Methodology for Effective Daylighting in Courtyard Houses of Composite Climate

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Abstract: Studies have shown the relevance of the courtyard houses and passive strategy that plays a significant role in energy reduction, providing thermal comfort and visual comfort. Generally, designing the courtyards was considered suitable for thermal comfort. North India lies in the composite climatic zone, and courtyard houses in this region have a distinctly vernacular style. Many studies all around the world were conducted to analyse courtyard houses and followed different methodologies. The aim of this paper is to uncover and formulate a research methodology to analyse effective daylighting in courtyard houses of composite climate; approximately forty research papers were reviewed to find out the research methodology. The year of publication, climate zone, sky models used, weather file, building type, verifying method, simulation tools, daylight matrices, and methodology adopted were studied in the reviewed literature to formulating the methodology. The study concludes that experimental models were commonly used for daylight analysis, moreover climate-based sky can be used for detailed simulation instead of the Daylight factor with overcast sky conditions.

Keywords: Calibration, Composite climate, Courtyard houses, Effective daylight, Methodology, Modelling, and Simulation.

I. INTRODUCTION

The 21st century is the age of innovation. Rapid growth and development can be seen in the real estate market of the world in the last 50 years. The use of passive strategies to reduce the energy demand of the building was in trend in the past decade. Courtyards, as a feature of vernacular architecture, were used generally in the building of Hot-Dry climate. Courtyards were the important feature of the houses of composite climate. Generally, the composite climate is studied for energy and thermal comfort analysis. Passive daylighting plays a key role in achieving lighting energy reduction, thermal delight, and visual comfort in buildings. The use of passive strategies was propagated in the building design to make the building more climate-responsive and energy-efficient. The research aims to formulate a research methodology for the analysis of effective daylighting in courtyard houses of composite climate. The main objective of the research was:

- To study literature related to the courtyard analysis based on daylight, energy performance, thermal comfort, quality of space analysis.
- To study the year of publication, climatic zone, sky condition, building type, verifying method, simulation tools, daylight matrices, and methodology adopted for the study.

The energy requirement of a building is rapidly increasing day by day. In residential buildings, most energy is consumed in ventilation, cooling, and artificial lighting. The energy-efficient building that adopts passive daylighting is considered a useful strategy. The question of the research is, what will be the suitable methodology for the analysis of effective daylighting in courtyard houses of composite climate? The research was limited to the courtyard houses of composite climate, and the focus was oriented towards daylighting only. The study covers the background of the courtyard and daylight. The analysis covers the year of publication, climatic zone, sky condition, building type, verifying method, simulation tools, daylight matrices, and methodology adopted for the study in the reviewed literature.

II. RESEARCH BACKGROUND

A. Courtyard

A courtyard is a circumscribed space open to the sky, often surrounded by a building or a complex structure. In Western and Eastern building styles, courtyards serve as traditional architectural features and have been used as a space of multiple functions by both ancient and contemporary architects.

Building material with high thermal mass, wind catchers, basement, verandah, and changes in sectional profiles were the key components of achieving thermal comfort in courtyard houses. According to the author, in the courtyard houses of the Hot-dry climate of Yazd, Iran, the inhabitants had to move horizontally and vertically in the Hot-humid climate of Bushehr, Iran. A symbiosis of the user and the courtyard’s technical parameters is essential in achieving comfort [1]. Buildings in different climatic conditions require different strategies. For a deeper understanding, we require detailed simulation and analysis [2].

B. Daylight and daylighting

Daylight is the visible range on the electromagnetic spectrum, which is between 400nm to 700nm. Daylighting is the controlled emission of natural light in the interiors.
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Direct solar illuminance should be ignored, and only sky illuminance shall be considered as daylighting of building interiors [3]. The Sky illuminance value depends on the spot, day, time, and geographic location.

III. LITERATURE STUDY

Literature study provides us the background knowledge, methodology adopted in the previous studies, and finding gaps in the research. A total of forty literature were reviewed, which can be seen in Tables 1 to 6. Twenty-six out of forty literature were based on the courtyard analysis, and the remaining fourteen were based on the daylight simulation tools and other parameters. Figure 1 depicts the number of the reviewed literature. A maximum of 41%, i.e., twenty-two were based on daylight [2, 4-24], 29%, i.e., sixteen were based on thermal comfort [1, 2, 11, 13, 18, 19, 25-34], and 15%, i.e., eight were based on energy-related topics [9, 10, 13, 14, 24, 35, 36]. Thus, it is evident from the study that daylight is the first choice of the present researchers for analyzing the built space.

Fig. 1. Number of reviewed literature based on studied parameter.

A. Year of publication

Figure 2 shows the number of reviewed literature based on the year of publication. 73%, i.e., twenty-nine of the reviewed literature were published in the last five years (2016-2020) [1, 2, 9-14, 18-24, 28-34, 36-38], 18%, i.e., seven literature were published (2011-2015) [4, 5, 26, 27, 39-41]. The capabilities of new matrices were enhanced, because of the availability of a variety of simulation tools, due to which a number of researches have been seen in recent years.

Fig. 2. Number of reviewed literature based on the year of publication.

B. Climatic zone

Indian standards recognize five climatic zones in India: Hot-dry, Warm-humid, Temperate, Cold, and Composite. “A climatic zone that does not have any season for more than six months may be called a Composite zone” [3]. In the overall reviewed literature, 26% of the literature belonged to the Composite climate [9, 10, 18, 22, 25-28, 30, 33, 35, 36], 24% to Hot-arid climate [1, 8, 11, 12, 14, 19, 22, 32, 34-36], 20% to Hot and humid climate [1, 6, 7, 22, 28, 29, 35, 36, 38] see Figure 3. Figures 4, 5, and 6 depict the percentage of different climate zones in the reviewed literature based on energy, daylight, and thermal comfort. The analysed charts show the Composite climate was studied in 36% of energy-based literature [9, 10, 35], 16% of daylight-based literature [9, 10, 22], and 41% of thermal comfort based literature [18, 25-28, 30, 33]. There was a significant gap in the study of the courtyards of Composite climate based on daylight.
| Sl.no | Author and Year | Objective | Location and Climate | Type of Building | Courtyard Dimension | Calibration | Parameters Studied | Analysis Criteria | Methodology | Simulation Tool | Conclusion |
|-------|-----------------|-----------|----------------------|------------------|---------------------|------------|-------------------|-----------------|-------------|----------------|------------|
| 1     | A and Gaddi (2006) | The research focuses primarily on the impact of solar heat gain with differing proportions on the energy demand of the assayed building shape. | The climate of Tempe, Rome, Italy | Residential building | The ratio of the floor perimeter of the assayed building height | NA | Solar heat gain, Thermal comfort | Analyzing effects of solar heat gain on heating and cooling load of building | Simulation based | IES-Radiance | The open courtyard forms were the most preferable for the purpose of reducing the cooling load in summer and heating load in winter. |
| 2     | Al-Dawoud et al. (2014) | The energy efficiency of a central atrium is investigated and contrasted with the energy output of a courtyard of the same geometric proportions. | Hot, dry climate, Phoenix, Arizona, Hot, humid climate, Miami, Florida, Temperate climate, Chicago, Illinois, Cold climate, Madrid, Spain | General Courtyard building Model | LA 1m X 4m; 1.5m X 3.8m Floor to Floor | NA | Energy analysis | Analyzed for different Glazing type, No. of floors, and glazings | Simulation and experimental | DOE2.1E | For shorter structures, the open courtyard building exhibits better energy efficiency. |
| 3     | Acosta et al. (2014) | The main aim of this article is to offer a quick and precise predictive method for calculating the daylight factor for different points on the floor of square and rectangular atria under overcast sky conditions. | Overcast sky condition | General Courtyard building Model | Square courtyard, 3m wide, and with a height varying between 1 and 15 m, a height/width ratio of 4.25% was used for all trials. | Daylighting and visual comfort | Daylighting factors in the centre of the floorplan for each courtyard model, considering variable height and reflected area of walls. SC, DF, IRC, DV were checked. | Simulation and experimental | Radiance software | The predictive methods developed in this research provide an approximation of the calculation of the daylight factors for characteristic parts of a courtyard. |
| 4     | Eden, H (2015) | In order to enhance the lighting and visual comfort, the research seeks to address the impacts of many courtyard shapes. | Overcast sky condition | Mixed use building | The circle, the rectangle (1:2, 1:3), the square, and the triangle. | NA | Daylighting and visual comfort | DFs calculated in OExcerast | Simulation based | SOLWE by CERMA laboratory and OISAPPR (indoor) | The courtyard surface is the key element deciding the degree of light rather than the difference of the heights of the adjacent masses in the lower layers. |
| 5     | Gulati et al. (2014) | The goal of the study was to evaluate the core urban courtyard houses, adapted colonial bungalows and core rural mud houses in Lucknow to determine what factors or strategies can contribute to the improved efficiency. | Composite Climate | Residential building | NA | Data collected with actual site data | Thermal comfort, Study of all studies' on-sight data was undertaken with regard to the planned comfort bands | Simulation and experimental | manual collection of data from the sites. | Ecotech | In the different areas of the area, all the generic vernacular house styles of Lucknow were found to be thermally comfortable due to various multiple passive strategies embraced by them to fight the extremes of outdoor conditions. |
| 6     | Taleghani et al. (2014) | The aim of this paper is to focus on heat mitigation strategies in urban courtyard blocks in the Netherlands. | Temperate di male, De Bilt (52 N, 4 E), Netherlands | Urban Courtyard | 10 X12 m and 30 X90 m with step of 10 m. | Data collected with actual site | Thermal comfort | Analysis of different courtyard type with climate change in 2050, all kinds, relatively, green space | Simulation and experimental | manual collection of data from the sites. | ENVI-met | This research suggests using water pool and green areas as the most effective heat mitigation strategies for urban blocks in the Netherlands. |
| 7     | Gharauni et al. (2015) | The goal of this analysis is to analyze the effect of aspect ratio and courtyard height on the amount of average Daylight Factor (ADF) in different vertical top atrium floors. To select the acceptable degree of aspect ratio and courtyard height. | Hot and Humid, Malaysia | Office building | The model simulates four square models: rectangular atrium with width X length and height 5m and 10m. | Results of physical and simulated model were calibrated | Daylighting in the building | Examining the amount of Average Daylight Factor (ADF) in office space over the work plane. | Simulation and experimental | IES-Radiance | It concluded that the minimum aspect ratio of atrium height (h) to aspect ratio (l) is h/l = 0.63 for the reasonable amount of ADF in neighboring atrium spaces, |
| Sl.no | Author and Year | Objective | Location and Climate | Type of Building | Courtyard Dimension | Collaboration | No. of Parameters Studied | Analysis Criteria | Methodology | Simulation tool | Conclusion |
|-------|-----------------|-----------|----------------------|------------------|--------------------|--------------|-------------------------|-----------------|-------------|----------------|------------|
| 8     | Mohsenin et al. (2015) | The goal is to assess and optimize airflow and proportions to improve energy efficiency of atrium buildings. | Warm and humid - U.S Climate Zone 3 | Office building | Central, attached and semi-enclosed atrium types with an atrium of 2743 x 2743 (90 ft x 90 ft), 3743 x 214 (120 ft x 70 ft), and 2286 x 1286 (75 ft x 420 ft). | Data of physical and simulation model are validated. | Data of physical and simulation model are validated. | Daylighting in the building | Simulation and experimental, using DesignBuilder with data collected from model. | DesignBuilder | This paper provides preliminary data for daylight in atrium buildings, which can be expanded as an online interface for architects. |
| 9     | Guedouh et al. (2015) | To investigate in daylighting efficiency of different building typologies under specific climate conditions of hot and arid regions. | Hot and Arid region with desert climate | Residential building | Mono block of size 15x25m with different typologies. With opening ratios of 0.25, 0.50 and 0.66. | NA | NA | Daylighting in the building | Simulation and experimental, simulation run for different typologies modeled in DesignBuilder and done a comparative analysis. | DesignBuilder | Courtyard regulate natural lighting, the control of the courtyard opening ratio helps to reach the annual illuminance levels desired, but the deep courtyard loses this privilege, more the courtyard is deep, less the interior’s spaces are illuminated. |
| 10    | Gangwar and Kaur (2015) | The objective is to investigate these works of architects after independence. | Various regions of India | General Courtyard building | NA | NA | Space quality | Literature review | NA | It is not necessary to imitate the indigenous courtyard system in a similar fashion as these used in past, the systems on these courtyard systems could be used with changing needs of life style, social structure, cultural transformation and technological advancement. |
| 11    | Kargarhadad et al. (2015) | This research aims to fill the information gap in the more familiar hot climate about the role of the central courtyard in a hotted climate by contrasting its efficiency with a courtyard. | Iran (Yazd, hot and dry) | Residential building | 12x24x8x6.7 and 24x17x5.3m | NA | NA | Thermal comfort by shading | Analyzing different sizes, forms and dimensional ratios. | Literature review | Occupants have been forced to move (horizontally in Yazd and vertically in Bushehr). |
| 12    | Markus, B (2016) | To examine the design criteria for courtyards in different climatic zones. | NA | General Building | NA | NA | Thermal Comfort, Ventilation and Daylighting | Analyzing different sizes, forms and dimensional ratios. | Literature review | NA | The performance of air movement and daylighting in courtyard buildings depends on the design variants. The shape and scale of the courtyard have a direct influence on shade conditions, building ventilation and heating. |
| 13    | Martinelli and Matzarakis (2016) | The current research focuses on outdoor conditions, with the term “courtyard” referring specifically to the shared open space rather than the surrounding buildings. | Six cities of Italy: Arezzo, Milaan, Compolbasso, France, Lecce, Grotania | Urban Courtyard | The study takes into account five courtyards of the same 2000 m square shape and the various buildings: 8 m, 12 m, 16 m, 20 m and 24 m in height, resulting in 5 different height-to-width ratios: 25:5, 35:5, 45:5, 55:13, and 65. | NA | NA | Thermal comfort | The thermal comfort measurement is based on the estimation of the Physiologically Equivalent Temperature (PET) using the RayMan model. | Mathematical, based. Five cities of different climatic zones were selected. PET is calculated in the RayMan model. | As a general rule, for warmer climates, higher W/W ratios of 4.5 to 5.5 may be advised to be carefully tested for each individual case, whereas for colder climates, lower-medium W/W ratios of 35 to 45 may be suitable. |
| Sl. No | Author and Year | Objective | Location and Climate | Type of Building | Courtyard Dimension | Calibration | No. of Parameters Studied | Analysis Criteria | Methodology | Simulation tool | Conclusions |
|-------|-----------------|-----------|----------------------|------------------|---------------------|------------|------------------------|-----------------|-------------|-----------------|-------------|
| 14    | Tan et al. (2016) | Studied evaluated the role of geometry factors - the atrium shape and the ratio of length to width - on building thermal energy performance in courtyard building. | Composite climate, Xi’an, China | Residential building | NA | Gill calibrated with on-site data | Daylighting and energy requirement in the building | Checking daily gift factor (DF) in the surrounding rooms. | Simulation and experimental based. | Design Builder | Results show that a courtyard which height to width ratio is less than 1 have better lighting performance. No advantage was observed for height to width ratio more than 5. |
| 15    | Bule et al. (2017) | The key objective of this analysis is to examine the central courtyard design as a passive cooling technique in Universiti Teknologi Malaysia (UTM) buildings to increase indoor thermal comfort. | Warm and humid, Johor, Malaysia | Institute building | NA | NA | Thermal comfort | On surveying all the 46 courtyard cases a quantitative analysis was done. | The approach of this research included creating a guideline for thermal comfort. Formally (DF) courtyard in thirty-two (32) UTM buildings were surveyed, and the data was interpreted and analyzed using the statistical description process. | Theory and Literature | The study shows that courtyards are common architectural components used in UTM buildings. They are divided into shapes that are fully enclosed and semi-enclosed. The fully-enclosed rectangular courtyard is the most typical courtyard shape. Approximately 72% and 60% of the surveyed area and has overhangs and horizontal shading features. |
| 16    | Gupta et al. (2017) | Checking thermal comfort of the rural dwelling of composite climate. | Composite climate, Jharkhand, India | Residential building | NA | Gill calibrated with on-site data | Thermal comfort | The study over three mud dwellings. Temperature and humidity were checked. | Data collection from the site and calibrated with simulation data. | Ecotech | All courtyard type dwellings do not necessarily show better thermal performance in summer and winter. |
| 17    | Kadissa et al. (2017) | By studying the effect of geometrical parameters on outdoor comfort levels this research aims to desist different configurations of urban open spaces. | Constantine’s Semi-Arid climate, Algeria | Urban courtyard | Forms were used for buildings ranging in scale length and width in increments of 15 m, from 30 m to 135 m, with building heights ranging from 3 m to 72 m in increments of 3 m (five floors). | NA | Thermal comfort | This study explores the physiological equivalent temperature (PET), a thermal comfort index which takes into account all the environmental parameters which influence thermal comfort. | Numerical modeling is used in this study which concentrates on the relation between the microclimate of an open space on the HW aspects of the surrounding buildings. | The findings show that the direct sunlight in the region, average radiant temperature and wind speed are affected by the urban shape and play a significant role in achieving optimal levels of thermal comfort. |
| 18    | Saffari et al. (2017) | In terms of geometric properties and orientation, the aims is to identify the best design model for courtyards in order to improve thermal comfort in modern desert houses. | Hot and Arid region, Iran | Residential building | Varying | NA | Shading performance, Thermal comfort | The study over ten houses, models were generated and analyzed | Simulation based | Design Builder | In hot dry climate, decreasing length to width ratio obtaining greater shading role in the design of courtyards, which means that the courtyard of square shape performs better than rectangular shapes. |
| 19    | Acosta et al. (2018) | The purpose of this analysis is to provide an easy and accurate method for the determination of the factor of the height to width at different points in the rectangular courtyard or atrium open space based on the variable geometry and reflectance of the space. | Temperate climate, Seville, Spain | Scale model with laser cutting in fiber board and a existing courtyard | Scale model data is calibrated with site data | Daylighting and the energy performance | In both cases DF was analyzed considering the sky component and reflective component. | Data collection from the scale model and existing courtyard and comparing it. Experimental method (DF). | Methodical and experimental method. | As expressed in the OPA (1), OPA (4) and OPCD (5) equations, the predictive method defined in this study provides an accurate procedure for determining daylight factors at specific points in a space in the courtyard or central atrium. |
| 20    | Guadalupe et al. (2018) | The present study aims to establish a dual relationship between thermal and luminous courtyard building environments in hot and dry regions. | Hot and Arid region | Different cases of Sample models with different: Opening ratio, Aspect ratio, Shadow solar index, Glazed percentage. | Opening ratio - 0%, 1%, 5%, 10%, 20% | NA | Thermal Comfort and Daylighting | The models reflect various typologies courtyard, traditional 1 and 2 that were analyzed on the basis of the following parameters, such as number of stories, opening ratio of the courtyard, aspect ratio, percentage of openings (glazed surface)(Illumination - I). | The simulations were taken under clear sky condition under different season. | Design Builder | The Deep Courtyard building is the perfect model for solving this problem in hot and dry regions. |

Table III: List of reviewed literature based on the courtyard (Continued).
The paper introduces vernacular houses responding to climate. The purpose of this research is to provide simple-to-use rules in creating effective daylighting in courtyard houses of composite climate. The study critically reviews and compares software used for daylighting in the building. The survey from this study showed the best design model was defined and presented in order to optimize thermal comfort.

### Table-IV. List of reviewed literature based on the courtyard (Continued).

| Sl.no | Author and Year | Objective | Location and Climate | Type of Building | Courtyard Dimension | Type of Building | Analysis Criteria | Methodology | Conclusion |
|-------|-----------------|-----------|----------------------|------------------|---------------------|-----------------|-------------------|-------------|------------|
| 21    | Ofstad et al. (2019) | The paper explores the effect of continuous double layer walls on thermal performance | Surabaya, East Java, Indonesia | Residential building | Office Building | Office Building | Radiance | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
| 22    | Ahmad et al. (2020) | The paper explores the effect of continuous double layer walls on thermal performance | Saudi Arabia, Hot climate | Office Building | Office Building | Energy Plus | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
| 23    | Cicha et al. (2020) | The paper explores the effect of continuous double layer walls on thermal performance | Chhatisgarh, India | Residential building | Residential building | Radiance | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
| 24    | Ofstad et al. (2020) | The paper explores the effect of continuous double layer walls on thermal performance | General Courtyard | Office Building | Office Building | Radiance | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
| 25    | Saha et al. (2020) | The paper explores the effect of continuous double layer walls on thermal performance | Residential building | Office Building | Office Building | Radiance | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
| 26    | Saha et al. (2020) | The paper explores the effect of continuous double layer walls on thermal performance | Residential building | Office Building | Office Building | Radiance | Simulation and experimental, Computer simulation | Simulation and experimental, Computer simulation shows the best effective for daylight efficiency. |
Methodology

| Sl.no | Author and Year | Objective | Location and Climate | Type of Building | Courtyard Dimension | Calibration Parameters Studied | Analysis Criteria | Methodology | Simulation Tool | Conclusions |
|-------|-----------------|-----------|----------------------|------------------|---------------------|-------------------------------|------------------|-------------|----------------|-------------|
| 1     | Reinhardt et al. (2021) | To validate the Radiance based daylight simulation for a test office. | Different sky conditions | General office model | NA | Validated | Daylighting in the building | Analyzing the model in different sky conditions and layouts with different shading: DA | Experimental and simulation | Radiance and DAYSIM | The treatment of direct sunlight influences the accuracy of the daylight coefficient estimate. |
| 2     | Naiki (2025) | This paper proposes a new model called Useful daylight illuminance (UDI) to test daylight in buildings. | Climate based sky | NA | NA | BRE CIBER validation | Daylighting in the building | Analyzing the annual daylight illuminance using weather file, UDI | Experimental and simulation | Radiation | Many of the interpretive flexibility of the popular daylight factor method is retained by the supportive daylight illuminance model. |
| 3     | Roudsar et al. (2013) | The main objective of the paper is to understand the use and widening of environmental analysis tool for Rhino and Grasshopper. | NA | NA | NA | NA | Sustainability | Literature study | Be Comparison with other similar environmental analysis tools. | Literature study | Lighting shows best results on the basis of process and analysis of a building. |
| 4     | Zhai and Michel (2013) | Rules of building simulation tools in sustainable building design | NA | NA | NA | NA | Sustainability | Building energy modeling, Computational fluid dynamics, Lighting modeling, Life cycle | Theory | Literature study | Idea generation on sustainability. |
| 5     | Baghthe et al. (2016) | The research examines the main factors of residential open space quality in relation to design in approach to urban spatial organization | Tehran, Iran | Residential | NA | NA | Quality of Open spaces | Revising the Theories of urban spaces. | Theory | Literature study | Lack of planning and design criteria of physical - spatial, in the construction of new urban areas can be substantial problems in housing and environmental roles to be. |
| 6     | Balwi et al. (2010) | The goal was to examine the effect on the forecast of daylight availability in an indomable of the collection of one weather file or another. | Five European locations (Copenhagen, London, Milan, Nancy, Rome) | Office Building | NA | Weather data is calibrated with the Satélite Light archive. | Daylighting in the building | Results were analyzed both in terms of annual and monthly Light Exposures and dynamic daylight performance metrics. Analysis of UDI, Bicon and UDI | Simulation and experimental | DAYSIM (version 3.5a) | The results recorded in this paper show that the use of weather files from IWEC, Meteonorm and Satélite Light for dynamic daylight simulations results in similar results for a north-oriented environment. |
| 7     | Sudan et al. (2016) | The research is to understand the total energy saving for the home, and can also be extended to other structures, by thermal as well as daylighting for compact climate. | Composite Climate, Yaravvi | Office building | NA | Data calibrated with actual site data | Thermal and Daylighting energy | Hourly data recorded such as Hourly lighting power, Luminous Flux daily and monthly energy saving, CO2 mitigation | Simulation and experimental | NA | No requirement for artificial lighting during the day was needed. By using the daylight principle in the building, annual energy savings of 367.61 kW h have been reported. |
| 8     | Ogan et al. (2017) | This manuscript herein analyses the significance of interior daylight in simulation results by thoroughly comparing the energy use intensity (EUI) levels for a reproducible set of floorplans against the ASHRAE prescriptive zoning scheme. | Cooling-dominated (Phoenix weather), heating-dominated (Anchorage weather) and a mixed climate (Boston weather) | General Building | NA | NA | Energy use Intensity/EUI and its four components: lighting, electric, heating and cooling loads | Cubic case is simulated and analyzed with 5% of error, same repeated for three other climatic conditions. | It contains two main sections. The first section presents a process of typological sorting for floor plans based on their exterior or morphology and interior orientations, the second section these samples are translated into energy models. | Architecture, Rhino, Grasshopper | Archic, Rhino, Grasshopper | This paper shows cases with significant inconsistencies in predicted energy use intensity for the ASHRAE 90.1 Appendix G thermal zoning when compared to actual floorplan layouts. |
| Sl. no | Author and Year | Objective | Location and Climate Type of Building Courtyard | Dimension Calibration Parameters Studied | Analysis Criteria | Methodology | Simulation Tool | Conclusion |
|-------|-----------------|-----------|-------------------------------------------------|----------------------------------------|-----------------|-------------|-----------------|------------|
| 9     | Hafith et al. (2017) | This thesis explores Concept Builder's abilities in simulating the thermal behavior of the courtyard | Hot climate region, Baghdad, Saudi Arabia Courtyard model | NA | The results of the model simulation were correlated with real-life Therm and Daylighting energy | Hourly temperature analysis was performed. | DesignBuilder | The findings indicate that the effects of the ConceptBuilder simulation are very different from the results measured, questioning the software's applicability in this particular case. |
| 10    | Mendata et al. (2018) | The research is to test the process of measuring the daylighting widely used in architectural study | Uniform sky simulation model with Overcast sky | A square model of a space measuring 8 x 4.5 meters with an opening on one side of it. | NA | Daylighting in the building | Simulation and experimental: SNI/DPMB method, IRE Daylighting Protocols, computer programs using Dialux and Volumetric software | Get positive results, established similar results in different conditions with different methods. |
| 11    | Brembilla et al. (2019) | The main objective of the work was to compare some of the widely available Radiance-based software methods, expressing their results in terms of annual daylight metrics. | Blended CIE (for 4 component method) and Perez All-weather model | Four classroom spaces are used to carry out an inter-model comparison between performance metrics | NA | Inter-model comparison | Simulation run for all five methods and inter-model comparison is done. | Find 4Plus ad is more efficient |
| 12    | Kumar and Kavitha (2019) | In this paper, the impact of daylighting in residential buildings was studied and analyzed. | All climatic zones of India Residential Typologies | NA | Daylighting in the building | A review of literature was done to document and analyze the well-being in terms of user's daylight comfort in the residential buildings. | Ecotect daylight simulation performed using Radiance Beta 12.0 | Factors such as location, weather condition, and environmental built are directly interdependent on the natural climatic and geographic conditions. Hence, the interior structure of residential buildings and window sizes are important for daylight efficient design. |
| 13    | Royori (2020) | The purpose of this analysis is to determine the influence of Radiance parameters and model-related components on the accuracy of Radiance simulation results by comparing the results of field measurements and simulation. | Overcast sky General model | NA | Daylighting in the building | Analysing ODF at a point at different time. | Manual data collected and experimental and simulation based | The results obtained also suggest that the height-to-width ratio and height-to-width ratios are 6:1 to 5:1, while horizontal and vertical surfaces are ideal for testing purposes in close windows and in middle space along the longitudinal direction. |
| 14    | Nazirollahi (2020) | The key purpose of this paper is to provide applied solutions for the use of more natural lighting techniques as an alternative to artificial lighting, which aims to minimize the consumption of electrical energy while supplying visual comfort. | Overcast sky General office model | NA | Daylighting, visual comfort, energy performance in the building | Analysing ODF. | Experimental and simulation based | The results obtained also suggest that the height-to-width ratio and height-to-width ratios are 6:1 to 5:1, while horizontal and vertical surfaces are ideal for testing purposes in close windows and in middle space along the longitudinal direction. |
C. Sky model

Sky condition plays a crucial role in the analysis of energy performance and daylighting. The daylight factor was one of the initial matrices that were used for the research based on overcast sky conditions. New daylight matrices use climate-based sky in the simulation, in which sun position varies with the location, day, and time. The climate-based sky gives more clear and accurate simulation results. Figures 4, 5, and 6 depict the percentage of different climate zones and sky conditions used in the reviewed literature based on energy, daylight, and thermal comfort. Figure 5 shows that 44% of the reviewed literature based on daylight used experimental models, in which 28% used the overcast sky condition [4, 5, 15, 20-24] and 16% used the climate-based sky [13, 15-17]. No experimental model was used for the study of thermal comfort. It was found that experimental models were generally used for the analysis of energy and daylight. The overcast sky conditions were widely used for daylight analysis, which was not very specific. For the daylight analysis actual cases with climate-based sky were used in limited literature; it was a gap.

D. Weather file

Weather files were consolidated weather data of the overall year of a particular location, monitored and recorded by the local weather station. Weather files were very helpful in conducting modern-day research through simulation and analysing the building. For India, weather files related to all climatic zone are available on the ISHRAE website: ISHRAE “Typical Year” weather files can be used in the simulation program.

E. Building type

Various types of building typologies were analysed in the reviewed literature, such as Residential, Experimental models, Office, Mixed-use, Urban courtyard, Institute, and General building/Standard building. Figure 7 shows the percentage of different building types in the overall reviewed literature, 29%, i.e., eleven have studied residential typology [8, 9, 22, 25, 26, 30, 32-34, 38, 41], 29%, i.e., eleven studied the experimental models [4, 10-12, 15, 19-21, 23, 24, 35]. Figure 8, 9, and 10 depicts the number of building types used in the reviewed literature based on energy, daylight, and thermal comfort. For the energy analysis, a maximum of 57%, i.e., four of the literature were experimental models [4, 10, 24, 35], 29%, i.e., two were office typology [13, 14], and 14%, i.e., one literature was residential typology [9]. Figure 9 depicts the number of different building types in the reviewed literature based on daylight. 43%, i.e., nine of the literature studied were experimental models [10-12, 15, 19-24], 29%, i.e., six were office typology [6, 7, 13, 14, 17, 18], 14%, i.e., three were residential typology [8, 9, 22], 5%, i.e., one mixed-use building [5], and 9%, i.e., two were general buildings [2, 17]. Figure 10 depicts the number of different building types in the reviewed literature based on thermal comfort. 43%, i.e., six of the studied literature were residential typology [13, 25, 26, 30, 32-34], 22%, i.e., three were urban courtyard [27, 28, 31], and 14%, i.e., two were experimental models [11, 18].

The analysis provides us an idea that, generally, experimental models were considered for the study for daylighting and energy. While for thermal comfort, residential typologies were studied in maximum cases. There was a gap in the study of daylighting in courtyards of the residential typology.
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F. Verifying method

Figure 11 shows the percentage of reviewed literature verified with calibration, validation, and not verified. 35% of the literature was calibrated, 15% were validated, and 50% of the literature was not calibrated or validated. Figure 12 shows the percentage of verifying methods used in the reviewed literature based on daylight. 45% of studies were calibrated [6, 9, 10, 14, 17-19, 21], and 20% were validated [4, 7, 9, 28] based on daylight. The study says that calibration and validation is the major step in the research based on daylight analysis.

G. Simulation tools used

Figure 13 illustrates the different state-of-the-art simulation tools which were used in the reviewed literature. Radiance was introduced in 1994; it is a command-line-based program. Radiance doesn't have any user interface, which is a negative point, but it is very accurate in calculating the daylight in both overcast and climate-based sky conditions. In the overall reviewed literature, Radiance was used in the maximum, i.e., six [4, 12, 15, 16, 22, 23], Design builder was used in five [8, 9, 11, 19, 32], and Velux-Relux were used in five [13, 20, 24]. In the reviewed literature, which talked about the energy analysis, Velux-Relux was used in two [20], Design builder was used in one [19], DOE2.1E. was used in one [35], and Archsim was used in one [7] of the reviewed literature; see Figure 14.

Figure 15 illustrates the number of reviewed literature that discussed daylight; Radiance was used in six [4, 12, 15, 16, 22, 23], and DAYSIM was used in three [15, 17, 21]. Figure 16 illustrates the number of reviewed literature based on thermal comfort, majorly Designbuilder were used in two [11, 32], Ecotect was used in two [26, 30], and ENVI-Met were used in two [27, 31], of the reviewed literature. Honeybee-ladybug was used in 5%, i.e., one literature based on daylight [23].
It is a plugin software of Grasshopper that uses Radiance and DAYSIM for daylight analysis. The software carries user friendly format and free accessibility to the user. It is suggested to use Honeybee-ladybug in the research based on parametric environmental analysis.

**H. Daylight matrices adopted**

Figure 17 depicts the number of different daylight matrices used in the reviewed literature based on daylight. Maximum 35% i.e. eleven of literature used DF (Daylight Factor) [4-10, 20-24], 19% i.e. six used UDI (Useful Daylight Illuminance) [7, 14, 16, 17, 21, 22], 19% i.e. six used DA (Daylight Autonomy) [7, 13, 15, 17, 21, 22], 9% i.e. three used sDA Spatial Daylight Autonomy [7, 14, 21], 10% i.e. three used ASE (Annual sunlight exposure) [7, 14, 21], and 9% i.e. three used E (Illumination) [8, 12, 13]. DF was analysed in the overcast sky conditions, and all other matrices were analysed in climate-based sky conditions that define the detailed analysis of the building. Illumination (E) was used in a few of the literature, which defines the amount of light at a point on a particular day at a specific time. It was a gap in the reviewed literature to consider illumination level analysis for the existing case.

**I. Methodology adopted**

The reviewed literature was categorized as per the methodology adopted in the studies. In the overall analysis, 50%, i.e., nineteen of the literature were adopted the experimental-simulation methods in which collected site data were calibrated or validated with the simulation data [4, 6-9, 13, 16-20, 23, 24, 26, 27, 32, 35], or physical models were analysed in different conditions to achieve the results. 21%, i.e., eight of the literature were based on the simulation methodology, in which direct simulation was carried to achieve the results [5, 12, 21, 22, 25, 32, 36]. 10%, i.e., four of the literature used mathematical methodology [10, 28, 29, 38], 5%, i.e., two of the literature used mathematical-simulation [1,31], 3% i.e., one of the literature used parametric [14], 8%, i.e., three of the literature used theoretical [39,40], and 3%, i.e., one of the literature used experimental methodology [10] see Figure 18.

Figure 19 depicts the number of the reviewed literature based on the methodology adopted for energy analysis. 50%, i.e., six of the literature adopted experimental-simulation methods [9, 35], 25%, i.e., one used simulation methodology [36], and 25%, i.e., one used parametric methodologies [14]. Figure 20 shows the number of the reviewed literature based on the methodology adopted for daylight analysis.
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The Experimental-simulation methodology was used in 64%, i.e., fourteen of the reviewed literature [4, 6-9, 13, 15-20, 24], and 23%, i.e., four of literature adopted simulation methodology [5, 11, 12, 21, 23]. Figure 21 shows the number of the reviewed literature based on the methodology adopted for thermal comfort analysis. The experimental-simulation methodology was used in 41%, i.e., five of the literature [26, 27, 30, 34], 25%, i.e., three used simulation [11, 25, 32], and 17%, i.e., two of the literature used mathematical methodology [1, 31]. It can be seen that experimental-simulation methodology was used in maximum numbers of the reviewed literature. For any research work based on daylighting, calibration or validation were important for verification of the data; together with these verifications, the experimental-simulation methodology should be adopted.

J. Methodology framed

The research begins with reviewing the literature of the associated field. The study of literature was divided into two parts.

- Part 1 carries the literature associated with the courtyards, courtyard houses of Composite climate, daylighting in courtyards, parameters related to courtyards, and daylighting.
- Part 2 carries the literature associated with the methodology, which covers simulation technics, associated software, weather files, sky conditions, calibration, and analysis of data.

Analysis of the literature review was done to find out the study gap to formulate the methodology.

The second stage was selecting the case studies. The criteria for determining the cases were based on the age of the houses, type of courtyards, type of placement of courtyards, climatic zones, and collection of the data from the site.

Collecting the illumination data with a certified Lux meter. The analysis of courtyard parameters was done that plays a key role in achieving adequate daylight in the courtyard with the help of plans and sections.

The third stage carries the modeling cases on the software, as precise as the actual site condition. Models of all the cases can be replicated on Sketch Up 2017, then simulation of all the case studies can be carried out on the parametric daylighting analysis software. Honeybee-Ladybug based on Radiance is recommended for the simulation. Grid-based illumination analysis to be done with fixed radiance parameters and weather file. Calibrating the site data with the simulation data for the same time and dates. Further simulation to be done on the standard days of the year, such as equinox and solstice. Comparing and analyzing all cases to find the results. Figure 22 illustrates the methodology framed for the study of effective daylighting in the courtyard houses of composite climate.
IV. CONCLUSION
The paper fulfills the aim of the research to formulate a research methodology for the analysis of effective daylighting in courtyard houses of composite climate. Studying the publication year, climate zone, sky model, weather file, building type, verifying method, simulation tools, daylight matrices, and methodology adopted of the reviewed literature framed the methodology Figure 22. Moreover, this research paper gives the following outcomes.

- From the study, it is evident that daylight is the first choice of the present researchers for analyzing the built space.
- It will be helpful to refer to the latest literature study for the research work. The capabilities of new matrices were enhanced because of the availability of a variety of simulation tools.
- Courtyard houses of Composite climate were generally studied for thermal comfort in major cases. The study of the courtyard houses in Composite climate for daylighting purposes was minimal; it is required to fill the gap.
- The experimental model’s based research studied in the reviewed literature used overcast sky conditions for the Daylight factor in significant cases. Studies using climate based sky condition seems in limited cases, future researches can be done using climate based sky for detailed analysis.
- For the daylighting analysis, the researchers prefer the experimental model instead of actual residential typology; on the other hand, real cases were used in the major reviewed literature for thermal comfort analysis. It is advised to use actual residential typology for future daylighting study.

- Various simulation tools were used in the reviewed literature; their maximum was based on energy plus and radiation. Honeybee-Ladybug is suggested for the parametric environmental study.
- New daylight matrices based on climate-based files can be used for achieving detailed results.
- For any research work based on daylighting, calibration or validation were important for verification together with experimental and simulation methodology can be adopted.

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