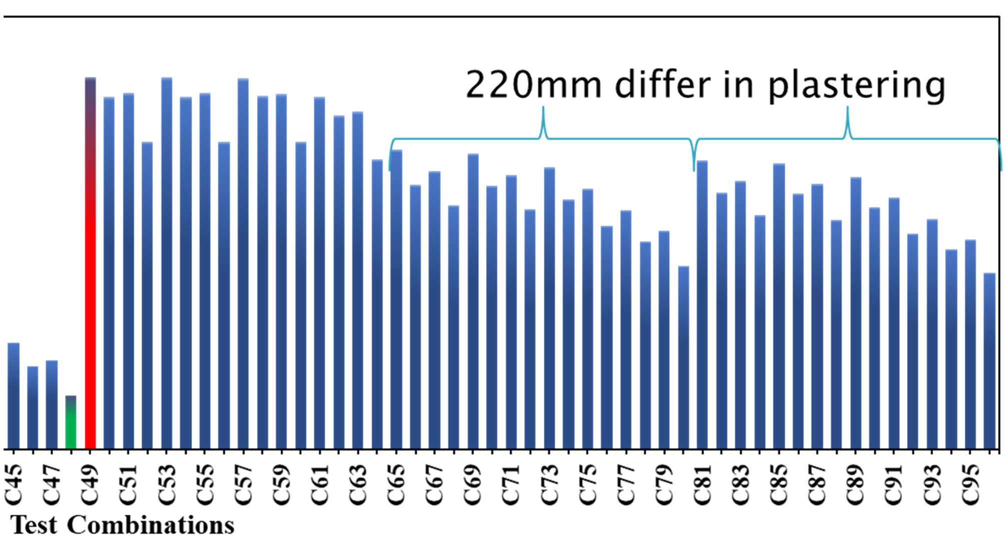


Figure 6.36 Annual energy estimates of various test combinations

6.3.2.3 Window-to-Wall Ratio

To evaluate the impact of increasing the glazing area on energy demand, the glazing area of the building envelope of the most energy-efficient case (C48) is incrementally increased from 10% to 60% with 10% WWR increment intervals. The percentage of glazing area for each model, ranging from 10% to 60%, is calculated, and new windows with adjusted dimensions are assigned to the models. Energy simulations are conducted for all six new models, and the electricity demand results are compared.

The results, as shown in Figure 6.37, indicate a significant increase in energy demand as the glazing area is increased. Specifically, there is an increase of 24,526 kWh in electricity demand from 10% to 60% of WWR. This demonstrates the importance of carefully considering the glazing area in building design to optimize energy efficiency and minimize energy consumption.

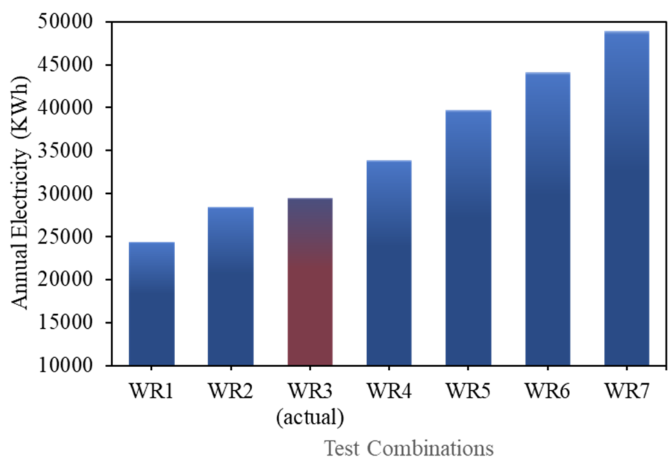


Figure 6.37 Annual energy estimates of different WWR ratios

6.4 CONCLUSION

As part of this study, a methodology for determining the best design alternative using BIM and MCDM techniques is developed. The BIM platform is Revit and the MCDM method is a combination of AHP and TOPSIS that best fit the objectives to be achieved. A medium is required to act as a link between Revit and MS Excel in order for an integrated synergy to occur (the MCDM platform). Dynamo, a computational design tool, is used for this purpose.

The models are ranked and the data is exported to Revit. Two case study buildings in various stages of construction are used to test the proposed solution. Following the analysis, Model 1 is chosen as the best alternative among three models of case study building 1. It is discovered that option 2 is chosen as the best alternative among the three options of case study building 2. It is discovered that 65.4% of stakeholders are aware of the use of BIM and computational design to help overcome early design stage challenges, while 32% are unaware. Designers, particularly structural engineers, use a variety of design alternatives to achieve a sustainable design. However, combining BIM and MCDM will help to make the sustainable mantra a reality, particularly in terms of design that saves energy.

The proper orientation of building will absorb a sufficient amount of solar energy and natural light through the openings to illuminate the inner space of the building. This will drastically reduce the consumption of conventional sources of energy. There are various factors, which control energy requirements such as the occupant's life style, building glazing, elements and components, orientation, shape and size of the building. In summer, occupants need a low amount of solar gain and in winter, a good amount of solar interception is required. Depending on the actual orientation and the sun path motion, the energy of heating and cooling systems is varied. This study avoids cumbersome manual estimates of energy consumption with different orientations of the building, which involves errors in computations. The use of potential BIM is not common among practitioners of energy estimates. This may be due to a lack of education, training and or no local governmental policies. Therefore, the benefits of estimating energy requirements for different building orientations and elements at the early design stage are lacking.

In this study, different building orientations are considered to study the energy requirements by considering a case study of a multi-family residential building, located in Kabul, Afghanistan. For building modelling purposes and energy simulation, Autodesk Revit and web-based building performance analysis tool – Autodesk Green Building Studio are used. The results showed that there is a huge difference between the simulated electric energy versus the actual electric bill values. The actual building conditions are considered in arriving at the revised simulation values. The results showed a cost saving of $1,393 from the best orientation +315 (Test 21) to the worst orientation +165 (Test 11) for the full life cycle span of the building. The present study aimed to visualise the effect of building orientation on energy demand and the impact can be minimised by the use of proper solar shading devices. A detailed view is described for the use of GBS in performing alternative simulations. It is suggested to develop a model in Revit with minute details for better analysis. The case study cannot be generalised for all of Afghanistan's residential buildings. A future study is planned to be performed on different buildings with different building envelopes using other energy simulation tools.

Simulated vs Actual energy comparison: Simulated annual electricity consumption for the G+2 building orientation is 39,861 kWh, closely matching the actual annual consumption of 40,858 kWh, with a minimal error of 2.65% well within permissible limits. An annual electricity consumption reduction of 1.66% is observed when the low raise building is oriented 150 degrees clockwise from its actual orientation. Conversely, an increase of 3% is noted when it is oriented 15^{o} anticlockwise. Furthermore, a significant reduction of 24.75% in annual electricity consumption is identified (between worst to best combination) when specific material combinations, (adobe masonry walls, mud floors and roofing), are used in the G+2 building, which is oriented 150^{o} clockwise from its actual orientation.

Energy Savings: Notably, the study reveals energy savings of 1,779 kWh, with the best orientation (Test 21 +315) outperforming the worst orientation (Test 11 +165) in terms of annual energy estimates (electric + Fuel). Special Building Shape: The 1.8k building boasts a unique design to maximize sunlight utilization. Results demonstrate that the existing building orientation (Actual) yields the most favourable annual energy demand, while rotation Test 6 90^{o} results in the highest demand.

The main objective of the study is to investigate the local construction material behaviour on building energy consumption. For this purpose, the different local construction materials that are conventionally used in buildings are assigned to the main components of the 3D model in Revit. In total 6 types of walls, 4 types of roofs and 4 types of floors are created from various local materials and all aforementioned building elements are combined to gather and 96 models are built. gbXML format of all 96 models is imported to GBS cloud for energy simulation. Finally, it is observed that combination No. 48 which is made of adobe brick walls and mud roofs and floors is the best one from energy conservation point of view as it consumes 29,496 kWh of electricity annually which is the minimum electricity consumption option among all combinations. The worst case is combination No. 49 which is made of CMU block walls and RCC roofs and floors with annual electricity demand of 32,440 kWh. Incorporating a WWR of 10% and 60%, relative to the actual WWR of 20.30%, resulted in a further reduction of 17.42% and an increase of 39.66% in annual electricity consumption for the G+2 building when oriented 150° clockwise from the actual orientation. An increase in WWR percentages correlates with higher electricity demand. Thus, the study recommends smaller WWR for the construction of energy-efficient buildings.

Summary: The study developed a methodology using BIM and MCDM techniques to determine the best design alternative, integrating Revit and MS Excel. Dynamo facilitated the integration, and two case study buildings were used to test the solution. Model 1 was chosen as the best alternative for building 1, while option 2 was the best for building 2. The study found that 65.4% of stakeholders are aware of BIM and computational design benefits for early design stages. Combining BIM and MCDM can make sustainable design, particularly energy-saving design, more achievable. Proper building orientation can significantly reduce energy consumption by maximizing natural light and solar energy absorption. The study identified the best orientation for a multi-family residential building in Kabul, Afghanistan, using Revit and Autodesk Green Building Studio. Simulated versus actual energy consumption showed a minimal error, and the study suggests developing detailed models for better analysis. Energy savings were observed with the best orientation, and specific material combinations yielded significant reductions in energy consumption. The study's main objective was to investigate the impact of local construction materials on building energy consumption, with the best combination consuming the least electricity annually. Varying window-to-wall ratios influenced electricity consumption, with smaller ratios recommended for energy-efficient buildings. The selected types of walls, roofs, and floors represent the locally available construction materials that are commonly used in buildings in the region. These materials were chosen to reflect the typical construction practices and preferences in the local context, ensuring that the study's findings are relevant and applicable to the regional or country levels. The selection of these materials allows for a comprehensive analysis of their impact on building energy consumption, providing valuable insights for future construction projects in similar environments.

CHAPTER 7

VALIDATION OF COMFORT PARAMETERS

This chapter focuses on the outcomes of the fourth sub-objective, which involves the reconstruction of CCI utilizing ANN-MLP in the context of the case study building. The subsequent step involves the validation of the reconstructed CCI through comparison with in-situ observed datasets. The primary objective is to validate the performance of the developed Multilayer Perceptron (MLP) model in reconstructing and predicting indoor comfort parameters. This validation is crucial to ascertain the accuracy, reliability, and applicability of the model in real-world scenarios. The chapter aims to compare the simulated data generated by the MLP model with observed data to assess the degree of alignment and correlation between the two datasets. Key performance metrics such as Nash-Sutcliffe Efficiency (NSE) and Pearson's correlation coefficient (r) are utilized to quantify the model's performance and determine its effectiveness in replicating the observed indoor comfort conditions.

7.1 INTRODUCTION

In recent times, there has been significant progress in machine learning methodologies, unlocking novel prospects for real-time control of indoor environmental quality. This facet is crucial for the overall health, well-being, and productivity of building occupants. Ongoing research has diligently concentrated on refining monitoring devices and strategies while innovating techniques for accurately estimating indoor conditions. The pervasive use of machine learning algorithms in this domain has experienced a notable surge. Despite these advancements, the real-time monitoring of extensive multizone working areas remains a formidable challenge (Martínez-Comesaña et al., 2021). This study aims to address this challenge by introducing an interpolation methodology grounded in optimized multi-layered perceptron neural networks. The primary objective is to precisely estimate the real-time indoor environmental conditions within a building. To demonstrate the effectiveness of this methodology, it was applied to the hostel building at the NITW in India. The outcomes of this approach yielded interpolated values for indoor temperature, illumination, and acoustical parameters. Machine learning techniques emerged as highly effective tools for solving intricate problems, particularly in the realms of data prediction and reconstruction. This study employs a learning-based model, specifically the MLP, to reconstruct 66 observed datasets. The performance of the ANN model is evaluated at both parametric and CCI levels, and subsequently benchmarked against existing data. The developed learning-based model demonstrates a remarkable ability to precisely reconstruct CCI, showcasing its potential for advancing our understanding of and interventions in indoor environmental quality on a global scale.

This study stands out as one of the pioneering endeavours to reconstruct CCI and subsequently validate it by leveraging observed datasets obtained from diverse rooms across multiple floors of a hostel building. The individual parametric indexes reconstructed from the hostel rooms are employed to calculate CCI, which is then cross-validated with the CCI derived from direct observations. The implications of this research extend beyond the local context, offering valuable insights that could address comfort-related gaps in institutional buildings on both a regional and global scale.

7.2 METHODOLOGY

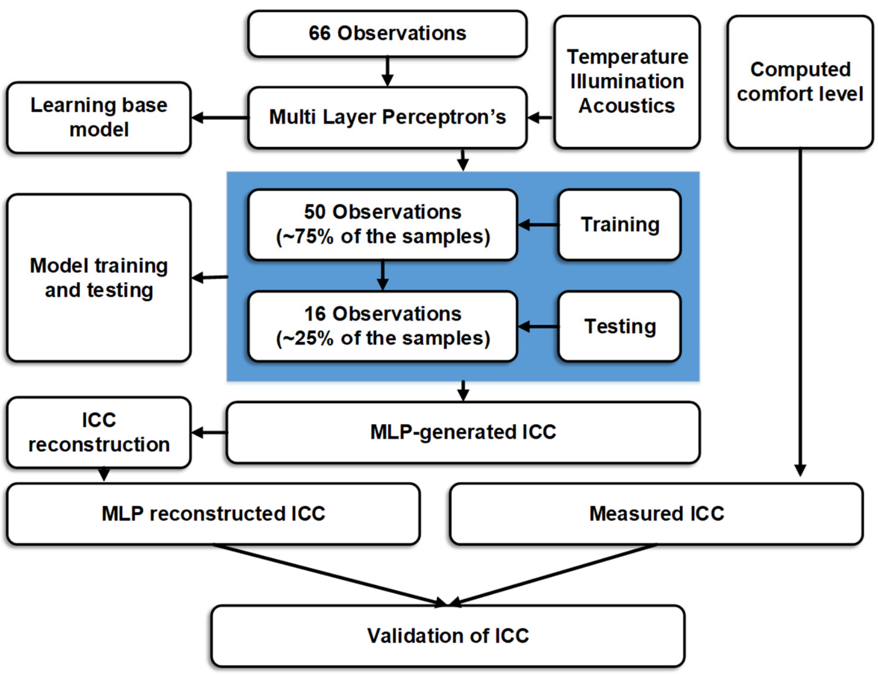


Figure 7.1 Flow chart of objective 4

Predictive models aim to discern a connection between a set of predictors (TI, VI, and AI) and the target variable CCI (Bishop, 2006). Out of 66 sets of observed data, 75% of the data (50 sets) is used for training the model, and 25% (16 sets) are used for testing the model. Within this study, the MLP model is utilized to predict and reconstruct CCI, resulting in a continuous series of 66 observations. Subsequently, the developed CCI model is juxtaposed with the observed CCI data for comparison. Additionally, individual parametric data reconstruction is carried out to evaluate the level of conformity with the actual data. The methodology outlining the process of reconstructing CCI and its validation is visually depicted in **Error! Reference source not found.**.

The input layer of the neural network included three neurons representing Temperature, Illumination, and Acoustics. The architecture of the ANN-MLP model involved the use of one layer for each of the hidden and output layers, resulting in a total of three layers.

7.2.1 Artificial Neural Networks (ANN)

The foundation of ANN is inspired by the intricate biological neural network in the brain, comprising billions of interconnected neurons. This complex structure serves as the fundamental basis for ANNs. Evolving alongside advancements in information processing, ANNs have proven instrumental in simulating the brain's distributed storage properties and achieving massive parallel processing capabilities. An ANN operates as a data processing system, intricately woven into a network of interconnected components known as neurons. These neurons are organized into layers, each linked to the neurons in the subsequent layer. The term "weight," akin to the signal intensity within a biological neural network, signifies the strength of connections between adjacent layers. In the training or learning phase, the weights of these interconnections are systematically adjusted until the inputs yield the desired output. Achieving the desired output involves employing diverse training rules for weight adjustment, tailored to the specific training data provided to the network. In this study, the MLP emerges as a widely embraced and popular ANN model (Bishop & Nasrabadi, 2006). Specifically, MLP is harnessed to reconstruct the CCI dataset based on 66 observations. The ensuing sections offer a succinct overview of MLP, shedding light on its pivotal role in this research endeavour.

7.2.2 Multi Layer Perceptron (MLP)

Comprising a network of interconnected nodes or neurons, the MLP operates by linking these neurons through weights. The output signals are subject to modification through a straightforward nonlinear transfer, achieved by an activation function (Bayram et al., 2016). Commonly employed activation functions include the Unit step (Heaviside), Linear, and Logistic (sigmoid) functions. The connecting weights play a crucial role, as they scale the output of a node and subsequently feed it forward, serving as an input to the nodes situated in the subsequent layer of the network. This directional flow of information processing characterizes the MLP as a feed-forward neural network, a representation illustrated in Figure **7.2**. The structure of the MLP, with its interconnected nodes and weight-adjusted signal flow, underscores its effectiveness as a powerful tool in various applications. (Bishop, 1995).

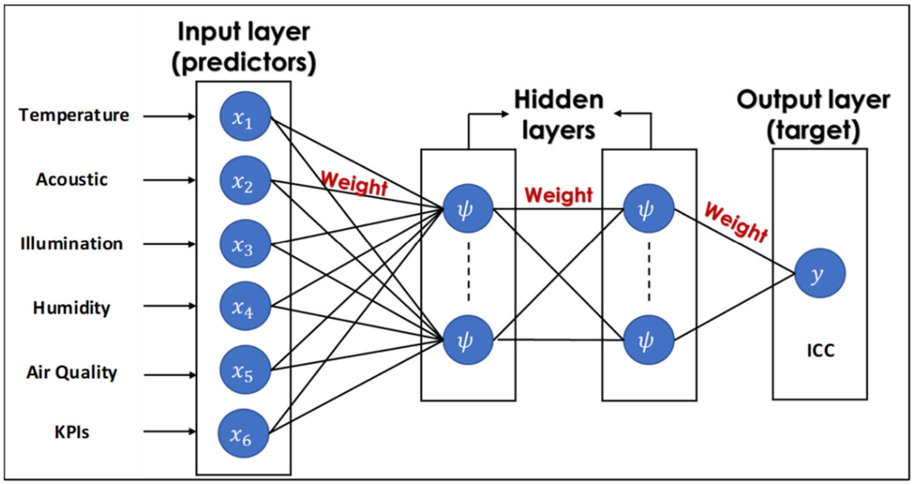


Figure 7.2 Structure of Multilayer Perceptron

The MLP architecture is flexible, accommodating one or more hidden layers, followed by an output layer. The output from each layer serves as the input for the subsequent layer in a sequential fashion. The neural network structure involves the input and output layers, positioned at the inception and conclusion, respectively, while any intermediate layers function as hidden layers. Each connection between neurons in different layers is associated with its unique weight, and the activation functions, typically utilizing the sigmoid function, remain consistent across all layers. Depending on the application, the output layer can employ either a sigmoid or linear function. The well-established learning method for MLP is the backpropagation technique, a generalization of the Least Mean Squared rule (Du & Swamy, 2013). Backpropagation is a weight correction technique that propagates errors from one layer to the next, initiating from the output layer and working backward.

The performance of the MLP model hinges on specified variables, the training dataset and the number of hidden layers. A small number of hidden layers may result in less precise detection of nonlinear functions, while an excessively large number may lead to overfitting of the training data. Consequently, determining the optimal number of hidden layers becomes a crucial aspect of the analysis.

This model serves as a tool for understanding and representing the relationships between input predictors and the corresponding output variable in a given dataset. The MLP's capability to discern and represent these complex mappings makes it a valuable tool in various applications, particularly in the realm of machine learning and artificial intelligence (Bishop & Nasrabadi, 2006).

- The multilayer perceptron is a model that captures a functional mapping between a set of predictors (x) and the target variable (y).

$$y = f(x) + \varepsilon \quad (7.1)$$

- In the given context, the equation can be expressed as follows: where f denotes the mapping, ε represents process noise, and $\{x_i\}_{i=1}^{M}$ signifies a set of M predictors. Additionally, within this framework, a hidden layer is incorporated, comprising K hidden neurons.

$$a_k = \sum_{i=1}^{M} w_{ki}^{(1)} x_i + w_{k0}^{(1)}, \quad k = 1, \dots, K \quad (7.2)$$

- In this expression, $a_k =$ hidden neuron; $\left\{w_{ki}^{(1)}\right\}_{i=1}^{M} =$ denotes unknown weights associated with each input neuron and $w_{k0}^{(1)} =$ represents an unknown bias term utilized for correcting the estimation bias. Subsequently, the given equation undergoes processing through a transfer function to generate outputs from the hidden neurons.

$$z_k = \psi(a_k), \; k = 1, \dots, K \quad (7.3)$$

- In this context, z_k signifies the output, and ψ denotes the transfer function, specifically the sigmoid function, known for its output range between 0 and 1. To complete the connection between the hidden layer and the output layer, linear transfer functions are employed.

$$y_j = \sum_{k=1}^{K} w_{jk}^{(2)} z_k + w_{j0}^{(2)} \quad (7.4)$$

- In this expression y_j represents the output neuron, indicating the model predictions $(j = 1, \dots, J)$. Throughout the training period, the backpropagation technique is employed to iteratively resolve unknowns, ultimately achieving optimal weights in each layer of the neural network. This iterative process helps fine-tune the model and enhance its predictive accuracy.

7.2.3 Performance Metrics

The performance of the developed MLPs is assessed using two key metrics: Pearson's correlation coefficient (r) and Nash-Sutcliffe Efficiency (NSE). Pearson's correlation coefficient is a measure of the linear correlation between two datasets and is represented as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{7.5}$$

Where *x* denotes the dataset, and *y* signifies the index. The suffix i varies from 1 to n. $\bar{x}$ and $\bar{y}$ denote the means of the *x* and *y* scores, with *n* representing the total number of observations. The Pearson correlation coefficient (*r*) falls within the range of -1 to +1. A higher positive or negative value of r signifies a stronger correlation between the variables *x* and *y*.

Nash-Sutcliffe Efficiency (NSE) evaluates the predictive skill of a model relative to the mean of observations. The NSE is a metric that ranges from -∞ to 1, providing a measure of how well the model captures the observed variability in comparison to a simple mean.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_i-y_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{7.6}$$

In this context, where the number of observations is denoted by *n*, *x* and *y* represent the observed and simulated datasets, and $\bar{x}$ and $\bar{y}$ denote the means of *x* and *y* scores. The Nash-Sutcliffe Efficiency (NSE) is calculated as per the formula. Here, a higher NSE value (positively oriented) indicates a stronger correlation between the observed *x* and simulated *y* datasets.

7.3 RESULTS AND DISCUSSIONS

The neural networks are trained at the sub-indices scale using predictor and predictand datasets. Employing a trial-and-error approach, the initial setup includes the Levenberg-Marquardt algorithm for training (Levenberg, 1944; Marquardt, 1963), a learning rate of 0.05, 1000 epochs, and the Mean Squared Error (MSE) as the cost function. The training process concludes either when the MSE drops below 0.001 or after 1000 iterations. Upon meeting the termination criteria, the final model parameters and predictive performance are documented. The range of hidden layers is set from 1 to 2, with the number of neurons in each hidden layer varying from 3 to 15. Throughout the training and testing periods, the developed MLP model consistently achieves high accuracy. The observed training and testing data for parameters such as

Illumination, Temperature, and Acoustics are depicted in Figure 7.3. while CCI datasets are illustrated in Figure 7.4. The reconstructed values for the test data are highlighted in red in Figure 7.5 & Figure 7.6 for both parameter indices and CCI, respectively.

The comparison involves assessing the magnitudes and spatial patterns of two commonly used metrics, NSE and r, derived from both observed and modeled CCI during the testing period.

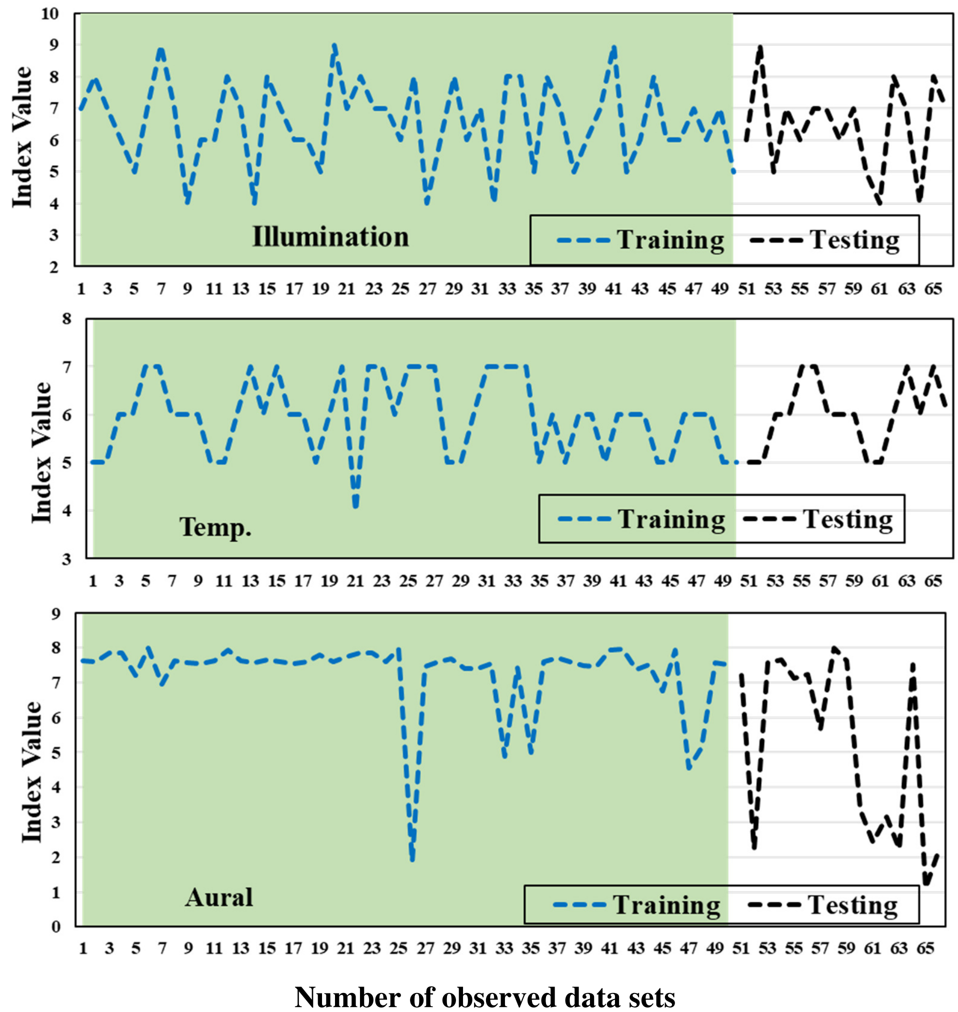


Figure 7.3 The observed training (blue line) and testing (black line) data of the parameters Illumination, Temperature and Acoustics

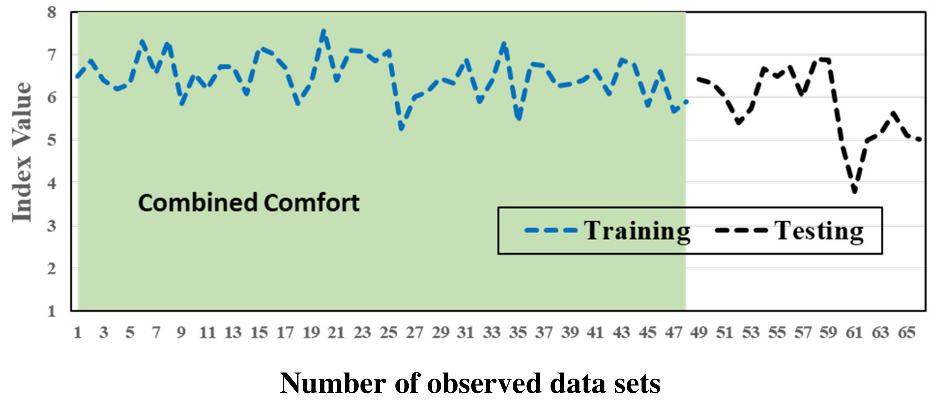


Figure 7.4 The observed CCI training (green line) and testing (black line) data.

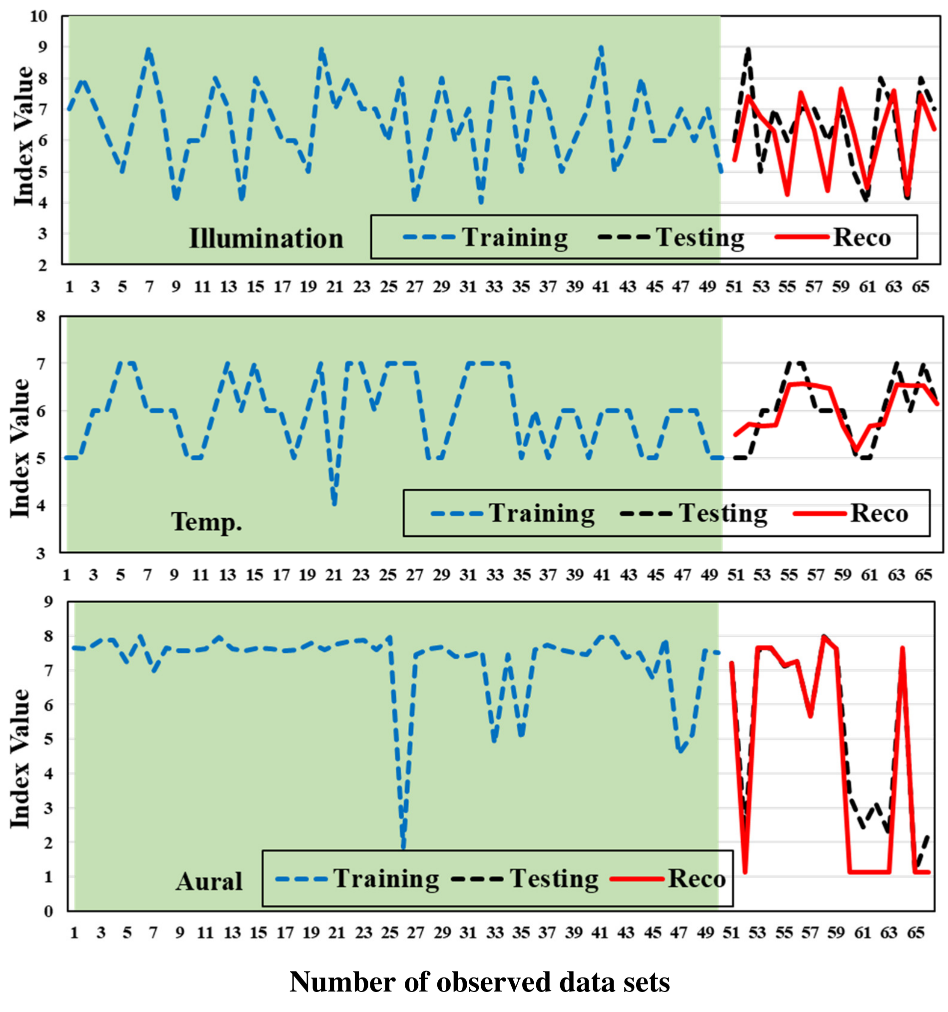


Figure 7.5 The reconstructed parametric data (red line) for the testing data of the parameters Illumination, Temperature and Acoustics

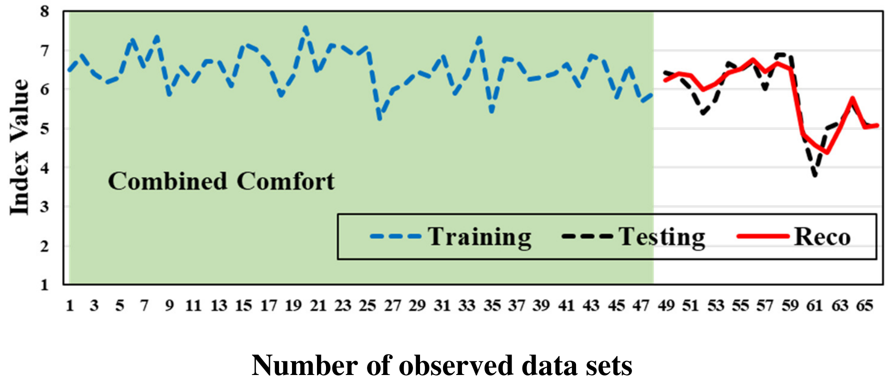


Figure 7.6 The Reconstructed CCI (red line) of the test data

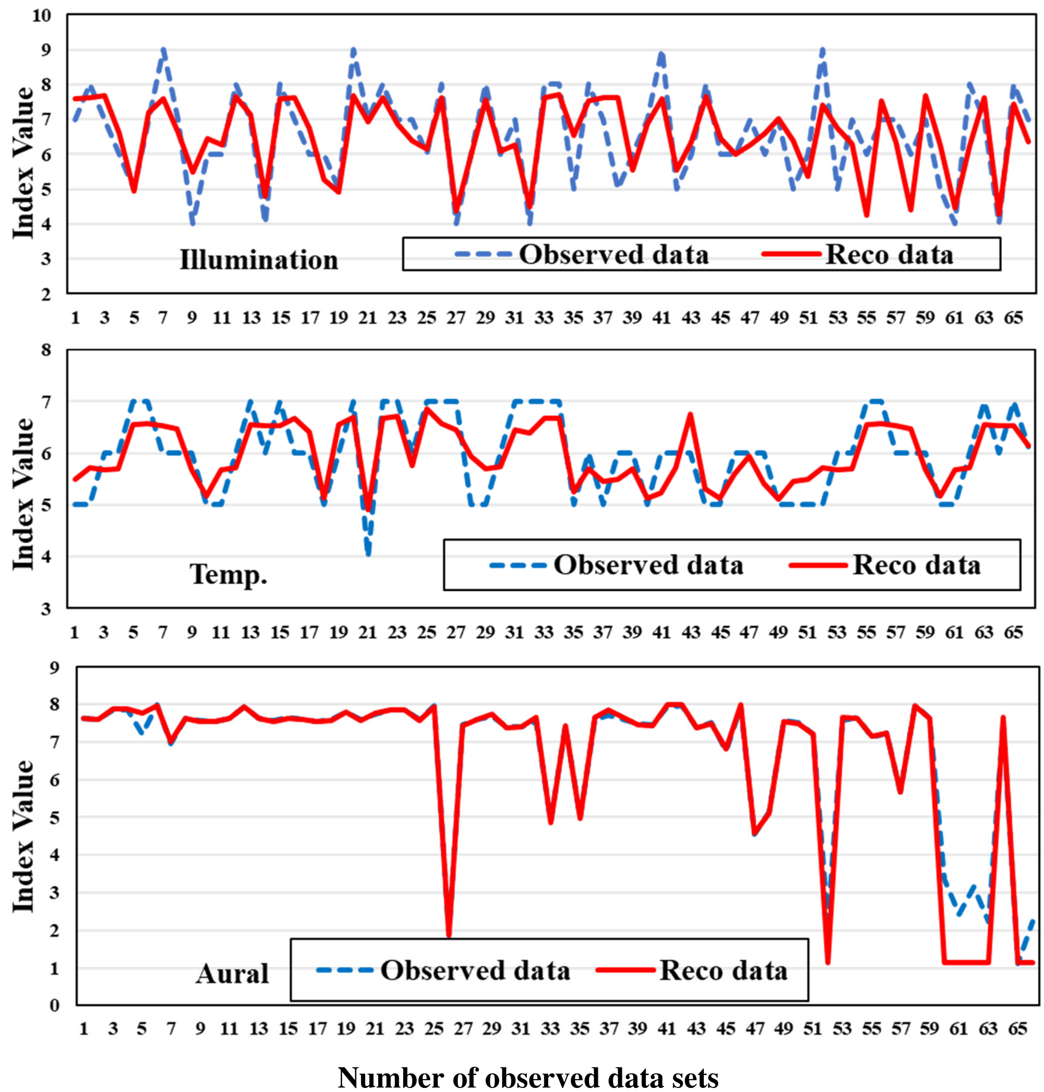


Figure 7.7 The observed parametric data (blue line) Vs MLP reconstructed data (red line)

The implemented MLP model successfully reconstructs complete datasets, demonstrating a notable alignment with observed data. Figure 7.7 illustrates the reconstructed values for parametric indices alongside the observed values, while Figure 7.8 presents the reconstructed CCI values.

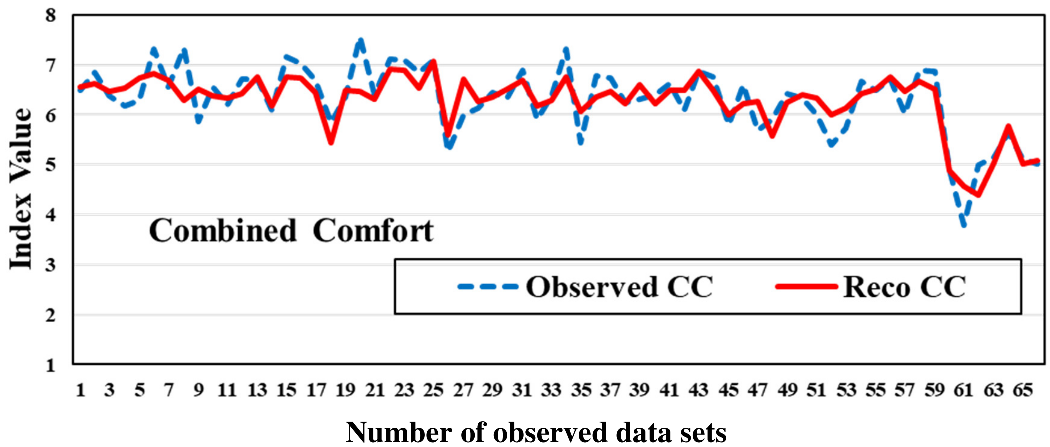


Figure 7.8 The observed CCI data (blue line) Vs MLP model based reconstructed data (red line)

The significant alignment between reconstructed and observed values validates the efficacy of the developed methodology for estimating indoor environmental conditions. This underscores the contribution of the research towards advancing the monitoring and control of indoor environmental quality in a building.

Performance Metrics

A performance metric serves as a measurable gauge to evaluate how well simulated data mirrors observed data. Notably, a high level of performance metric values is observed, with NSE values consistently exceeding 0.6 and r values surpassing 0.8 for the majority of parameters.

Table 7.1 Performance metrics

Parameters	**SSD**	**MSD**	**RMSD**	**CC**	**NSE**	**R^2**
VI	47.21	0.72	0.85	0.77	0.59	0.60
TI	14.15	0.21	0.46	0.81	0.65	0.66
AI	14.80	0.22	0.47	0.99	0.93	0.97
CCI	10.43	0.16	0.40	0.82	0.67	0.67

The visual index exhibits lower NSE and CC values, while the acoustical index demonstrates higher NSE and CC values, exceeding 0.9. The findings underscore the robust performance of the developed MLP model across all parameters (refer to Table 7.1**Error! Reference source not found.**). Here, in the deviation/error category, abbreviations such as Sum of Squares of Deviation (SSD), Mean Square Deviation (MSD), Root Mean Square Deviation (RMSD) are utilized. Additionally, performance metrics such as Pearson Correlation Coefficient (CC), Nash–Sutcliffe Efficiency (NSE), and R^2 are employed for assessment.

7.4 CONCLUSION

The Multilayer Perceptron (MLP) model, tailored for each parameter index, has demonstrated commendable performance in both reconstructing and predicting the overall indoor comfort. The modelled data, generated by the MLP, exhibits a high level of correlation, with correlation coefficients ranging between 0.77 and 0.99. Notably, the Illumination parameter stands out for its particularly strong correlations compared to other parameters. In terms of accuracy assessment, the model showcases a maximum relative error of around 14% and a minimum of 1%, falling well within the acceptable range for simulation-based modelling. This accuracy lends credibility to the precision of the developed Artificial Neural Network with Multilayer Perceptron (ANN-MLP) model in predicting indoor comfort conditions.

The refined ANN-MLP model emerges as a valuable tool for architects and facility managers, offering a means to design and maintain indoor environments that are not only comfortable but also stimulating. The high correlations observed, ranging from 0.77 to 0.99, underscore the model's accuracy and reliability. This implies that the MLP model can be relied upon as a robust predictive tool, empowering professionals in the field to make informed decisions for creating optimal indoor spaces.

CHAPTER 8

CONCLUSIONS

This Chapter is organized as follows: Section 8.1 summarises the thesis. Section 8.2 presents the overall conclusions of the study. Section 8.3 describes the research contributions. Section 8.4 Limitations of the study and section 8.5 describes the future scope of the work.

8.1 SUMMARY OF THE THESIS

A comprehensive study of this thesis is divided into four phases, employing sophisticated methodologies to assess the indoor comfort of a specific case study building. In Phase – I, Key Performance Indicators (KPIs) are meticulously tailored using the Fuzzy Analytical Hierarchy Process (FAHP) based on stakeholders' perceptions. The study categorizes indicators, conducts a reliable questionnaire survey, and ranks them, revealing crucial factors influencing overall comfort. Phase – II introduces the Combined Comfort Index (CCI) and extends the analysis to the entire building. Specific areas are identified as conducive to comfort, and room comfort variations are explored, with notable trends based on location. The study evaluates acoustic and illumination comfort, introduces optimal design choices, and assesses stakeholder awareness of advanced design methods. Energy-saving considerations delve into the impact of building orientation, material combinations, Window-to-Wall Ratio (WWR), and special building shapes. The thesis introduces the Artificial Neural Network-Multilayer Perceptron (ANN-MLP) model, demonstrating its commendable performance in predicting the CCI. The dominance of the Acoustic Index (AI) is highlighted, and the model's error ranges fall within acceptable limits. In essence, the thesis provides a holistic understanding of factors influencing indoor comfort, offering practical design recommendations for energy efficiency and occupant well-being. It establishes a reliable methodology for future studies in similar domains, contributing valuable insights to the field of building performance assessment.

The novelty in this thesis lies in several key aspects:

1. **Tailored Key Performance Indicators (KPIs)**: The use of the Fuzzy Analytical Hierarchy Process (FAHP) to customize KPIs based on stakeholder perceptions is innovative. This approach ensures that the indicators used to assess indoor comfort are finely tuned to the specific context of the case study building.

2. **Combined Comfort Index (CCI)**: The introduction of the CCI as a comprehensive metric for indoor comfort assessment is novel. This index allows for a holistic evaluation of comfort levels across different areas of the building, providing insights into overall comfort performance.
3. **Application of ANN-MLP Model**: The use of the Artificial Neural Network-Multilayer Perceptron (ANN-MLP) model for predicting the CCI demonstrates an innovative approach to indoor comfort assessment. The model's ability to accurately predict the CCI highlights its potential as a valuable tool for building performance assessment.
4. **Energy-saving Considerations**: The study's focus on energy-saving considerations, including the impact of building orientation, material combinations, Window-to-Wall Ratio (WWR), and special building shapes, showcases a comprehensive approach to building design that integrates comfort and energy efficiency.
5. **Practical Design Recommendations**: The thesis goes beyond theoretical analysis to provide practical design recommendations for improving energy efficiency and occupant well-being. This practical focus adds value to the study by offering actionable insights for architects and designers.
6. **Reliable Methodology**: By establishing a reliable methodology for future studies in similar domains, the thesis contributes to the field of building performance assessment. This methodology can serve as a benchmark for future research, ensuring rigor and consistency in indoor comfort assessment.

8.2 OVERALL CONCLUSIONS

In our pursuit to deepen understanding of indoor comfort and building performance, this study crafted tailored Performance Indicators, ensured data reliability through a comprehensive survey, and highlighted the crucial role of "Thermal condition" using FAHP. The introduction of the Combined Comfort Index (CCI) offered a comprehensive measure, revealing a favourable rating building. Room comfort analysis and the selection of optimal design choices, are the key insights. Additionally, the developed ANN-MLP model showcased precision in predicting the CCI, offering architects and facility managers a valuable tool. In summary, these findings contribute essential insights for designing energy-efficient and occupant-friendly buildings, supported by a versatile methodology. The following concise conclusions encapsulate the key findings and contributions:

- The initial phase of this work established eighteen performance indicators as the foundational framework for a comprehensive assessment of various factors in the case study building. Ensuring reliability, a questionnaire survey generated robust and trustworthy data, with a high reliability score exceeding 0.8, forming the basis for subsequent analyses. Additionally, the classification of performance indicators into four distinct domains, excluding economic considerations, enhances clarity and coherence, facilitating a structured examination of the building's performance. The subsequent application of the sophisticated Fuzzy-AHP methodology further revealed critical insights, ranking Thermal condition as the highest, followed by Lighting quality and Acoustic quality, providing valuable information on factors influencing overall comfort within the building.
- The introduction of the Combined Comfort Index (CCI) emerges as a novel metric integrating fundamental parameters, providing a comprehensive assessment of comfort within the investigated space. The 1.8K hostel building achieves a CCI of 0.65, indicating favourable conditions on the higher floors of Block A and the lower floors of Block B for illumination, acoustic quality, and thermal comfort. A detailed room comfort analysis reveals significant variations among different rooms, with Rooms R3 and R2 displaying notably higher comfort levels based on the Combined Comfort indicator. Interestingly, a discernible trend based on room location suggests that east-side rooms at higher levels and west-side rooms at lower levels generally provide more comfortable conditions. Further examination of acoustic and illumination comfort highlights Room R1's excellence in acoustical comfort (AI: 0.68) but relatively lower Illumination Index (VI: 0.56). Room R5 achieves a neutral comfort rating (AI: 0.59), while lower-level east-side rooms exhibit better comfort. The application of CCI to the entire building yields a comfort rating of 0.65, indicating overall comfort. Correlation findings between mean votes assigned to rooms and CCI, for both Specific Question (S.Q) and Overall Question (O.Q) metrics, reveal substantial R-squared values of 0.7 and 0.8, respectively, underscoring the effectiveness of the composite thermal, acoustic, and visual comfort indicator formulation in the study.
- In the realm of design selection, Model 1 and Option 2 emerge as the optimal choices among the three models for Case Study Building 1 and 2, respectively. Moreover, the study sheds light on stakeholder awareness, indicating that 65.4% are cognizant of the

use of BIM and computational design to address early design stage challenges, while 32% lack awareness of these innovative methods.

- The significance of building orientation is underscored by the minimal error of 2.65% in the annual electricity consumption comparison, affirming the reliability of the simulation approach. Noteworthy energy savings are revealed as changes in orientation lead to a 1.66% reduction when oriented 150 degrees clockwise and a 3% increase at 30 degrees anticlockwise. Specific material combinations, such as adobe masonry walls, mud floors, and roofing in the building oriented 150 degrees clockwise, result in a substantial 24.75% reduction in annual electricity consumption. Impactful variations are observed among 96 material combinations, with Combination 48 (adobe brick masonry, mud roof and mud floor) emerging as the most energy-efficient, demanding 29,496 kWh annually, while Combination 49 (CMU block masonry, RCC roof and RCC floor) consumes the most at 32,440 kWh. A reduction in firebrick thickness from 350mm to 220mm increases energy demand by 754 kWh. The Window-to-Wall Ratio (WWR) proves influential, with an increase from 10% to 60% resulting in a demand spike of 24,526 kWh. Notably, the butterfly architecture of the 1.8K hostel maximizes sunlight use, with the existing building orientation yielding the most favourable annual energy demand of 42,82,402 kWh, while a 90-degree rotation increases it to 42,99,536 kWh.
- The performance evaluation of the developed ANN-MLP model for each parameter index showcases commendable capabilities in both reconstructing and predicting the Combined Comfort Index (CCI). The model demonstrates a high degree of correlation, with coefficients ranging between 0.77 and 0.99, indicating a strong alignment between predictions and actual observations, thereby emphasizing its reliability in assessing indoor comfort conditions. Notably, among various parameters, the Acoustic Index (AI) stands out with the highest correlations, underscoring its significance in determining overall indoor comfort and highlighting the model's precision in capturing this crucial factor. The model's error range, with a maximum relative error of approximately 14% and a minimum of 1%, falls well within acceptable limits for simulation-based modelling, affirming the robustness and accuracy of the developed model.

In essence, the comprehensive study provides a thorough understanding of the factors influencing indoor comfort within the context of the case study building. It not only offers practical design recommendations for energy efficiency and occupant well-being but also establishes a reliable methodology for future studies in similar domains.

8.3 RESEARCH CONTRIBUTIONS

In the pursuit of advancing our understanding of indoor comfort and building performance, this study makes significant contributions through a multifaceted approach. The following research contributions underscore the novel insights and innovations derived from this comprehensive investigation:

- Through literature and analysis, this study has crafted a comprehensive set of Performance Indicators tailored to effectively evaluate the performance of Institutional buildings.
- This research introduces a holistic approach to assessing environmental comfort by integrating thermal, acoustic and illumination conditions, providing a comprehensive understanding of comfort factors.
- The study proposes a novel metric, the CCI, which unifies multiple comfort parameters, offering a single, easily interpretable measure of overall comfort within a space.
- The work leverages BIM software and energy evaluation tools to explore the impact of building orientation, material combinations and WWR on energy consumption, contributing to more energy-efficient building designs.
- Developed an accurate ANN-MLP model for indoor comfort prediction offers architects and facility managers a valuable tool for creating and maintaining comfortable indoor environments.

These contributions collectively advance the knowledge frontier in the field of building performance assessment, providing practical tools and insights for architects, designers, and facility managers striving to create environments that prioritize occupant comfort and energy efficiency.

8.4 LIMITATIONS OF THE STUDY

While the study provides valuable insights into indoor comfort and building performance assessment, it is essential to acknowledge certain limitations that may impact the interpretation and generalization of the findings:

- Economic considerations and indoor air quality have been omitted from the analysis, given the context of the case study building within a large university. These factors are deemed to have minimal influence on the outcomes, potentially limiting a holistic understanding of building performance. Subsequent research endeavours could explore the incorporation of economic factors to enhance the overall comprehensiveness of the evaluation.
- The organization and layout of spaces to enhance easy movement, functionality, and a feeling of openness, and the design and arrangement of furniture and other elements within a space to maximize comfort and encourage healthy postures are omitted in achieving building comfort, which couldn't affect the results of the present study. However, it's important to note that these aspects might be crucial parameters for different types of buildings, especially in diverse geographical locations.
- The study highlights optimal design choices and material combinations based on specific parameters, emphasizing the need to consider their sensitivity to changes in external factors or evolving construction technologies. However, the exploration of human behaviour factors impacting indoor comfort, beyond physical parameters like thermal conditions and lighting, is limited in the study. Further research could delve into the substantial influence of occupant behaviour and preferences on building comfort.

Understanding these limitations is crucial for interpreting the study's findings appropriately and for guiding future research efforts in refining methodologies and addressing potential constraints.

8.5. FUTURE SCOPE OF THE WORK

The future scope of the work involves several avenues for exploration and enhancement:

- Explore the refinement and expansion of comfort metrics, potentially incorporating additional parameters such as indoor air quality and ergonomic factors to create even more comprehensive comfort indices.
- Investigate the integration of smart technologies, such as IoT sensors and automation systems, to continuously monitor and adjust indoor environmental conditions in real-time for optimal comfort and energy efficiency.

- Conduct longitudinal studies to assess the long-term effects of comfort parameters on occupants' health, well-being and productivity in educational buildings, providing insights into the sustainability of comfort-enhancing interventions.
- Comparative studies across diverse geographical locations and building types can provide valuable insights into how building performance and comfort parameters vary in different contexts, informing more universally applicable design principles.
- Conducting a more extended monitoring period and considering seasonal variations can offer a more nuanced understanding of indoor comfort conditions, ensuring the robustness of findings across different times of the year.

By exploring these future avenues, the work can contribute to a more comprehensive and adaptable framework for designing buildings that prioritize both comfort and sustainability.

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RESEARCH PUBLICATIONS

Journals

1) Yarramsetty, S., Rohullah, M. S., Sivakumar, M. V. N., & Anand Raj, P. (2019). An investigation on energy consumption in residential building with different orientation: a BIM approach. Asian Journal of Civil Engineering. https://doi.org/10.1007/s42107-019-00189-z

2) Yarramsetty, subbarao., MVN, Sivakumar., & P, Anand Raj. (2023). Enhancing Comfort in Tropical Institutional Buildings: Integrating Thermal, Acoustic and Visual Performance with a Unified Index. International Journal of Engineering. https://www.ije.ir/article_177745.html

3) Yarramsetty, S., Sivakumar, M. V. N., & Anand Raj, P. (2023). An Integrated Approach to Building Planning Using the Multi-Criteria Decision Method (MCDM) and BIM. International Journal of Sustainable Construction Engineering and Technology.

Book Chapters

1) Yarramsetty, S., Sivakumar, M. V. N., & Anand Raj, P. (2021). Reduction of Annual Energy Consumption of Multifamily Dwellings Using BIM and Simulation Tools. RILEM Bookseries, 29, 285–297. https://doi.org/10.1007/978-3-030-51485-3_19

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5) Subbarao, Y., Sivakumar, M. V. N., & Anand Raj, P. (2017). Recent Developments in Life Cycle Assessment and Service Life Prediction: A Review. Urbanization Challenges in Emerging Economies, 509–520. https://doi.org/10.1061/9780784482032.052

BRIEF CURRICULUM VITAE

Mr. Yarramsetty Subbarao is a full-time research scholar in the Department of Civil Engineering, National Institute of Technology, Warangal-506004, India. He has received his undergraduate degree in Civil Engineering from Institute of Engineer's India (IEI), Kolkata and postgraduate degree in Building Technology and Construction Management from Indian Institute of Technology Madras, Chennai, Tamil Nadu. He has 10 years industrial work experience which includes some of multinational companies like Johns Lang Lasalle (JLL), Banglore. TATA Consulting Engineers Ltd (TCE). Jamshedpur, Jharkhand., Paharpur Cooling Towers Ltd (PCTL). And national company Visual Architects. Guntur. He has 9 years of teaching experience includes working with Maharshi Dayanand University (MDU), Rohtak, Haryana. KL University (KLU), Vaddeswaram, Guntur, Andhra Pradesh, Vasireddy Ventatadhri Institute of Technology (VVIT), Nambur, Guntur, Andhra Pradesh. Chalapathi Institute of Engineering and Technology (CIET), Lam, Guntur, Andhra Pradesh. His research interests are in the areas of building durability variations with environmental implications, combined comfort considering thermal, acoustical and illumination parameters and energy conservation methods. During his doctoral research, he has published 10 papers in International peer-reviewed journals and conferences.

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