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An Innovative Predictive Model for Indoor Thermal Comfort Condition of Residential Buildings to Mitigate Urban Warming: Case Study Kolkata, India

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ABSTRACT

The thermal comfort of building interior is one of the most important components of its thermal performance. The reliance of a building on artificial conditioning depends primarily on its inner comfort conditions. In recent times, this higher reliance of buildings on artificial ventilation and air conditioning has led to firstly, the creation of the heat island effect within cities, and secondly, the continuous warming of urban centers (particularly metropolises) with respect to the region and the hinterland to which they belong. The aim of this research is to investigate the relationship between the indoor thermal condition of old and new buildings to the contributing factors and to develop an innovative predictive numerical model to design buildings ensuring better indoor thermal comfort conditions. To date, no such composite predictive model has been innovated, although a considerable amount of work has been done on the factors separately. Considering the global urban warming since 1970 this research has sampled an equal number of residences from "Old Buildings" built before 1947 CE and "New Buildings" built after 1970 CE. This study is based on a composite analysis of the thermal performances of sample buildings against the physical factors influencing thermal performance—initially through examination of correlation and thereafter by developing a set of innovative numerical predictive models between indoor thermal conditions and their contributing parameters. This new numerical model shows a 55% curve-fitting on the thermal comfort index used.

Keywords: Urban warming; Heat island mitigation; Thermal comfort; Heat index; Residential building; Predictive model

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1. Introduction

Buildings provide a protective enclosure for their inhabitants. Due to the varied climates in each region, the houses built there also differ in their design, material, orientation, and orientation to adapt to the local climate. Vernacular architecture developed at different places throughout history has played this role extremely well by providing an insulated indoor environment. On the other hand, since the development of mechanical air-conditioning, buildings have become increasingly dependent on HVAC systems to maintain artificial comfort conditions [1]. In order to study the indoor thermal condition of a building, all built masses can therefore be divided into two categories—conditioned and non-conditioned [2].

Since the last few decades, a global warming of 1.09 degree centigrade has been observed all over the globe [3]. This phenomenon has become observed more intensely in the urban areas where the heat effect has concentrated within smaller areas of the city creating the Urban Warming effect as coined by IPCC. According to the data sheet of 2018 published by IPCC [4], an urban warming of 2.6 degree centigrade is observed for the city of Kolkata, which also happens to be the highest among all cities globally. The built mass of a city contributes to the major share of this warming, and for the city of Kolkata, 73% of this built mass belongs to the residential buildings [5].

The urban heat island phenomenon, which serves as a trap for atmospheric pollutants, deteriorates the quality of life and has a socio-economic impact in the urbanized areas [6–9]. In urban areas, too much reliance on mechanical HVAC systems may harm the environment in two ways: first, CFC gases are released into the air, depleting the ozone layer, and second, buildings that are poorly designed and heated up can lose their internal heat into their external environment, contributing to the growth of urban heat islands [10].

The Urban Heat Island (UHI) is a common phenomenon whereby urban/developed areas experience higher air temperatures (in and above) than undeveloped/rural surroundings [11–14]. The annual mean air temperature of a city with one million or more people can be 1 to 3degree centigrade warmer than its surroundings, and on a clear, calm night, this temperature difference can be as much as 12 degree centigrade [14]. Santamouris [15] has observed in a study of 101 Asian and Australian cities that UHI magnitude can vary from 0.5 to 11 degree centigrade with an average of 4 degree centigrade. Mohan et al. observe that the UHI magnitude can even intensify to a magnitude of 4 to 8 degree centigrade in dense and compact urban areas [16].

A primary objective of the Ministry of Urban Development's Smart City Mission, launched in 2015, is to promote sustainable development and green building. Sustainable Environment is the eighth of the ten Core Infrastructure Elements discussed in Article 2.4 of the Smart City Mission document [17]. The document also includes "Energy Efficient and Green Building" as one of its twenty-one Smart Solutions proposed under Article 2.5. As a result, architects and planners alike have a responsibility to take all feasible steps toward a sustainable built environment.

As per the IPCC Intergovernmental Panel on Climate Change—Sixth Assessment Report—Regional Fact Sheet—Urban Areas [4], the three main factors that contribute to amplifying the warming of urban areas are:

(i) Urban geometry
(ii) Human activities
(iii) Construction materials

The three above thrust areas also corroborate with the indoor thermal condition and thermal performances of a building and thus influence the thermal comfort of a built environment.

The literature study of this research shows that works on the comparison of thermal performance after classifying buildings according to their age have been done in various parts of India. A number of researchers have also assessed the thermal comfort offered by the residential buildings in Kolkata, among whom some have also classified residential buildings by age into old and new groups before comparing their thermal performance.

However, these researchers have not attempted to establish any conclusive numerical model that first takes into account the combined contribution of various architectural parameters to the thermal comfort of a residence, and finally uses the same to forecast the probable thermal comfort that a designed building can achieve. This research therefore takes this as its aim in order to identify a way to make new buildings in Kolkata more thermally efficient.

1.1 Aim of the research

To improve the design approach and methodology of the residential buildings of Kolkata by imbibing the traditional knowledge system of the old indigenous traditional building design and construction of the city.

1.2 Objectives of the research

Several objectives are formed in order to achieve the said aim:

(i) To identify the old and the new buildings for the purpose of comparison of their thermal comfort.

(ii) To identify suitable indices for the purpose of this comparison of thermal comfort.

(iii) To ascertain the degree of association between the indoor thermal condition of old as well as new buildings with the physical factors affecting thermal condition.

(iv) To explore and establish the composite relationship between indoor thermal conditions with the influencing factors.

2. Theoretical framework

Thermal comfort is dependent on the "condition of equilibrium" in a person's thermal balance, according to Szokolay [18]. According to ANSI ASHRAE Standard 55-2013 [19], thermal comfort is "the state of mind expressed by satisfaction with the thermal environment". In his research, Hansen [20] defined it as "a state of no driving impulse towards correcting the environment".

Thermal comfort assessment is based on two models according to de Dear et.al. [21]. Fanger [22] developed the first model based on predicted mean value (PMV) and predicated percent dissatisfaction (PDD). ISO standards from 1984 and 2005 and ASHRAE Standard 55-2013 adopted these indices. A second model, proposed by Humphreys [23] and Nicol [24], is the Adaptive Comfort Model.

The factors that contribute to thermal comfort are categorized under three categories by Szokolay [18]: the Environmental Factors, the Personal Factors, and the Contributing Factors. A number of pioneers have endorsed these or other similar factors, including Fanger [22], Humphreys [23], Nicol [24], Olgyay [25], and Koenigsberger et al. [26]. According to Djongyang et al. [27], thermal comfort is primarily a subjective model that takes into account both objective environmental factors and subjective human perception factors. In their review of previous thermal comfort research, Djongyang et al. [27] and de Dear et al. [21] highlight the dependence of models and indices on how humans perceive and react to objective environmental factors.

2.1 Literature review

Considerable amount of work has been done to assess and compare the thermal comfort of residential buildings in Kolkata, a city located in a tropical wet and dry climate zone. In spite of this, Pellegrino et al. [1] have raised the question of whether the climate responsiveness of residential buildings in India has received sufficient research. According to them, non-residential building types dominated research in this field until the turn of the 21st century. UNHABITAT [28] also confirms the same:

> *"Sustainable architecture in tropical climates is still an unexplored field, and it is an extraordinary challenge for architects, who should be willing to integrate basic information about building physics and aesthetics, and to abandon the approach, (now old and out-dated) which imitates the architecture of developed countries." (pp. 9)*

An inventory of heritage residential buildings or "the great houses of Calcutta" was conducted by Taylor et al. [29] in their book. This comprehensive work not only inventoried and documented selective heritage residences of the city, but also introspected how the residential architecture of Calcutta evolved by amalgamation of architectonic and climatic inputs from all its pre-cursor styles. In another work by Bose [30], a similar detailed inventory was prepared and compared that reveals the unique architectonic and constructional features of old residential buildings of Kolkata. Similarly, Bose [31] worked on the detailed inventory of residences of the Chitpore area of Kolkata, one of the oldest districts in the city. Pellegrino, et al. [32] compared bioclimatic features and thermal comfort between heritage and modern buildings in Kolkata. Taking into consideration the design and construction approaches of old buildings, Bose and Sarkar [33] developed a sustainable approach for making the top floors of modern buildings more thermally comfortable. Using Kolkata as a focus, Pellegrino et al. [34] sought to improve thermal comfort within Indian homes.

Comparative studies have also been conducted in other parts of India that have the same climatic zone. In the southern peninsular region of India, significant work has been conducted. As part of their study on Tamil Nadu vernacular architecture and climate responsiveness, Radhakrishnan et al. [35] analyzed detailed information on its adaptability to the climate. Similarly, Madhumathi et al. [36] examined the indoor thermal comfort of traditional rural Tamil Nadu houses in order to examine their sustainability. A comparative study of the thermal performance of traditional and modern buildings in Tamil Nadu was conducted by Shanti Priya et al. [37]. There were considerably fewer samples and sampling areas were not necessarily urban in nature, despite the fact that traditional buildings performed better. A study by Subramanian et al. [38] compared traditional buildings of more than a century to modern residential buildings of less than twenty years of age and found that traditional houses offer both subjectively (resident feedback) and objectively (measurable indices) better indoor thermal comfort conditions.

In other regions of the world, researchers have also found similar results when comparing traditional architecture to modern architecture in similar climate zones. A study published in 2005 by Tablada et al. [39] examined naturally ventilated residences in a humid, warm environment of Cuba and compared their performance with Fanger's PMV model. The research of Mahar et al. [40] examines the modern residential buildings and, in particular, the unplanned and uncontrolled RCC frame structures of Quetta, Pakistan to determine that most of them fail to provide adequate thermal comfort for their occupants. Through measurements of energy consumption and thermal comfort, Benkaci and Benabbas [41] compare the performance of vernacular architecture with the contemporary architecture of Algeria.

A postgraduate dissertation by Rai [42] examined the traditional and contemporary architecture of Kathmandu, Nepal, and then used passive cooling features from the traditional architecture in a simulation approach. It does not, however, attempt to conduct any conclusive comparison between the thermal comfort of these two types of buildings before using the building features of old traditional buildings in the simulation.

All of the studies discussed above follow either the PDD/PMF or the ACT model as described by de Dear et al. [21]. Each of these two models involves objective, measurable data as well as subjective feedback based on perception. In an initial reconnaissance of old indigenous residential buildings in Kolkata, it was found that a substantial number of them were uninhabited. In this case, it would not be possible to collect subjective data from these buildings. This research therefore uses a composite index Heat Index (HI) proposed by the National Oceanic and Atmospheric Administration, Govt of USA.

2.2 Heat index (HI)

The heat index is a composite index that takes into consideration the ambient dry bulb temperature (DBT) and the relative humidity (RH) of a shaded area and combines them to give a measurement of the perceived temperature of that place.

Steadman in the year 1979 first proposed the concept of heat index in the research on the effect of sultriness on the effect of heating and proposed this index as a "temperature-humidity index" [43]. This research was further corroborated in a following paper by Steadman [44], which further considered the effect of wind and direct radiation on heat index.

Based on this work, the heat index was developed by the National Oceanic and Atmospheric Administration, Govt of USA [45] that would consider the DBT and RH and would assume a static condition of activity, clothing and wind velocity in a shaded space free from direct solar radiation [46].

The National Oceanic and Atmospheric Administration defines heat index as:

"The heat index, also known as the apparent temperature, is what the temperature feels like to the human body when relative humidity is combined with the air temperature." [47]

The Heat Index (HI) can be calculated using the Rothfusz Regression equation (1) prescribed by the Weather Prediction Centre of the NOAA [48].

$$\begin{aligned}HI = &-42.379 + 2.04901523t + 10.14333127r \\ &- 0.22475541tr - 0.00683783t^2 - 0.05481717r^2 \\ &+ 0.00122874t^2r + 0.00085282tr^2 - 0.00000199t^2r^2\end{aligned} \tag{1}$$

where,

HI = Heat Index (in degree Fahrenheit)

t = Ambient Dry Bulb Temperature ((in degree Fahrenheit)

r = Relative Humidity (percentage value between 0 and 100)

with the following adjustments:

$$HI_{rev} = HI + [(r - 85)/10] * [(87 - t)/5]$$

when, $r > 85\%$.

3. Research methodology

In the study, residential buildings are considered since they constitute the majority of Kolkata's built-up area. Only the non-conditioned, naturally ventilated housing stocks have been considered because their interior thermal condition is determined only by natural and design factors.

The residential buildings of Kolkata are categorized into three groups for this research:

(i) Buildings that are constructed before 1947 CE, i.e., the year of India's Independence from colonial British rule. These buildings have been considered in the research as "Old Buildings".

(ii) Buildings that are constructed from 1970 CE onwards till the current time. The datum of 1970 has been considered based on the Study of Critical Environmental Problems' report [50] that is considered as the basis of global warming consciousness. These buildings have been considered in the research as "New Buildings".

(iii) Buildings constructed between 1947 CE and 1970 CE. This group of buildings, constructed between 1947 and 1970, have not been considered because the design typology, construction methods, and construction materials have undergone significant changes in response to the social, political, and economic changes that have affected the World, India, and specifically Calcutta (or Kolkata as it is now known) and hence showcase a hybrid design approach [29].

3.1 Delineation of study region

An old rural settlement by the name of "*Kolikata*" existed from the medieval times and even found mention in the rent-roll of the Mughal emperor Akbar [49]. However, the city of Kolkata was established by the British East India Company in 1690. The European quarter of the city developed around the newly constructed Fort William and the immediate vicinity of Maidan (the central urban open ground that was created as a defensive buffer around the Fort).

The city of Kolkata is thus divided into three distinct parts, viz, the North, Central and the South. As Taylor and Lang [29] describe them, the "Great Houses", or ancient indigenous residences belonging to the Indian citizens of Kolkata, are primarily located in the North.

For the purpose of selecting sample residences for study, the city of Kolkata has been divided into three zones. These zones are delineated in the following regions (**Figure 1**):

- *The Northern City, or the Old Traditional City*, is the area between Mahatma Gandhi Road and Dumdum Road. To the east, Jessore Road follows CIT Road to Sealdah.
- *The Central or European Quarter* of the city is located between Mahatma Gandhi Road on the north and Acharya Jagadish Chandra Bose Road on the south. Acharya Prafulla Chandra Roy Road forms the eastern boundary of this area.
- *Southern or the Newer City*—AJC Bose Road, APC Roy Road, and Sealdah Station form the northern boundary of this area, while the South Suburban Railway track runs south of the Ballygunge area and Rabindra Sarovar Lake forms the southern boundary.

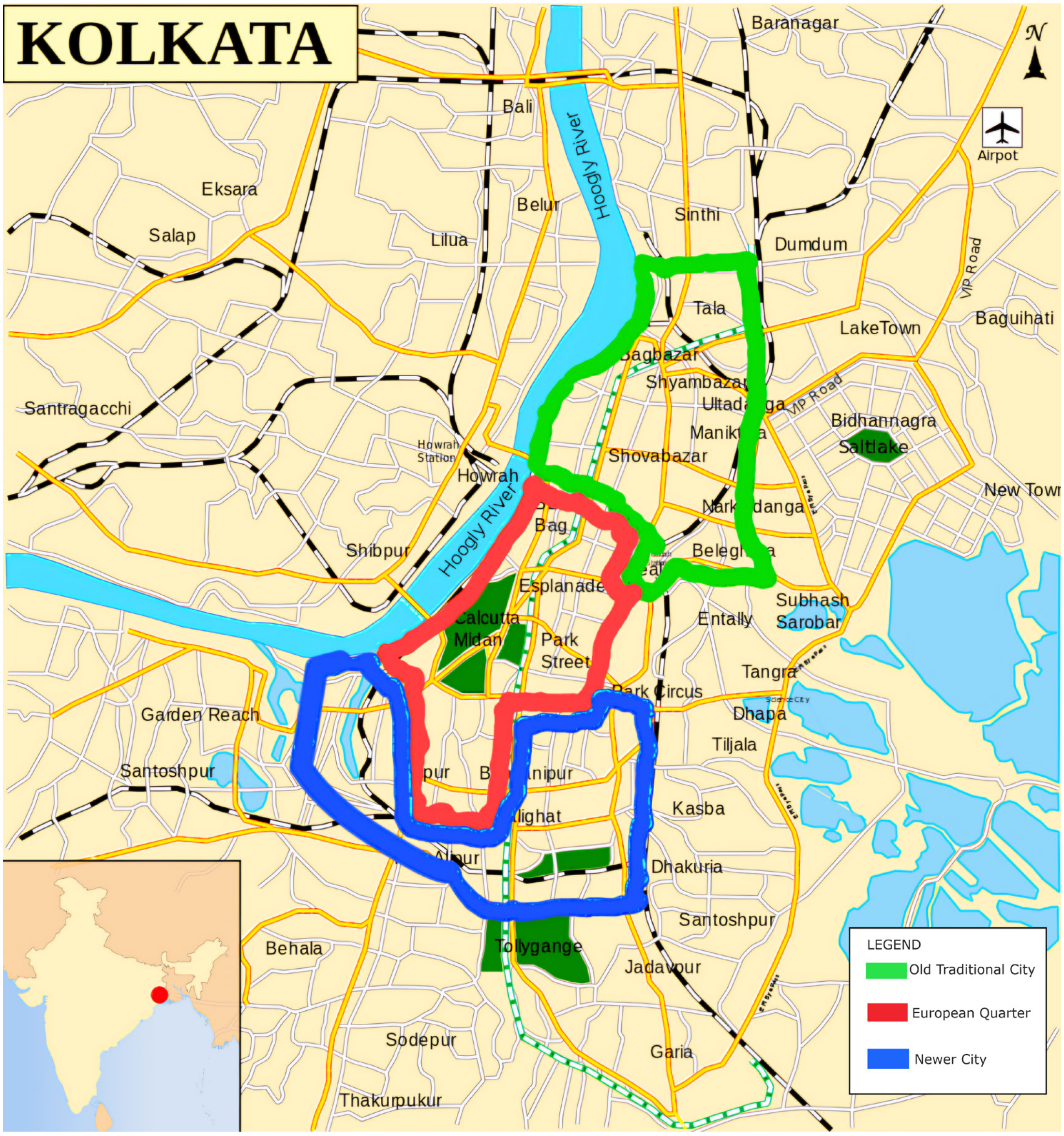

Figure 1. Map of Kolkata with delineation of research zones.

Source: Wikimapia Creative Commons.

3.2 Inventory of study buildings

The study buildings have been sampled from the Northern and the Southern part of the city as the Central part was the European colonial quarter which is beyond the scope of this research.

The building samples include ten numbers each of "Old" and "New" buildings. As shown in **Tables 1 and 2**, these buildings are listed with their locations within Kolkata as well as the year they were built. In order to protect the private information of the owners, the identities of these buildings have been masked.

The sampled old buildings show an average age of one hundred forty-eight (148) years, whereas that of the new buildings is twenty-one (21) years.

3.3 Study of buildings

Each building was studied, measured and drawn, and climatic data were recorded in the following manner:

Step 1: *Marking the location of the building:* In a static satellite image of Kolkata, taken from the Google Earth website, the location of the building is marked.

Step 2: *Recording of the architecture of the building:* A scaled drawing of the building is prepared at this stage. In order to measure distances, a HTC laser distance meter is used. All parts of the building are also photographed in detail.

Table 1. List of Old Buildings of Kolkata surveyed (arranged in chronological order).

Sl	Nomenclature	Area	Year of construction	Age (in years)
1	**Old Residence 1**	Pathuriaghata	1782	242
2	**Old Residence 2**	Pathuriaghata	1830	194
3	**Old Residence 3**	Khidirpur	1843	181
4	**Old Residence 4**	Shobhabazar	1860	164
5	**Old Residence 5**	Bagbazar	1876	148
6	**Old Residence 6**	Vivekananda Road	1895	129
7	**Old Residence 7**	Shobhabazar	1903	121
8	**Old Residence 8**	Gopal Neogi Lane	1906	118
9	**Old Residence 9**	Bagbazar	1920	104
10	**Old Residence 10**	Gariahat	1942	82
Average age of sampled Old Buildings in years				**148**

Table 2. List of New Buildings of Kolkata surveyed (arranged in chronological order).

Sl	Nomenclature	Area	Year of construction	Age (in years)
1	**New Residence 1**	Belgachhia Dutta Bagan	1984	40
2	**New Residence 2**	Lake Town	1992	32
3	**New Residence 3**	Lake Town	2000	24
4	**New Residence 4**	Lake Town	2000	24
5	**New Residence 5**	Dumdum	2000	24
6	**New Residence 6**	Khidirpur	2001	23
7	**New Residence 7**	Dumdum Motijheel	2007	17
8	**New Residence 8**	Lake Town	2013	11
9	**New Residence 9**	Bagbazar	2016	8
10	**New Residence 10**	Dumdum	2016	8
Average age of sampled Old Buildings in years				**21**

Step 3: *Recording of Indoor Climatic Data:* Data is collected using HTC data loggers for 48 hours in each building at 15-minute intervals—generating 192 temperature data per building for each day. With the exception of a few old buildings that are uninhabited, the data-logger is kept in a room that has a maximum or standard occupancy expectation throughout the day—a practice in compliance with ASHRAE 55 regulations [19]. They are kept on a table, stool, or un-enclosed horizontal surface that is not magnetic, non-heating, and does not have any nearby magnetic field, 0.6–1 m above the ground at a distance of 1 m from the nearest wall. A data-logger machine should be kept at least 1.0 m away from the center of any window on the nearest wall. Using HTC digital anemometers at 1.0 m above ground level, wind velocity data is recorded manually every three (3) hours.

Step 4: *Recording of Ambient Climatic Data:* Data on ambient temperature and relative humidity are collected every 15 minutes, using HTC data loggers, for 48 hours—resulting in 192 temperature records. A simultaneous set of ambient climatic data is recorded for every building. This data-logger is placed in shaded and ventilated outdoor areas. A HTC digital anemometer is used to manually record outdoor wind velocity data at a height of 1 m from the ground every three hours.

In some old buildings, different floors within the same building block exhibit significant differences in thermal performance. Thus, these floors are studied separately based on their thermal conditions. In this way, the Old Buildings group has fifteen samples, whereas the New Buildings group has only ten samples.

3.4 Physical attribute data within building inventory

Steadman [43,44] in the research on thermal comfort and heat index identifies almost twenty factors that affect the perception of sultriness and thermal comfort within a building interior that is free of direct solar exposure, many of which are subjective human-perception influencing factors. In the book on buildings sciences, Szokolay [18] identifies four design variables that affect thermal performance to the greatest extent—shape, fabric, fenestration, and ventilation. Simha [50] in the research on Thermal Comfort in India identifies that the design characteristics that influence indoor comfort are six in number—materials, orientation, fenestration, adjustable shading, cooling systems, and adequate controls. However, the factors identified by Simha include artificial comfort control mechanisms, and hence include conditioned buildings as well in the purview. Nayak and Prajapati [2] in their handbook divide the factors affecting thermal comfort into multiple groups, viz, design variables (including the form of building, the orientation of building, the envelope of building, and shading devices), material properties (including thermal conductivity, thermal resistance, thermal transmittance and density/porosity), climatic factors (includes solar radiation, humidity, pressure, and winds) and building occupancy and operations. Gupta and Chakraborty [51] in their work on traditional houses vis-a-vis thermal comfort identify five factors that affect thermal comfort—orientation of building, surface area versus volume ratio, ventilation, building materials, and extent of shading.

4. Comparative building attributive data

Considering various research and works on the domain, this research has identified the following building design attributes that are estimated to have maximum influence on the indoor thermal performance in the residential houses of Kolkata. These attributes have been categorized under two groups, viz, measure and computed as in **Figure 2**.

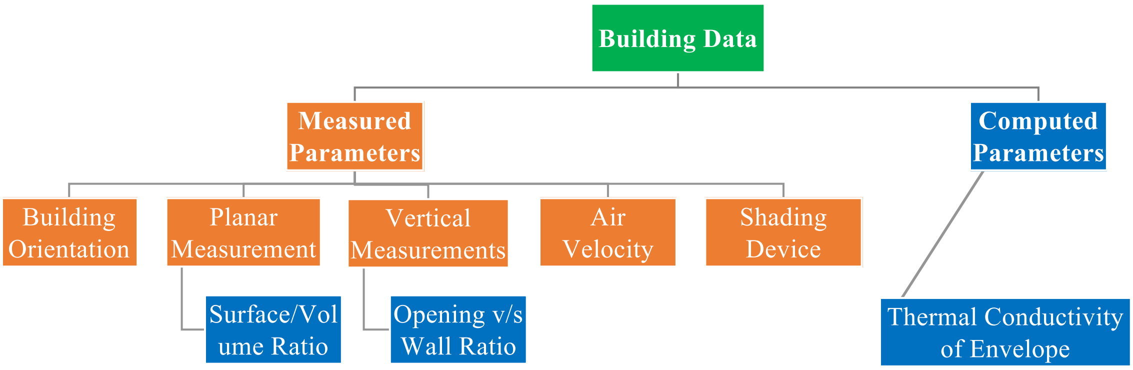

Figure 2. Flow chart showing building parameters.

A brief description of these attributes and a concise representation of the collected data are stated as follows:

4.1 Building orientation

Every other aspect remaining the same, the thermal performance of a building is affected by its orientation. This can be attributed to the difference of the incidence angle of the sun on the various surfaces of a building as caused by the change of orientation. Proper orientation of a building can contribute as a low cost thermal comfort intervention, resulting in a reduction in heating and cooling requirements of a building [52].

Nayak and Prajapati [2] in their work have classified the orientation of buildings in Warm and Humid climatic zones into four groups, and have also attached objective scaling/factors with each of these orientations based on their relative cooling load requirement (**Table 3**).

Table 3. Building orientations and their objective effect on thermal performances.

Orientation of building	*Objective scaling/factors*
Northwest-Southeast	1.00
North-South	0.88
Northeast-Southwest	0.85
East-West	0.96

Building orientations have been noted on site with the help of magnetic compass and satellite image of Google Map on android platform. Orientations have been marked following the practice adopted by Nayak and Prajapati [2] and are categorized in four (4) alignments. These data have been arranged separately for old (**Table 4**) and new (**Table 5**) buildings.

Table 4. Orientation factors of Old Buildings studied.

Serial No	Nomenclature	Orientation	Orientation Factor
1	**Old Residence 1**	Northeast-Southwest	0.85
2	**Old Residence 2**	Northeast-Southwest	0.85
3	**Old Residence 3**	East-West	0.96
4	**Old Residence 4**	Northeast-Southwest	0.85
5	**Old Residence 5**	Northeast-Southwest	0.85
6	**Old Residence 6**	North-South	0.88
7	**Old Residence 7**	Northeast-Southwest	0.85
8	**Old Residence 8**	Northeast-Southwest	0.85
9	**Old Residence 9**	Northeast-Southwest	0.85
10	**Old Residence 10**	East-West	0.96
Average of orientation factor for Old Buildings			**0.88**

Table 5. Orientation factors of New Buildings studied.

Serial No	Nomenclature	Orientation	Orientation factor
1	**New Residence 1**	East-West	0.96
2	**New Residence 2**	East-West	0.96
3	**New Residence 3**	East-West	0.96
4	**New Residence 4**	East-West	0.96
5	**New Residence 5**	North-South	0.88
6	**New Residence 6**	East-West	0.96
7	**New Residence 7**	North-South	0.88
8	**New Residence 8**	East-West	0.96
9	**New Residence 9**	Northwest-Southeast	1.0
10	**New Residence 10**	East-West	0.96
Average of orientation factor for Old Buildings			**0.95**

4.2 Thermal conductance (U value) of construction materials

This aspect takes care of two primary phenomena—(a) how much of the outside heat would be conveyed to the interior volume of air, and (b) what would be the resultant thermal lag inside the room. While the former influences the reaction of residents in the domain of the mechanical cooling process, the latter is mostly found to be responsible for the habitual occupational pattern of the indoor and outdoor spaces of a residence.

A survey of old and new buildings revealed that the former ones vary to some extent in terms of their material and method of construction. However, the latter ones do not vary much in material usage or thickness/dimension of members. Because of this variation, the thermal conductivity of the envelope had to be calculated right from scratch. In terms of the envelope, the study approach has taken into consideration the vertical planes, namely the walls and the horizontal planes, namely the slabs or roof separately. The material used and their thickness along the cross section of each composite member have been considered separately and then their material-based Conductivity (λ) has been calculated. The unit conductivity values have been consulted from Szokolay's "Data Sheet D.1.1: Thermal Properties of Materials" [18]. From this, the Resistivity ($R_{a\text{-}a}$) of the wall has been calculated as the summed-up value of all contributing conductivity values. The thermal conductance (U value) of the wall is finally calculated as the inverse function of resistivity [18]. These U values of different building envelopes are thus compared—separately for vertical and horizontal members (**Tables 6 and 7**).

4.3 Surface area to volume (S/V) ratio

This ratio corresponds to the compactness of the building. The larger the envelope engulfing a given volume of space, the more its exposure to the ambient air and incident sun. This ultimately results in the fact that the surface area versus volume ratio of a building becomes directly proportional to the absorption of heat from the ambient air.

Surface versus volume ratio is the first of the three derived parameters that have been computed based on the plan and height measurements. Data for old and new types of buildings are described below (**Tables 8 and 9**).

Table 6. Inventory of building materials and structural systems of Old Buildings and their computed U-values.

Sl. No	Official nomenclature	Building material - Wall	Building material - Slab	Structural system	Thickness of wall (in mm)	Thickness of slab above	Thermal conductance (U) of wall	Thermal conductance (U) of roof
1	**Old Residence 1**	1*	4*	A[#]	800	250	**1.57**	**3.4**
2	**Old Residence 2**	1*	4*	A[#]	800	250	**1.57**	**4.08**
2	**Old Residence 2**	1*	4*	A[#]	800	250	**1.57**	**3.26**
3	**Old Residence 3**	1*	4*	A[#]	600	250	**2.13**	**4.26**
3	**Old Residence 3**	1*	4*	A[#]	600	250	**2.13**	**3.52**
4	**Old Residence 4**	1*	5*	B[#]	600	150	**2.13**	**4.6**
5	**Old Residence 5**	1*	4*	A[#]	1000	300	**1.3**	**3.48**
5	**Old Residence 5**	1*	4*	A[#]	1000	300	**1.3**	**2.87**
6	**Old Residence 6**	2*	5*	B[#]	500	150	**2.59**	**5.42**
7	**Old Residence 7**	2*	4*	A[#]	600	150	**2.13**	**5**
8	**Old Residence 8**	2*	5*	B[#]	500	120	**2.48**	**5.01**
9	**Old Residence 9**	3*	4*	A[#]	400	150	**3.31**	**7.09**
9	**Old Residence 9**	3*	4*	A[#]	400	150	**3.31**	**7.09**
9	**Old Residence 9**	3*	4*	A[#]	400	200	**3.31**	**4.31**
10	**Old Residence 10**	3*	5*	C[#]	400	150	**3.31**	**5.42**
10	**Old Residence 10**	3*	5*	C[#]	400	200	**3.31**	**3.55**

Note: * *Material code: **1**: Brick with Lime Mortar and Plaster; **2**: Brick with Cement Mortar and Plaster; **3**: Brick Masonry; **4**: IPS on Steel Joist; **5**: RCC Slab.*

Structural system code: **A**: Load Bearing Structure; **B**: Load Bearing Wall with RCC Slab; **C**: RCC Frame Structure.

Table 7. Inventory of building materials and structural systems of New Buildings and their computed U-values.

Sl No	Official nomenclature	Building material - Wall	Building material - Slab	Structural system	Thickness of wall (in mm) (including plaster)	Thickness of slab above	Thermal conductance (U) of wall	Thermal conductance (U) of roof
1	**New Building 1**	2*	5*	C[#]	250	120	**5.18**	**8.83**
2	**New Building 2**	2*	5*	C[#]	250	125	**5.18**	**8.51**
3	**New Building 3**	2*	5*	C[#]	300	130	**4.26**	**8.22**
4	**New Building 4**	2*	5*	C[#]	300	130	**4.26**	**8.22**
5	**New Building 5**	2*	5*	C[#]	300	120	**4.59**	**8.83**
6	**New Building 6**	2*	5*	C[#]	250	100	**5.18**	**10.36**
7	**New Building 7**	2*	5*	C[#]	250	120	**5.18**	**8.83**
8	**New Building 8**	2*	5*	C[#]	225	110	**5.54**	**7.49**
9	**New Building 9**	2*	5*	C[#]	250	120	**5.18**	**7.04**
10	**New Building 10**	2*	5*	C[#]	250	100	**5.18**	**7.73**

Note: * *Material code: **1**: Brick with Lime Mortar and Plaster; **2**: Brick with Cement Mortar and Plaster; **3**: Brick Masonry; **4**: IPS on Steel Joist; **5**: RCC Slab.*

Structural system code: **A**: Load Bearing Structure; **B**: Load Bearing Wall with RCC Slab; **C**: RCC Frame Structure.

Table 8. Surface versus volume ratio of Old Buildings.

Serial No	Nomenclature	Volume (cu.m.)	Surface Area (sq.m)	Surface / Volume Ratio
1	**Old Residence 1**	9088.33	6741.55	**0.74**
2	**Old Residence 2**	11020.30	6798.06	**0.62**
3	**Old Residence 3**	1103.59	1447.16	**1.31**
4	**Old Residence 4**	1665.64	1324.68	**0.80**
5	**Old Residence 5**	39224.85	17836.61	**0.45**
6	**Old Residence 6**	1970.40	1690.00	**0.86**
7	**Old Residence 7**	3730.25	3802.87	**1.02**
8	**Old Residence 8**	714.04	988.25	**1.38**
9	**Old Residence 9**	754.95	911.00	**1.21**
10	**Old Residence 10**	2133.60	1286.80	**0.60**

Table 9. Surface versus volume ratio of New Buildings.

Serial No	Nomenclature	Volume (cu.m.)	Surface area (sq.m.)	Surface/Volume ratio
1	**New Residence 1**	1722.24	901.08	**0.52**
2	**New Residence 2**	601.50	429.40	**0.71**
3	**New Residence 3**	1465.95	672.00	**0.46**
4	**New Residence 4**	1465.95	672.00	**0.46**
5	**New Residence 5**	1339.20	736.80	**0.55**
6	**New Residence 6**	789.30	674.60	**0.85**
7	**New Residence 7**	1144.80	664.80	**0.58**
8	**New Residence 8**	1080.00	798.00	**0.74**
9	**New Residence 9**	739.50	788.60	**1.07**
10	**New Residence 10**	1092.00	662.00	**0.61**

4.4 Shading of the building skin

The parameter of shading of a building also directly relates to the amount of solar exposure the external surfaces (both wall and roof) of a building receive during daytime.

Shading of the external surface may occur due to three circumstances as follows:

(i) Shadow created by horizontal elements on the elevation or above fenestrations (such as chhajja, portico, overhanging balcony and such);

(ii) Mutual shadow of a vertical surface on other surfaces within the building (such as shadow created within the internal courtyard);

(iii) Shadow of the adjacent building(s) or flora on the surface of the building under study.

In some buildings, shading devices are either altogether present or absent. In others, some rooms have them, while others do not. The dimension, direction, and extent of these shading devices also vary. Sunshades and their shading extent have therefore been studied specifically in the rooms where data loggers were kept. These data are represented in **Tables 10 and 11** respectively.

The value of radiation for each building has then been normalized by comparing them with the level of radiation on an unshaded window of 1.2 m × 1.2 m. facing the south direction (414788 Wh/m^2-year).

Table 10. Window details, shading devices and total radiation on windows in Old Buildings.

Sl No	Official nomenclature	Survey room - No of windows	Survey room - Dimension of windows - Width	Survey room - Dimension of windows - Height	Chhaja depth (in m.)	Fin height (in m.)	Gap (in m.)	Extension (in m.)	Percentage of radiation on shaded window	Radiation on unshaded window	Window area (sq.m.)	Total radiation on window
1	**Old Residence 1**	2	1000	1300	0.3	0.3	0	0	90.59	199200	1.3	**234592**
2	**Old Residence 2**	0	0	0	0	0	0	0	100	0	0	**0**
3	**Old Residence 2**	0	0	0	0	0	0	0	100	0	0	**0**
4	**Old Residence 3**	3	1000	2100	0	0	0	0	100	199200	2.1	**418320**
5	**Old Residence 3**	1	1000	2100	0	0	0	0	100	308871	2.1	**648629**
6	**Old Residence 4**	3	1000	1800	0	0	0	0	100	199200	1.8	**358560**
7	**Old Residence 5**	6	1200	2000	0	0	0	0	100	308871	2.4	**741290**
8	**Old Residence 5**	0	0	0	0	0	0	0	100	0	0	**0**
9	**Old Residence 6**	4	1000	1500	0	0	0	0	100	308871	1.5	**463307**
10	**Old Residence 7**	2	1200	1500	0.3	FULL	0	0	80.89	414788	1.8	**603940**
11	**Old Residence 8**	3	900	1500	0	0	0	0	100	199200	1.35	**268920**
12	**Old Residence 9**	3	1000	1900	0.3	FULL	0	0	85.66	308871	1.9	**502700**
13	**Old Residence 9**	3	750	1900	0.3	FULL	0	0	62.24	5865	1.425	**5202**
14	**Old Residence 9**	6	1000	1900	0.3	FULL	0	0	80.89	308871	1.9	**474707**
15	**Old Residence 10**	1	1500	1200	0.3	0	0	0	95.88	414788	1.8	**715858**
16	**Old Residence 10**	4	1500	1200	0.3	0	0	0	95.88	414788	1.8	**715858**

Table 11. Window details, shading devices and total radiation on windows in New Buildings.

Serial No	Official nomenclature	Survey room - No of windows	Survey room - Dimension of windows - Width	Survey room - Dimension of windows - Height	Chhaja depth (in m.)	Fin height (in m.)	Gap (in m.)	Extension (in m.)	Percentage of radiation on shaded window	Radiation on unshaded window	Window area (sq.m.)	Total radiation on window
1	**New Building 1**	2	1500	1200	0.6	0	0	0	89.86	5865	1.8	**9487**
2	**New Building 2**	1	870	1200	0.6	0	0	0.2	84.32	308871	1.044	**271899**
3	**New Building 3**	2	1700	1400	0.3	0	0	0	96.37	308871	2.38	**708428**
4	**New Building 4**	2	1700	1400	0.3	0	0	0	95.88	414788	2.38	**946523**
5	**New Building 5**	2	1500	1200	0.6	0	0	0.15	84.32	5865	1.8	**8902**
6	**New Building 6**	2	1500	1400	0.6	0	0	0.2	68.65	414788	2.1	**597979**
7	**New Building 7**	2	1500	1400	0.6	FULL	0.15	0.15	69.63	308871	2.1	**451640**
8	**New Building 8**	4	1500	1400	0	0	0	0	100	5865	2.1	**12317**
9	**New Building 9**	3	1500	1300	0.6	0	0	0	77.54	308871	1.95	**467022**
10	**New Building 10**	2	3000	2700	0.3	0	0	0	95.88	414788	8.1	**3221360**

4.5 Ventilation

The degree of ventilation of the interior is a composite variable dependent on (i) opening versus wall ratio and (ii) indoor air velocity. These two parameters are therefore studied and discussed separately.

Opening v/s wall area ratio

This is a composite parameter and hence has been calculated based on the primary data of measured drawings done for each building. The data for old and new buildings are tabulated hereby in **Tables 12 and 13** respectively.

Table 12. Calculation of opening area versus wall area in the rooms under survey in Old Buildings.

Serial No	Nomenclature	Total wall area	Total window area	Total door area	Total opening area	Opening v/s wall area
1	**Old Residence 1**	99.07898	2.6	6.3	8.9	**0.09**
2	**Old Residence 2**	100.721	0	29.97	29.97	**0.3**
2	**Old Residence 2**	67	0	5.4	5.4	**0.08**
3	**Old Residence 3**	67.452	6.3	2.2	8.5	**0.13**
3	**Old Residence 3**	33.516	2.1	2.1	4.2	**0.13**
4	**Old Residence 4**	55.8056	5.4	6.3	11.7	**0.21**
5	**Old Residence 5**	133.44912	14.4	10.56	24.96	**0.19**
5	**Old Residence 5**	279.82764	0	15	15	**0.05**
6	**Old Residence 6**	67.8	6	2.2	8.2	**0.12**
7	**Old Residence 7**	71.304664	3.6	15.84	19.44	**0.27**
8	**Old Residence 8**	47.99296	4.05	2.2	6.25	**0.13**
9	**Old Residence 9**	41.74215	5.7	1.65	7.35	**0.18**
9	**Old Residence 9**	24.88665	4.275	1.65	5.925	**0.24**
9	**Old Residence 9**	60.403	11.4	1.65	13.05	**0.22**
10	**Old Residence 10**	64	1.8	4.2	6	**0.09**
10	**Old Residence 10**	60	7.2	4.2	11.4	**0.19**

Note: Window area “0” (zero) signifies indoor room with no window opening.

Table 13. Calculation of opening area versus wall area in the rooms under survey in New Buildings.

Serial No	Official nomenclature	Total wall area	Total window area	Total door area	Total opening area	Opening v/s wall area
1	**New Residence 1**	33.816	3.6	2.1	5.7	**0.17**
2	**New Residence 2**	63.06	1.044	8.4	9.444	**0.15**
3	**New Residence 3**	65.714	4.76	8.4	13.16	**0.2**
4	**New Residence 4**	65.714	4.76	8.4	13.16	**0.2**
5	**New Residence 5**	42.78	3.6	2.1	5.7	**0.13**
6	**New Residence 6**	67.95	4.2	12.6	16.8	**0.25**
7	**New Residence 7**	38.4	4.2	2.1	6.3	**0.16**
8	**New Residence 8**	74.532	8.4	12.6	21	**0.28**
9	**New Residence 9**	59.6008	5.85	4.2	10.05	**0.17**
10	**New Residence 10**	58.5	16.2	4.2	20.4	**0.35**

Air velocity

Discrete air velocity data were measured manually with the help of anemometer within each study building. It is found to be quite less in almost all houses during the physical survey period and even nil in many cases. These values are tabulated as below (**Tables 14 and 15**):

Table 14. Air movement and velocity inside Old Buildings.

Serial No	Nomenclature	Air velocity (m/s)
1	**Old Residence 1**	0.20
2	**Old Residence 2**	0.05
3	**Old Residence 3**	0.25
4	**Old Residence 4**	0.10
5	**Old Residence 5**	0.265
6	**Old Residence 6**	0.13
7	**Old Residence 7**	0.22
8	**Old Residence 8**	0.02
9	**Old Residence 9**	0.18
10	**Old Residence 10**	0.11

Table 15. Air movement and velocity inside New Buildings.

Serial No	Nomenclature	Air velocity (m/s)
1	**New Residence 1**	0.10
2	**New Residence 2**	0.00
3	**New Residence 3**	0.20
4	**New Residence 4**	0.05
5	**New Residence 5**	0.05
6	**New Residence 6**	0.15
7	**New Residence 7**	0.12
8	**New Residence 8**	0.26
9	**New Residence 9**	0.18
10	**New Residence 10**	0.02

5. Analysis of data

In a previous work, the authors have probed the indoor thermal conditions of these two sets of old and new buildings, which revealed that the indoor thermal performances of old buildings were collectively more comfortable than those of the set of new buildings [53]. This research, therefore, may be considered as a sequel of the previous work.

The data collected as described in the previous section for the parameters shortlisted is collated together as in **Table 16**. These data are then analyzed in two steps to address the two objectives of the research as stated in the introduction. First, each parameter is put into correlation analysis with two indices of dry bulb temperature and heat index. Following this, the parameters are then put together into a regression analysis separately with the two indices to arrive at two sets of predictive models.

5.1 Degree of association of indoor thermal index with measured parameters

The dependence of the two thermal measurement indices of DBT and HI on various building parameters individually has been examined through the computation of correlation coefficients pair-wise as shown in the matrices for old buildings (**Table 17**) and new buildings (**Table 18**). These coefficients are then interpreted on the basis of the correlation coefficient interpretation ranges [54] as follows:

(a) High Correlation having a coefficient of 1.0 to 0.7

(b) Moderate Correlation having a coefficient of 0.69 to 0.4

(c) Less Correlation having a coefficient of 0.39 to 0.1

(d) No Correlation having a coefficient of less than 0.09

The coefficients in **Table 17** and **Figure 3** show that there is a high degree of influence of surface area versus volume ratio in the old buildings, whereas the thermal conductivity of walls moderately influences the indices in old buildings. All other parameters seem to have negligible influence, and that of opening versus wall area ratio shows a negative influence on the internal comfort.

On the other hand, the coefficients in **Table 18** and **Figure 4** do not show any high degree of influence on the thermal comfort indices. However, four out of seven parameters have a moderate influence on the comfort indices in the new buildings. All other parameters have almost no influence on the thermal comfort in this group, while the parameter of thermal conductivity of the slab has a negative impact on the thermal comfort indices.

Table 16. Indicators of thermal comfort vis-a-vis the influencing parameters for all sample buildings.

Sl No	Nomenclature	Thermal comfort indicators		Values of parameter influencing indoor thermal comfort						
		DBT	Heat index	Building orientation	Air velocity	Shading device	Surface volume ratio	Thermal conductivity of wall	Thermal conductivity of slab	Opening v/s wall area ratio
1	**Old Residence 1**	30.25	35.12	0.88	0.2	0.57	0.74	1.57	3.4	0.09
2	**Old Residence 2**	28.78	33.66	0.88	0.05	0	0.62	1.57	4.08	0.3
3	**Old Residence 3**	33.02	38.07	0.96	0.25	1.01	1.31	2.13	4.26	0.13
4	**Old Residence 3**	31.4	40.85	0.96	0.25	1.56	1.31	2.13	3.52	0.13
5	**Old Residence 4**	30.17	37.17	0.85	0.1	0.86	0.8	2.13	4.6	0.21
6	**Old Residence 5**	29.78	34.24	0.88	0.265	1.79	0.45	1.3	3.48	0.19
7	**Old Residence 5**	29.5	35.13	0.88	0.265	0	0.45	1.3	2.87	0.05
8	**Old Residence 6**	31.1	40.4	0.88	0.13	1.12	0.86	2.59	5.42	0.12
9	**Old Residence 7**	28.82	31.2	0.88	0.22	1.46	1.02	2.13	5	0.27
10	**Old Residence 8**	32	38.37	0.88	0.02	0.65	1.38	2.48	5.01	0.13
11	**Old Residence 9**	31.23	36.98	0.88	0.18	1.21	1.21	3.31	7.09	0.18
12	**Old Residence 9**	31.48	35.88	0.88	0.18	0.01	1.21	3.31	7.09	0.24
13	**Old Residence 9**	31.51	36.29	0.88	0.18	1.14	1.21	3.31	4.31	0.22
14	**Old Residence 10**	30.57	34.23	0.96	0.11	1.73	0.6	3.31	5.42	0.09
15	**Old Residence 10**	29.77	34.23	0.96	0.11	1.73	0.6	3.31	3.55	0.19
16	**New Residence 1**	29.88	34.32	0.96	0.1	0.02	0.52	5.18	8.83	0.17
17	**New Residence 2**	32.26	39.28	0.96	0	0.66	0.71	5.18	8.51	0.15
18	**New Residence 3**	33.14	40.15	0.96	0.2	1.71	0.46	4.26	8.22	0.2
19	**New Residence 4**	31.46	38.43	0.96	0.05	2.28	0.46	4.26	8.22	0.2
20	**New Residence 5**	28.45	32.88	0.88	0.05	0.02	0.55	4.59	8.83	0.13
21	**New Residence 6**	30.02	37.49	0.96	0.15	1.44	0.85	5.18	10.36	0.25
22	**New Residence 7**	31.26	41.47	0.88	0.12	1.09	0.58	5.18	8.83	0.16
23	**New Residence 8**	33.2	39.26	0.96	0.26	0.03	0.74	5.54	7.49	0.28
24	**New Residence 9**	31.88	42.03	1	0.18	1.13	1.07	5.18	7.04	0.17
25	**New Residence 10**	33.16	38.87	0.96	0.02	7.77	0.61	5.18	7.73	0.35

Table 17. Computation and interpretation of correlation coefficients between the indices and the building parameters in Old Buildings.

Parameters	*Correlation with DBT*	*Degree of correlation with DBT*	*Correlation with HI*	*Degree of correlation with HI*
Building orientation	**0.30**	Less	**0.14**	Less
Air velocity	**0.05**	No	**–0.02**	No
Shading device	**0.04**	No	**0.01**	No
Surface area v/s volume ratio	**0.76**	High	**0.53**	Moderate
Thermal conductivity of wall	**0.41**	Moderate	**0.13**	Less
Thermal conductivity of slab	**0.34**	Less	**0.11**	Less
Opening v/s wall area ratio	**–0.33**	Less (Negative)	**–0.41**	Moderate (Negative)

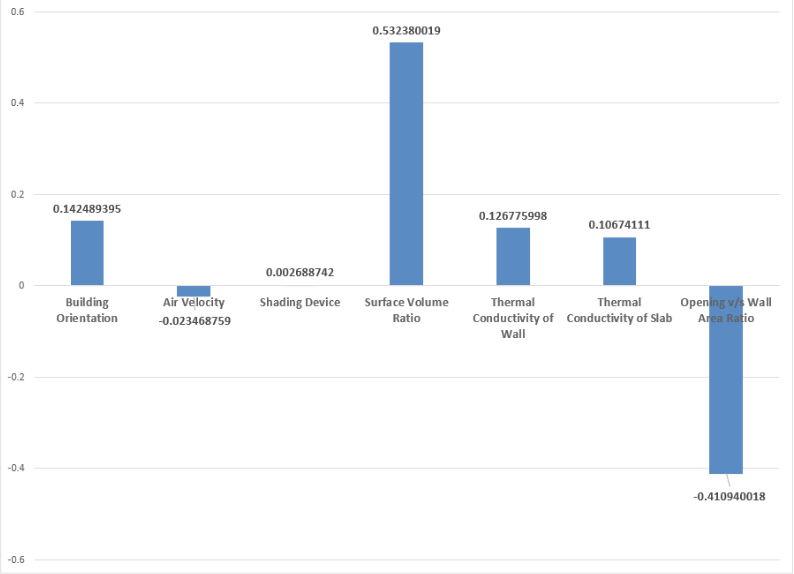

Figure 3. Correlation coefficients of heat index against the contributing factors for Old Buildings.

Table 18. Computation and interpretation of correlation coefficients between the indices and the building parameters in New Buildings.

Parameters	*Correlation with DBT*	*Degree of correlation with DBT*	*Correlation with HI*	*Degree of correlation with HI*
Building orientation	**0.50**	Moderate	**0.35**	Less
Air velocity	**0.28**	Less	**0.35**	Less
Shading device	**0.44**	Moderate	**0.22**	Less
Surface area v/s volume ratio	**0.08**	No	**0.40**	Moderate
Thermal conductivity of wall	**0.14**	Less	**0.17**	Less
Thermal conductivity of slab	**–0.63**	Moderate (Negative)	**–0.45**	Moderate (Negative)
Opening v/s wall area ratio	**0.54**	Moderate	**0.18**	Less

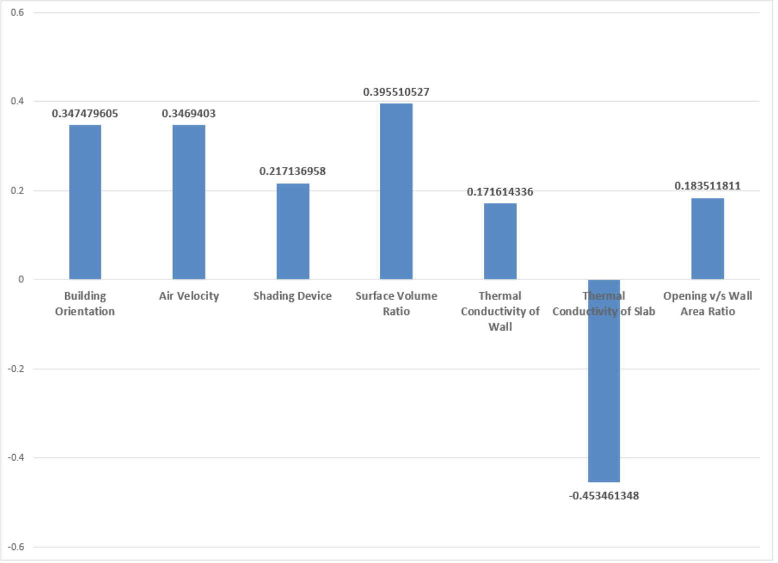

Figure 4. Correlation coefficients of heat index against the contributing factors for New Buildings.

However, we may not infer that other parameters having less or no correlation with the thermal comfort indices should be ignored. On the other hand, it may be explained that the calculated correlation coefficients are less due to the phenomenon of "Third Variable Problem" [54] where a third independent variable may influence the correlation between a pair of dependent and independent variables, thus an honest estimate of independent correlation cannot be drawn between the pairs.

5.2 Establishing relationship between thermal condition indices and physical parameters

In the final stage of analysis, the whole dataset has been put into linear regression analysis. The analysis was done with the help of the tool "Multiple Linear Regression Calculator" by Statistics Kingdom—a pre-programmed online software [55]. Regression equations were separately developed for the thermal measurement of DBT and Heat Index for the data set of Old Buildings and New Buildings. The following matrix shows the development of four equations (**Table 19**).

Table 19. Matrix showing development of model equations.

Building Types ↓ *Thermal Index* ➔	*DBT*	*HI*
Old Buildings	**Equation (2)**	**Equation (3)**
New Buildings	**Equation (4)**	**Equation (5)**

Regression equation for dry bulb temperature (DBT) in Old Buildings

The regression equation between DBT and the physical parameters is given as:

$$DBT = 22.216 + 4.518\ P_1 + 0.136\ P_2 - 0.0565\ P_3^2 + 2.699\ P_4 + 0.0509\ P_5^2 + 0.0012\ P_6^2 - 1.936\ \mathrm{Log}_{10}(P_7) \tag{2}$$

where,

P_1: Building Orientation
P_2: Air Velocity
P_3: Shading Device
P_4: Surface Volume Ratio
P_5: Thermal Conductivity of Wall
P_6: Thermal Conductivity of Slab
P_7: Opening v/s Wall Area Ratio
R^2 value = 73.8%;
Coefficient of multiple regression = 0.859;
Significant predictor—P_4

Regression equation for heat index (HI) in Old Buildings

The regression equation between DBT and the physical parameters is given as:

$$DBT = 39.496 - 3.794\ P_1 - 25.922\ P_2^2 + 0.212\ P_3^2 + 5.342\ P_4 - 0.138\ P_5^2 - 0.00323\ P_6^2 - 19.744\ P_7 \tag{3}$$

where,

P_1: Building Orientation
P_2: Air Velocity
P_3: Shading Device
P_4: Surface Volume Ratio
P_5: Thermal Conductivity of Wall
P_6: Thermal Conductivity of Slab
P_7: Opening v/s Wall Area Ratio
R^2 value = 55.4%;
Coefficient of multiple regression = 0.744;
Significant predictor—None

Regression equation for dry bulb temperature (DBT) in New Buildings

The regression equation between DBT and the physical parameters is given as:

$$DBT = 29.579 + 7.584\ P_1^2 + 3.617\ P_2 + 0.00332\ P_3^2 - 1.738\ P_4^2 + 0.34\ P_5 - 0.814\ P_6 + 12.674\ P_7^2 \tag{4}$$

where,

P_1: Building Orientation
P_2: Air Velocity
P_3: Shading Device
P_4: Surface Volume Ratio
P_5: Thermal Conductivity of Wall
P_6: Thermal Conductivity of Slab
P_7: Opening v/s Wall Area Ratio
R^2 value = 65%;
Coefficient of multiple regression = 0.806;

Significant predictor—None

Regression equation for heat index (HI) in New Buildings

The regression equation between DBT and the physical parameters is given as:

$$DBT = 32.213 + 7.118\ P_1 + 79.823\ P_2^2 + 0.128\ P_3^2 + 4.549\ P_4 - 0.388\ P_5 - 0.0176\ P_6^2 - 60.352\ P_7^2 \quad (5)$$

where,

P_1: Building Orientation

P_2: Air Velocity

P_3: Shading Device

P_4: Surface Volume Ratio

P_5: Thermal Conductivity of Wall

P_6: Thermal Conductivity of Slab

P_7: Opening v/s Wall Area Ratio

R^2 value = 37.6%;

Coefficient of multiple regression = 0.613;

Significant predictor—None

A comparison of the four equations and their coefficients (R^2) reveals that for both thermal indices the equations developed for the set of old buildings show more accuracy of prediction.

6. Conclusions

This research is aimed firstly at probing and ascertaining a relationship between the thermal condition and the contributing parameters so that these parameters may be manipulated to achieve better thermal conditions inside a built environment. It is thus concluded that the surface area v/s volume ratio and opening v/s wall area ratio have maximum influence on the thermal performance (measured as Heat Index or HI) of the "Old Buildings" (**Table 17**) whereas surface area v/s volume ratio and thermal conductivity of wall bears maximum influence on the indoor thermal condition (HI) for the "New Buildings" (**Table 18**). The thermal conductivity of the envelope is further dependent on the material being used as well as its thickness. In modern design problems involving constrained availability of space, the thickness of wall may not be indefinitely increased. However, the choice of material for these envelopes can be easily manipulated to create a better thermal condition indoors.

This research then develops a set of predictive numerical models that can be used to predict the probable thermal condition inside a proposed building before it is actually constructed. There are multiple sets of numerical models developed as stated in **Table 19**. The fitting of these models with the existing data varied from 38% to 74%, and a better curve fitting is observed for the Old Buildings—thus showing better consistency of design approach and use of construction material when compared to the New Buildings. However, the development of these models has been limited by the sample size of ten buildings each for either old or new buildings, which has limited the normality of the results. This dissertation can be furthered by increasing the sample size and at the same time putting the developed models in a process of numerical simulation for a set of studied buildings with known parametric values as well as observed thermal indices. This work thus aims to contribute in the form of a methodology for future research in this field.

In this study, only the non-manual parameters were considered, not the more subjective behavioral aspects of user perception and comfort. Incorporation of these aspects may further enrich the methodology and might also increase the probability of modifying the methodology suitable to the actual thermal conditions observed.

Author Contributions

Sanmarga Mitra: Conceptualization of research, Conduction of measured drawing, Collection and analysis of data, Data interpretation, Drawing of conclusion, Rough as well as final draft of paper; Shailendra Kr. Mandal: Conceptualization of research, Data interpretation, Drawing of conclusion, Review and scrutiny of first draft of paper, Final draft of paper.

Conflict of Interest

No conflict of interest was observed by the authors while conducting the research.

Data Availability Statement

This paper is developed on data computed on the basis of measured drawing and documentation of inhabited residential buildings, which is non-sharable due to confidentiality.

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