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The promise of BIM for improving building performance

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ABSTRACT

In order to raise awareness of the role of building information modeling (BIM) in improving energy efficiency and comfort conditions, the work introduces a strategy of combining building simulation tools and optimization methods. Furthermore, it emphasizes the fact that a combination of these strategies with BIM can improve not only the construction process but also enable exploration of alternative approaches. The work discusses the potential application of data integration methodology for an office environment and focuses on the review of the potential performance of integrated systems. It also explains how BIM can help facilitate review of results and methods for improving building performance in terms of energy efficiency and indoor environmental quality.

1. Introduction

The retrofit strategy represents an opportunity to upgrade the energy performance of buildings. Therefore, it is important to establish the optimal energy retrofit strategies for existing buildings. Ma et al. [1] stated that retrofitting of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions. Although there are a wide range of retrofit technologies readily available, methods to identify the most cost-effective retrofit measures for particular projects still present a major technical challenge. One of the biggest barriers to retrofit existing buildings is the lack of reliable data sources. In fact, retrofitting problems are related to multi-attribute decision issues and unfamiliarity with the existing systems. Furthermore, there are many challenges associated with the determination of real energy consumption. For example, the actual amount of energy used in the existing buildings is often uncertain due to climate change, user behavior change, building system changes, etc.

In order to improve existing building retrofit strategies, a systematic approach to identification of appropriate retrofitting options is needed. According to the study [2], energy efficient building retrofitting needs to not only be technically feasible, but also economically viable. It is important to consider integrated steps that include reviewing requirements, identifying options and conducting techniques (Fig. 1). In this context, a series of key factors such as building expectations, building information, user behavior, and retrofit technologies should be studied in deep.

The key factors identified in the process of retrofitting buildings should be considered regarding their condition. Furthermore, building retrofits that replace equipment and components should offer more opportunities for existing buildings to improve their energy performance. In order to obtain the complete state of a retrofitting process, it is essential to assess conventional technologies, design analysis, existing HVAC systems and construction technologies. It can also be useful to provide a framework for retrofitting existing buildings under uncertainty which result in better understanding their condition.

In order to improve the sustainability of refurbishment projects, it is necessary to integrate promising innovative tools which can not only develop efficient solutions but also accelerate the development of optimal comfort conditions. In this context, BIM is used as one of the most significant strategies to assist in meeting these objectives.

BIM can play a key role in analyzing and determining energy consumption in existing buildings. It has an important effect on the accuracy of estimates. As BIM is a tool to estimate accurate building information it can be used to predict the energy performance of retrofit measures by creating models of existing buildings, proposing alternatives, analyzing and comparing building performance for these alternatives and modeling improvements [1,3]. BIM is also accepted as a process and corresponding technology to improve the efficiency and effectiveness of delivering a project from inception to operation/maintenance [4].

In the context of architectural practice, especially in areas of sustainable design, innovative digital environments and tools can provide useful insights. For example, BIM has become ubiquitous within the architectural sustainable design for addressing the

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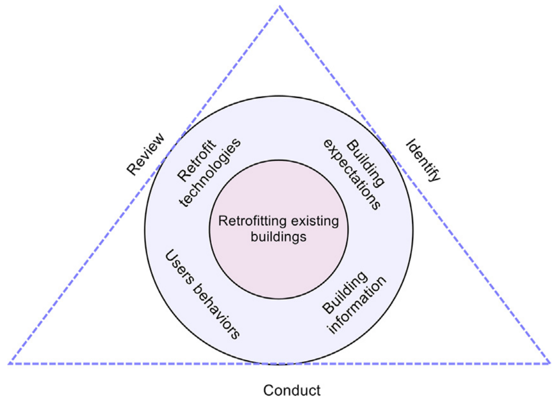


Fig. 1. Key elements influencing building retrofits.

issues related to a full lifecycle of a target project. BIM can offer an opportunity for extending the life-cycle analysis of buildings.

BIM is able to solve complex challenges in refurbishment projects. It can play a role in determining optimization requirements. It is considered as a long-term vision for building renovation. Furthermore, BIM is more cost and time effective to assess the sustainability of refurbishment projects and can contribute to economic growth.

According to Kensek [5], BIM is collaborative, encouraging the sharing of data, knowledge, responsibility, risk and reward. It fosters integrated project delivery (IPD), while still providing benefit to projects under other types of project delivery contracts such as design–bid–build, design–build, or CM (construction manager) at risk.

Gerrish et al. [6] discussed and identified the barriers facing implementation of BIM for building designers and operators as a performance optimization tool. The study [7] explores the engineering dimensions of common decision-making procedures within BIM systems including optimization methods, buildability and safety constraints and code compliance limitations. It argues that BIM can offer the further benefits in order to facilitate the conflicting nature of both energy efficient and engineering performance indexes.

A new study [8] finds BIM can be used to facilitate the impact of orientation on energy consumption in small-scale construction, and the study [9] investigates system interfaces between BIM and energy simulation, which can perform semi-automatic translation from the building models in BIM to building energy modeling (BEM).

It is clear that BIM applications in new buildings can create lifecycle stages from outset to demolition and can be used for prototyping, visualization, comparing different design options and facility management [10]. According to Stundon et al. [11] BIM is documented as an essential tool for the integration and amalgamation of intelligent and informative models, based on underlying information, integrated within a common data environment. In many cases, BIM has been leveraged to enable information sharing and reuse for interoperability between prevalent software tools in the AEC (Architecture, Engineering, and Construction) industry [12].

Energy efficiency and environmental issues have led to the emergence of digitalization and visualization technologies for analysis of natural and built environments. BIM is one of the most important tools in digitalization and visualization of data regarding natural and built environments and can provide fundamental adaptation strategies for climate change and sustainable operations. For example, the study [13] used BIM technology to conduct an energy consumption analysis and simulated re-design of an existing building. It investigated building envelope design alternatives on energy-saving effects in the BIM tool.

Determination of building energy performance is one of the most important steps of creating sustainable building retrofits. Energy performance of a building consists of the amount of energy consumed or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alia, heating, hot water heating, cooling, ventilation and lighting [14]. Energy performance is a systematic approach to evaluate the external climatic conditions, indoor conditions and cost factors. It includes criteria to improve the energy in buildings, evaluation of the applicability of renewable energy sources and criteria on how to limit greenhouse gas emissions. Calculation methods for the determination of energy performance are used in conjunction with primary energy consumption.

Simulation and measurement are two important methods to obtain energy use of buildings. The purpose of methods is related to environmental protection and the prevention of energy waste and regulation of the procedures and principles. According to EN ISO DIS 13790 Standard (2007) [15], one of the main standards to determine energy use of buildings, there are two paths for calculating the net energy for heating and cooling as follows: 1) simplified methods based on seasonal, monthly or hourly calculations; 2) comprehensive calculations, typically made with dynamic energy simulation programs.

In the context of building energy performance (BEP), analysis of presence patterns has a significant impact on the reliability of assessments. BEP is a measure of efficiency and comfort. It is widely used to evaluate the performance of energy systems and is expected to determine alternatives expectations in analysis works to meet energy loads with renewable energy. There are several ways of assessing of energy performance in the buildings.

In order to assess the actual energy consumption in buildings, it is essential to collect all data concerning the building envelope, the air-conditioning system, the lighting equipment, etc. In this context, building energy software tools and energy consumption surveys can also be utilized as methods for predicting building energy performance and requirements.

Energy efficiency and environmental awareness in the early design phases may affect whole building performance. Simulation programs play a significant role in decision making, the development of optimization methods, calculating and reporting building energy performance at the early stages of the design process.

Nowadays, building simulation programs are increasingly being used in several studies of energy performance, thermal comfort, lighting, etc. They are commonly classified by their calculation and level methods and are used in order to improve building energy performance or optimize energy consumption.

According to Hensen and Lamberts [16], computational building performance modeling and simulation on the other hand, is multidisciplinary, problem-oriented and wide(r) in scope. It assumes dynamic (and continuous in time) boundary conditions, and is normally based on numerical methods that aim to provide an approximate solution of a realistic model of complexity in the real world.

It should be noted that the primary purpose of energy performance building evaluation, is to develop effectiveness methods for reducing energy consumption and classification of energy consumption patterns. In this context, building elements are increasingly used to evaluate thermal and energy performance. Opaque components and transparent components are one of the most important elements of the building envelope. In order to ensure energy savings and comfort in the buildings, building elements need to be fully analyzed before construction process.

The role and importance of elements, especially in the building envelopes, can be categorized according to the environmental performance of materials used. It is necessary to establish a database based on environmental profile of elements which can provide options for renovation projects and energy efficiency schemes. It is also important to analyze the environmental impacts of each of the materials used throughout their life cycle. Performance visualization of building elements can provide a detailed insight into the environmental profile.

BIM software tools can be used for modeling building elements and carrying out energy optimization techniques. BIM-based building geometry data can also be used to visualize simulation models and results in building performance simulation (BPS) tools. For example, the study [17] focused on the way that BIM can used for building performance simulations and how daylighting analysis can be incorporated into a BIM environment. Furthermore, the study [18] developed a method to show how actual thermal properties can be automatically associated with BIM elements and enable reliable energy analysis for retrofit.

The main goal of building element analysis is to develop optimization scenarios to improve economic and environmental performance. In this context, dynamic building simulation plays a key role in supporting decisions and management process. BIM is considered as a useful tool to optimize the environmental performance of building elements and buildings. It can help to study the characteristics of building elements and the influence of environmental factors on buildings through computational techniques.

In order to develop an efficient building refurbishment, it is necessary to analyze the building elements and material properties. It should be noted that building element analysis can make an important contribution to develop retrofit solutions in terms of energy consumption, comfort and environmental quality. Building elements such as walls, windows, doors, and stairs can play a significant role in determining a building's energy use, thermal comfort and indoor air quality.

In this context, climatic data plays an important role in the evaluation of energy performance of buildings and their elements. It is important to consider what type of climate data are appropriate for energy models. Furthermore, it is essential to know the exact location of the proposed model in terms of longitude and latitude. Climate is defined as certain conditions of a geographical location based on parameters such as temperature, humidity, wind and solar radiation. Climate condition varies from region to region. Climate analysis is a method to better understand the spatial and temporal characteristics of climate. It can be useful to advance solutions to sustainable development and energy-efficient buildings.

Climate analysis can be used to create diagrams and graphic presentation of the weather to develop effective and sustainable strategies in the built environment. Climate sensitive approaches are one of the essential requirements for developing adaptation programs. They can address climate risk issues and opportunities. To achieve climate sensitive approaches, it is essential to obtain the understanding of climate conditions and existing environmental conditions.

The climate of a location is often influenced by a series of real weather condition segments during a period. It is necessary to determine the essential elements of climate that impact on both natural environment and built environment. Annual temperature, humidity, solar radiation and rainfall profiles are the most important elements of climate. In fact, they can provide more detailed information through diagrams to measure variability in climatic conditions. Each region is frequently represented by the geographic coordinate system which consists of latitude and longitude lines. In order to gain information about actual climate data, it is required to focus mainly on local and annual data profiles. For example, annual temperature profile provides a measure of the seasonal range of temperature. Its value is different from region to region and depends on away from the sun and the sun's rays.

Microclimate variables (temperature, humidity, air quality and solar radiation) are the key factors that affect both indoor and outdoor environments. It can be noted that analysis of microclimate variables can be useful to predict energy consumption in buildings. For example, increases in outdoor air temperature and humidity can often cause excessive energy demand, in particular in electricity demand. Evaluation of microclimate variables can present an opportunity to achieve energy savings.

The profiles of microclimate variables (e.g. temperature and humidity profiles) can be helpful to predict indoor and outdoor thermal comfort conditions. For example, outdoor temperatures and weather-related conditions can influence indoor thermal comfort, humidity and indoor air quality. Therefore, it is necessary to carry out a preliminary analysis of microclimate variables in order to determine comfort conditions.

In the context of environmental profiles, humidity is another significant factor that affects thermal comfort in both outdoor and indoor environments. It is defined as the amount of water vapor in the air. Therefore, in order to reduce humidity levels in the indoor environments, increasing the ventilation can be considered as an acceptable solution.

Relative humidity has a direct impact on thermal comfort. Furthermore, it is a meaningful parameter in determining thermal comfort [19]. It should be considered in planning for adequate environment.

It is well known that outdoor comfort in the urban environment is affected by outdoor temperature and humidity parameters. The determination of these parameters should be considered in the development of appropriate design strategies that can reduce the intensity of urban heat islands. Furthermore, they should be examined more carefully in view of their influence on the built environment. In this context, BIM can be designed to simulate urban environments and microclimates. For example, a BIM-based model was used to visualize the readings of air temperature and humidity levels in the subway spaces [20].

In addition, the solar radiation analysis can be considered to improve energy performance in buildings. The sun is a significant source of renewable energy, it would be worthwhile to explore the possibilities of converting solar radiations into electrical energy and thermal energy. Analysis of incident solar radiation which is based on two primary components such as direct radiation and diffuse radiation, can help to determine the amount of heat gained through building surfaces. It can also be used to calculate the optimum comfort ranges, building energy balance, heat-transfer rates, etc.

According to Causone et al. [21], the analysis of solar radiation effects on the built environment should be separated from the study of other kinds of thermal radiation effects. They examined solar radiation effects on radiant cooling systems and presented an approach that can convert solar radiation to cooling load which is defined as the direct solar load. Solar radiation analysis is a method to assess microclimate aspects and can be useful at the conceptual design stage of a project to find optimal strategies.

The availability solar radiation over a site is a major driver of building form and orientation. Solar radiation can contribute to the reduction of the heating and cooling loads in the buildings. However, solar radiation, in some cases, should be controlled by shading device to achieve significant cooling load reduction. In this respect, it is necessary to implement shading devices into transparent surfaces facing south.

In order to understand the impact of solar radiation on building performance, it would be useful to investigate different areas such as passive strategies, daylighting, and renewable energy. Solar radiation plays an important role in the development of some sustainable energy sources.

A detailed investigation of solar radiation amount and variability can be useful in order to optimize solar access of buildings. In fact, studies to analyze solar radiation should focus on establishing appropriate methods for optimizing objectives with regard to local climatic conditions. The contribution of solar radiation for prediction of energy consumption and thermal storage should be considered in the initial part of the design process. The study [22] showed that solar energy is a valid strategy for producing on-site renewable energy. A process map decisions regarding solar energy needs presented in this study.

In order to determine monthly direct and indirect solar radiation (solar energy potential value) and the amount of accessible solar energy, visualization and analysis tools (e.g. Geographic Information Systems (GIS) and BIM) have been developed and made available. These tools can help to understand the solar potential of buildings by sharing solar reports.

It is known that architectural design influences elements of the built environment and outdoor comfort. To achieve sustainability in the built environment, design strategies should attempt to create a consistent and comfortable microclimate. Furthermore, they should provide possibilities for improving energy efficiency and comfort through microclimatic landscape design and planning which make a crucial contribution to improve sustainability of buildings and cities.

A detailed analysis of outdoor parameters can help promote objectives of sustainable design. In addition to the parameters mentioned before, wind is another significant factor for assessing thermal comfort levels in the climate and urban areas. Also, wind is an important driving force for infiltration and ventilation because wind causes variable surface pressures on buildings that change intake and exhaust system flow rates, natural ventilation, infiltration and exfiltration, and interior pressures [23].

Wind is caused by differences in air pressure. It must be analyzed in terms of velocity and direction profiles to understand its impact on the environment. Efficient use and environmental protection of wind have beneficial effects not only on building performance but also on developing sustainable design principles. Accurate wind analysis is critical in estimating the potential of natural ventilation systems which is investigated by using wind tunnel tests and computational fluid dynamics (CFD) calculations. These analysis tools are being increasingly used for the prediction and the assessment of detailed wind environments around buildings. For example, BIM tools combined with Ecotect can be used for wind resource assessment.

To assess wind conditions in the urban environment in terms of velocity and direction, it is necessary to provide estimates of appropriate directional wind speeds and robust design strategies with regard to local climate conditions. To meet wind design requirements in cold climate zone buildings should be oriented perpendicular to the prevailing wind direction to minimize heat losses while in warmer climates, to take advantage of wind patterns for cooling purposes, they should be oriented in respect of the prevailing wind direction. The essential purpose of a wind analysis is to examine the mean wind profiles for promoting natural ventilation in urban buildings. In order to evaluate wind-driven natural ventilation, the primary vision is to determine the appropriate outdoor airflow rates that are consistent with acceptable indoor air quality levels.

2. Methodology

In order to understand the benefits of applying BIM to improve building performance, energy use and indoor comfort metrics of a case study were evaluated. The case study is one of the building blocks of science and technology center, University of Ferrara-Italy (UNIFE) Department of Physics and Earth Science. A proposed framework is used to explore the performance of existing building in Ferrara (Italy). The first step is to establish a framework to determine building energy and environmental performance of case studies. Building performance simulation (BPS) tools were used to assess them (Fig. 2).

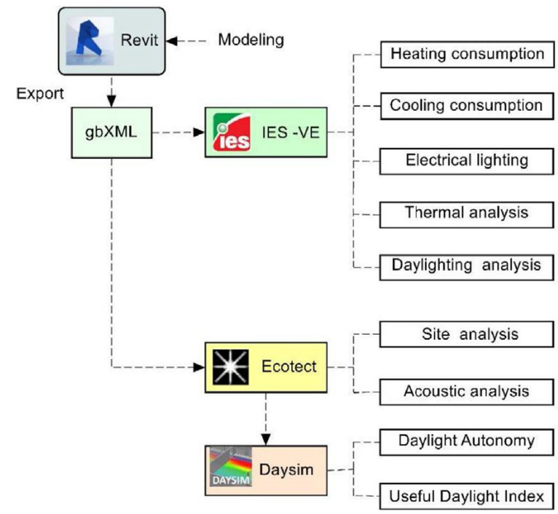


Fig. 2. Overview of building performance simulation (BPS) tools used.

Table 1
The relevant case study data.

Surface areas of floors	1130.025 m^2
Total south window	164.291 m^2
Total window area	1186.1 m^2
Height/stories	ground floor (3.80 m) & floor-to-floor (3.50 m)/4 stories
Total surface area	5442.546 m^2

The reference building (UNIFE) is based on Department of Physics and Earth Science, the home building of University of Ferrara-Italy in a Mediterranean climate, and is an office building occupied by teachers, researches and students (Fig. 3). It has 5 floors plus a basement. A detailed simulation analysis and review on case study has been given. ASHRAE 90.1-2007 (climate zone 4, mixed-humid) was used as a reference to simulate the energy consumption of case study. Before simulating, specific information input requirements for case study was identified (Tables 1 and 2).

Position of the sun relative is a major factor in providing daylight and passive design strategies in the buildings. In order to study building orientation in relation to solar radiation and passive solar gains through façades, a detailed solar analysis is performed by Ecotect 2011 for case study (Figs. 4–6). Furthermore, the analysis was performed to understand which faces or walls receive the maximum solar during a year. Building energy consumption is the amount of energy necessary to meet the requirements of thermal comfort, electric lighting and other equipment. The amount of passive solar can be considered as a natural energy reference to decrease the energy consumption of buildings. Solar access analysis can be used to determine the best building orientation on a site and provide the average daily incident of solar radiation values for all seasons. Also, it provides an indication of the energy absorbed by façades and opaque surfaces which is the main factor in determining the potential and performance of solar PV systems in the buildings.

In this context, a sun path diagram can be used to display the position of the sun which is determined by the solar altitude and solar azimuth. It is a function of site latitude, solar time, and solar declination. It also includes information such as horizontal and ver-

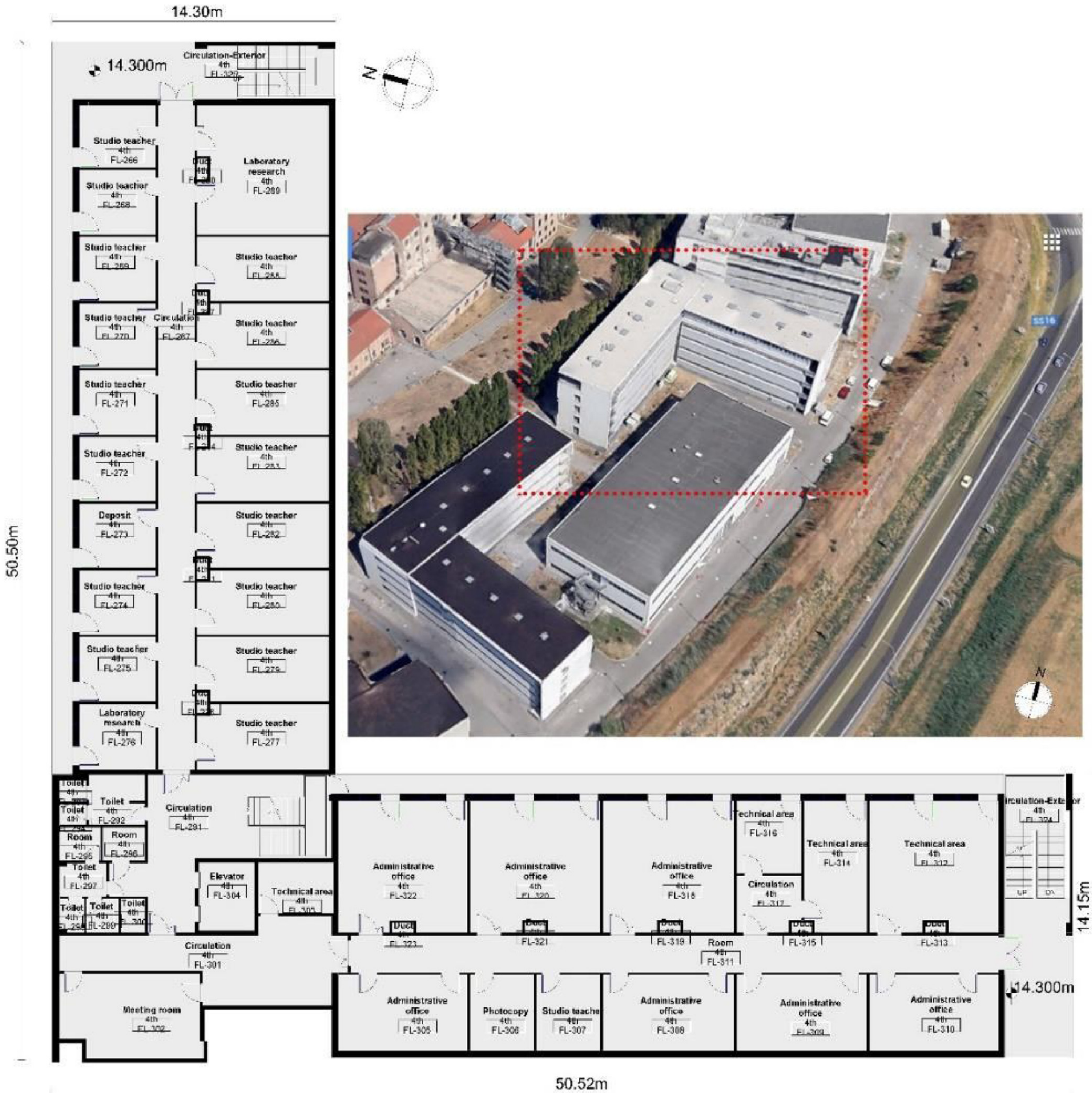


Fig. 3. 3D view of case study and its fifth floor plan (zone evaluated).

tical sun angles. The sun path diagram can be useful to determine the tilt angle of shading devices which impact indoor cooling loads and air temperature. It visualizes the building's shadow throughout an entire day and the spherical projection of the sun's position on the building.

Moreover, diffuse solar exposure is considered to evaluate the total amount of energy received at a specific façade when most exposed. It has a significant effect on thermal comfort and is included in the mean radiant temperature (MRT) calculation.

2.1. *Comfort and weather analysis*

It is important to understand outdoor environment condition before being able to develop a climate responsive building. The weather analysis tool is used to identify the outdoor environmental parameters for a particular location. It display different graphic images of various weather attributes. Furthermore, it can used to identify the potential application of passive design strategies. In this context, Climate Consultant 6.0 is used for the analysis and presentation of weather graphics. It reads the local climate data for all 8760 h per year in EPW (EnergyPlus Weather) format.

Bologna (Ferrara) has a humid subtropical climate. According to Climate Consultant 6.0, the temperature charts of Bologna (Ferrara) show that the mean temperature is higher than the comfort zone during four months of the year (June-September). In addition, the climate of city differs greatly in respect to relative humidity (Fig. 7).

Psychrometric chart presents physical and thermal properties of temperature and humidity parameters. It presents the relationship between air temperature and humidity in graphical form, and describes thermal comfort conditions for each climate category.

Table 2
Thermal properties of materials used in case study.

Construction	Layers	Material	Thickness (mm)	U value (W/m^2 k)
External wall	Outermost layer	Plaster	20	0.35
	Layer 2	Brick	180	
	Layer 3	Polystyrene foam	50	
	Layer 4	Block	120	
	Innermost layer	Plaster	15	
Internal partition	Outermost layer	Plaster	10	1.89
	Layer 2	Brick	120	
	Innermost layer	Plaster	10	
Floor	Outermost layer	Ceramic tiles	10	0.53
	Layer 2	Cement	10	
	Layer 3	EPS	50	
	Layer 4	Concrete	300	
	Innermost layer	Gypsum plaster	10	
Roof	Outermost layer	Aluminum	0.6	0.49
	Layer 2	Cement	120	
	Layer 3	Insulation	50	
	Layer 4	Concrete	300	
	Innermost layer	Gypsum plaster	10	
Glazing	Double glass aluminum sliding window			1.56

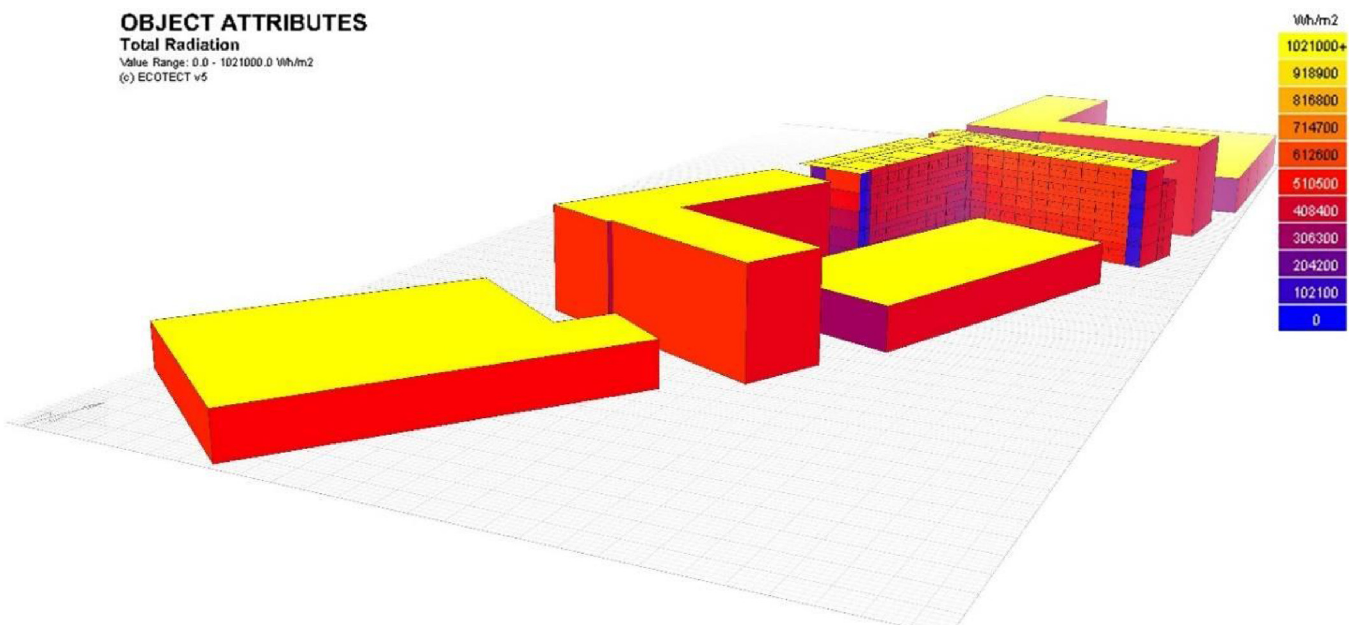


Fig. 4. Solar analysis of case study and its site plan performed by Ecotect 2011.

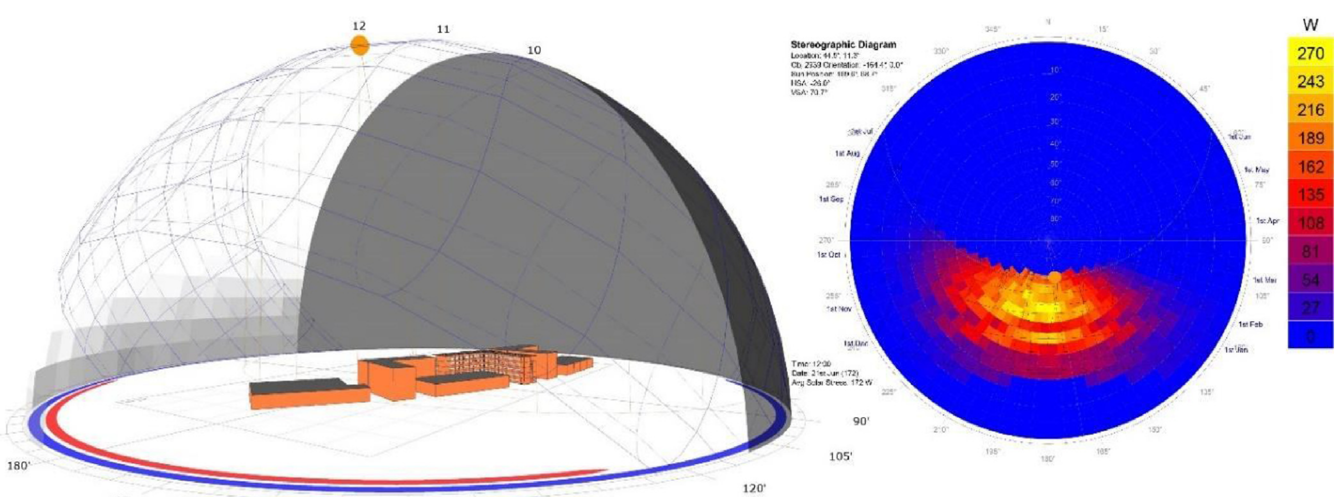


Fig. 5. Sun path diagram (left) and direct diffuse (right) of south façade of case study on 21 June performed by Ecotect 2011.

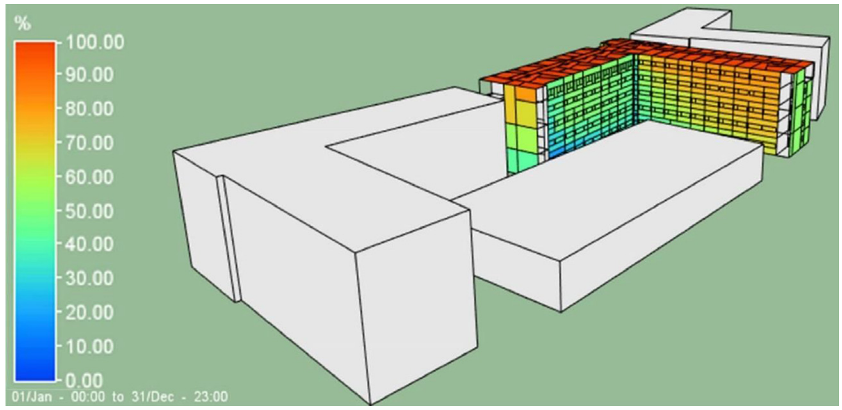


Fig. 6. Solar exposure of case study performed by IES- VE.

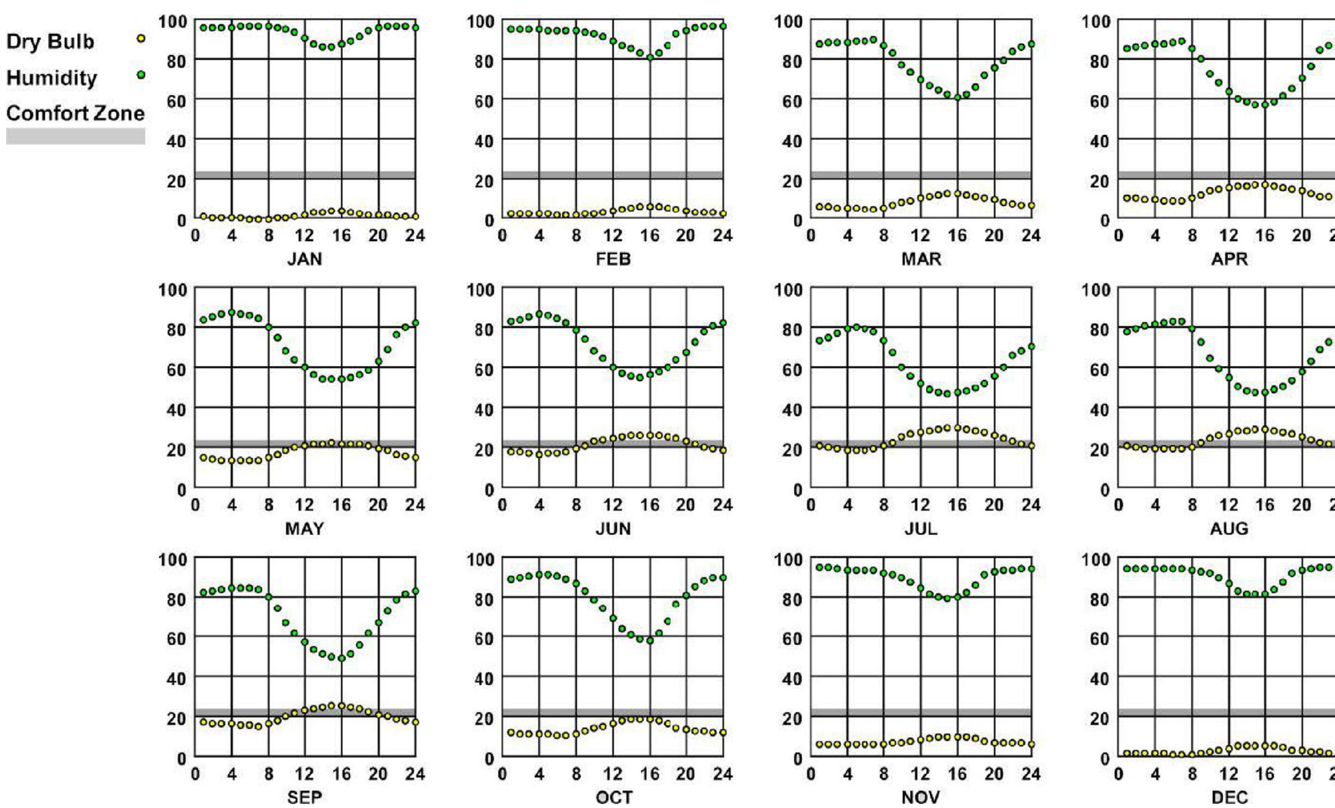


Fig. 7. Outdoor dry-bulb temperature and humidity data of Bologna (Ferrara).

It is considered as an important indicator using in climatic analysis. The psychrometric chart contains five physical properties as follows: 1) dry-bulb temperature (vertical lines); 2) wet-bulb temperature (diagonal lines); 3) dew-point temperature (horizontal lines); 4) relative humidity (curved lines); 5) Humidity ratio (horizontal lines). In this chart, the dark blue boxes show the comfort zone. In order to understand the yearly weather fluctuations in Bologna, Climate Consultant 6.0 was used to generate a psychometric chart (Fig. 8).

To develop a natural ventilation and passive cooling strategy, it is necessary to measure the averages of wind speed and direction. Wind has a significant effect on temperature, humidity, rainfall and degree of air pollution. Its prediction can be useful for planning natural ventilation and forecasting the weather.

The wind rose is a diagram to characterize both the direction and frequency of wind. Annual wind rose for Bologna (Ferrara), generated by Climate Consultant 6.0 (Fig. 9). In this diagram, the outermost ring shows the percentage of hours when the wind comes for each direction. Blue bars show the average temperature of the wind coming from that direction (light blue is in the comfort zone and dark blue is cool). Green bars show average humidity (light green is considered comfortable at 30% to 70% while dark green is too humid above 70%).Innermost circle shows the minimum, average, and maximum velocity of the winds from each direction.

In this context, Ecotect and WinAir were used to study the actual airflow around case study projects (Fig. 10). As can be seen below, airflows are mostly through the cross windows. The maximum air

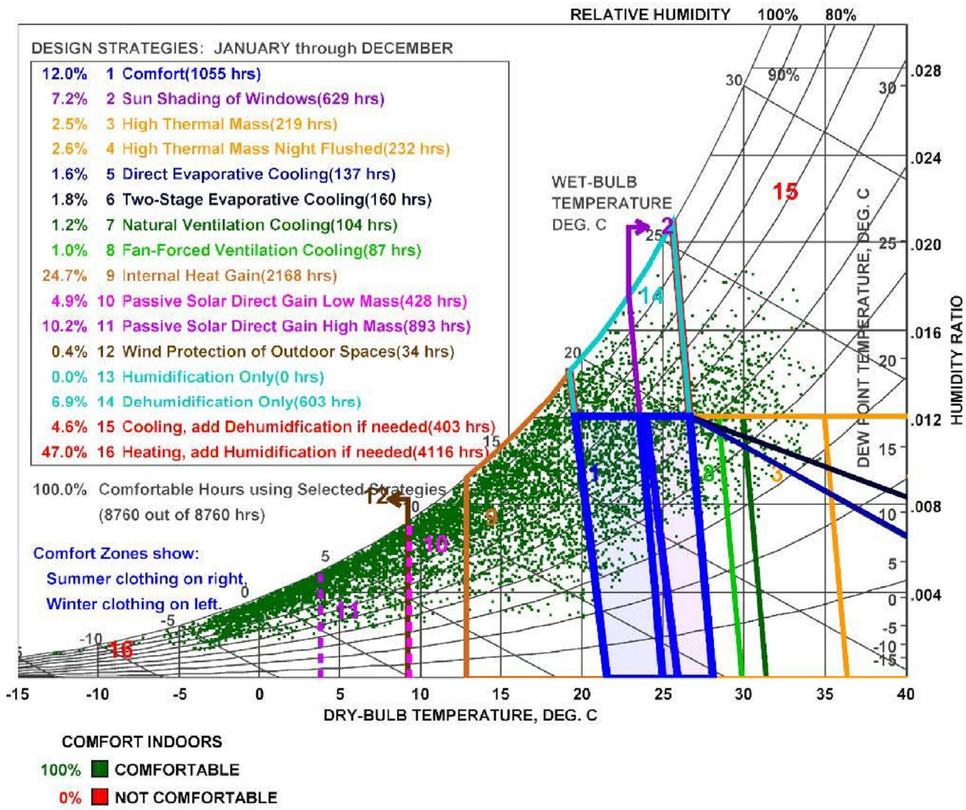


Fig. 8. Bologna (Ferrara)'s psychometric chart (ASHRAE Standard 55).

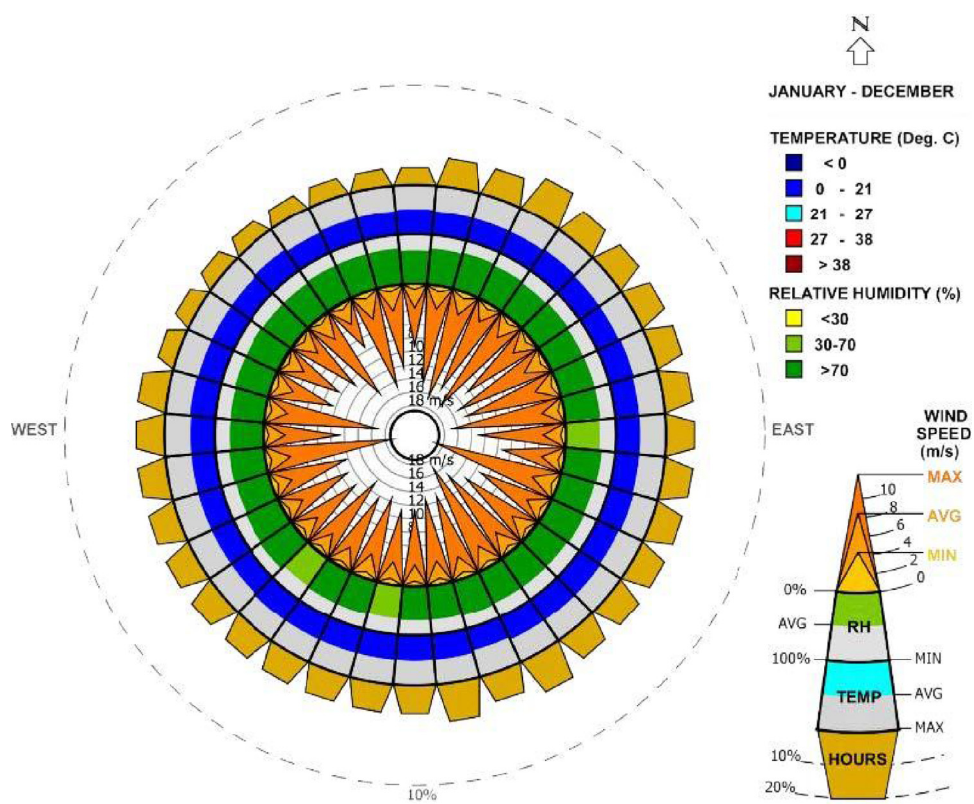
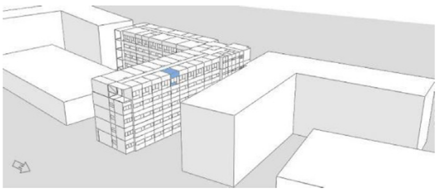
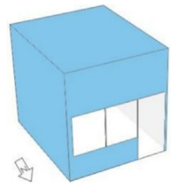
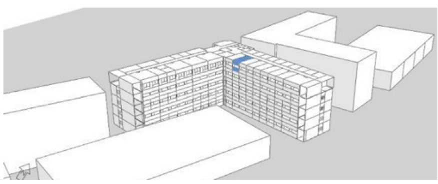
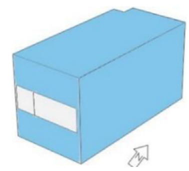
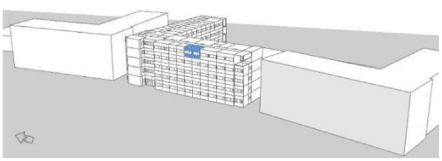
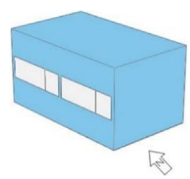
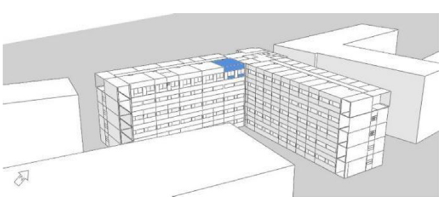
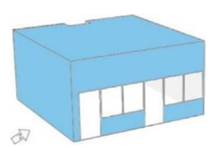


Fig. 9. Wind wheel of Bologna (Ferrara).

Table 3
The reference room zones of case study.

Position of the reference rooms	Façade side	Area m^2	Volume m^3
		12.01	42.04
		20.37	71.30
		24.37	85.28
		43.38	151.83

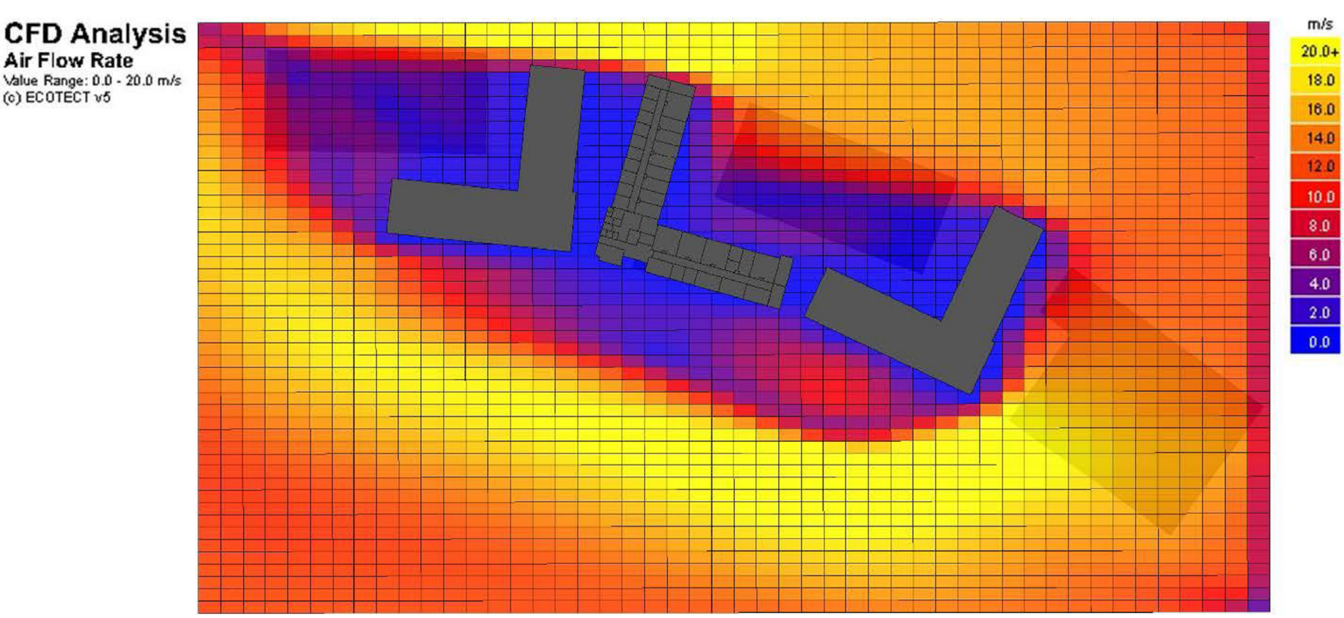


Fig. 10. Air flow analysis of case study and its site in the fifth floor.

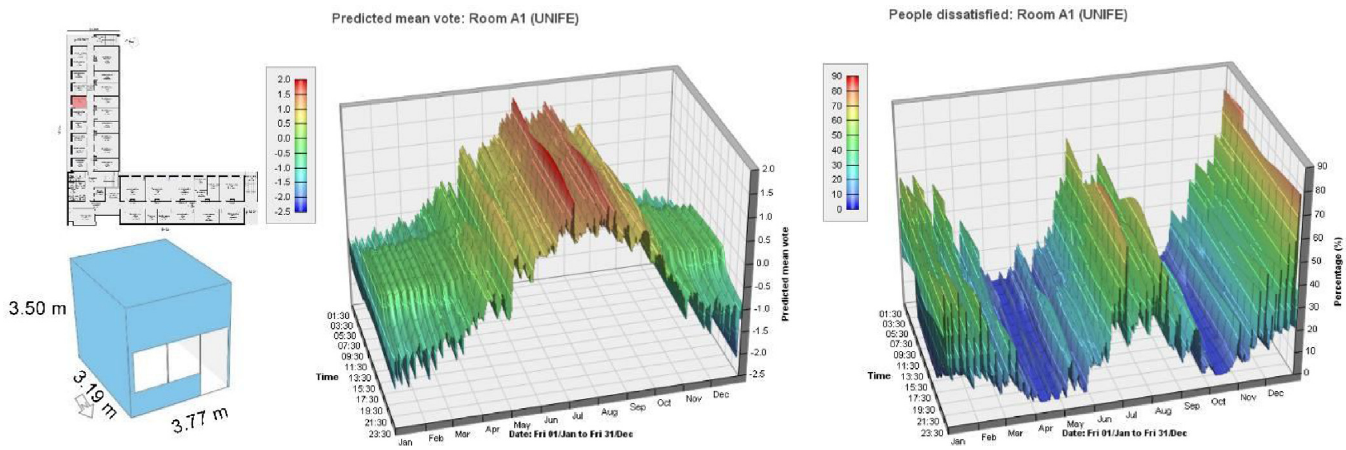


Fig. 11. PMV-PPD values (linked with solar radiation) for room A1.

flow in Bologna (Ferrara) is mostly from the north and north-west in summer.

2.2. Sensitivity Analysis

Indoor environmental quality (IEQ) is one of the major issues that should be evaluated in the context of building performance prediction. Building indoor environmental quality measurements are often performed in the areas of thermal, lighting, air quality and acoustic. Due to the complexity of analyzing all aspects of environmental factors and the lack of experimental metric, it can be useful to simulate narrow range of indoor environmental conditions. The first step was to define zones that will be integrated into the dynamic simulation. The reference building was modeled in Revit and then imported into Integrated Environment Solutions-Virtual Environment (IES-VE) simulation software. Four different types of rooms in the reference building were selected to analyze their energy performance and indoor environmental quality (Table 3).

For a whole building simulation, it is necessary to define thermal zones. In the current work, each room was defined as a thermal zone. For each room, the set point conditions, as well as internal conditions such as the amount of users and their activities, lighting and electric equipment were defined. Furthermore, schedule ventilation for openings (windows doors), HVAC temperature set points were considered for each thermal zone. Every room was bound by heat transfer surfaces. Openings such as doors or windows were simulated inside the wall surfaces.

2.2.1. Thermal comfort

Thermal comfort is one of the most important factors for improving the quality of the indoor environment. In case of built environment, users always try to achieve a thermally comfortable environment [24]. In this context, standards such as ASHRAE Standard 55 and ISO Standard 7730 are used to obtain appropriate thermal conditions in the buildings.

However, parameter values can be variable for people in different climatic zones. The first thermal comfort models were developed by Fanger and include the combination physical variables in both chart and graph form. Two models commonly used in thermal comfort are known as Fanger's predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD). They are recognized as thermal comfort index. They are also calculated in order to show satisfaction criteria and measure comfort levels at certain thermal environment.

Fanger defined PMV as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level". The PMV index is derived for steady state conditions but can be applied with good approximation for minor fluctuations of one or more of the variables [25]. It provides a score that corresponds to the ASHRAE thermal sensation.

Table 4
ASHRAE thermal sensation scale.

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

The value of the PMV index has a range from −3 to +3 and is a 7-point rating scale (Table 4). It represents the average thermal sensation felt by users inside conditioned space. According to ASHRAE, thermal sensation values of −1, 0, and +1 are usually supposed to represent satisfaction. While dissatisfaction is defined as not voting either −1, +1 or 0.

The PMV equation uses the four environmental parameters; air temperature (ta in o C), mean radiant temperature (t_{mrt} in °C), air velocity (ν in m/s), relative humidity (vapor pressure, pa in kPa) and two personal variables (clothing insulation (clo) and metabolic rate). The following equations show relationship between parameters.

$$\mathrm{PMV} = \int (t_a, t_{mrt}, \nu, p_a, I_{cl}, M) \tag{1}$$

PPD is calculated from PMV using the equation:

$$\mathrm{PPD} = 100–95 \times \exp(-0.03353 \times \mathrm{PMV}^4 - 0.2179 \times \mathrm{PMV}^2) \tag{2}$$

PPD predicts the percentage of occupants that are dissatisfied with the given thermal conditions. The PMV and PPD form a U-shaped relationship. In this respect, at PMV neutral (0), 5% of the occupants are still dissatisfied.

In order to calculate PMV-PPD values of case study, a full dynamic simulation was carried out in the selected zones (rooms). The simulation period was set from January to

December. Bologna (Ferrara) weather data was used in the simulation process. In case study the zones were considered to be occupied from 7 a.m. to 6 p.m. in weekdays. The internal heat gains were assumed for the occupied and unoccupied period in accordance with ASHRAE 90.1-2004 guideline.

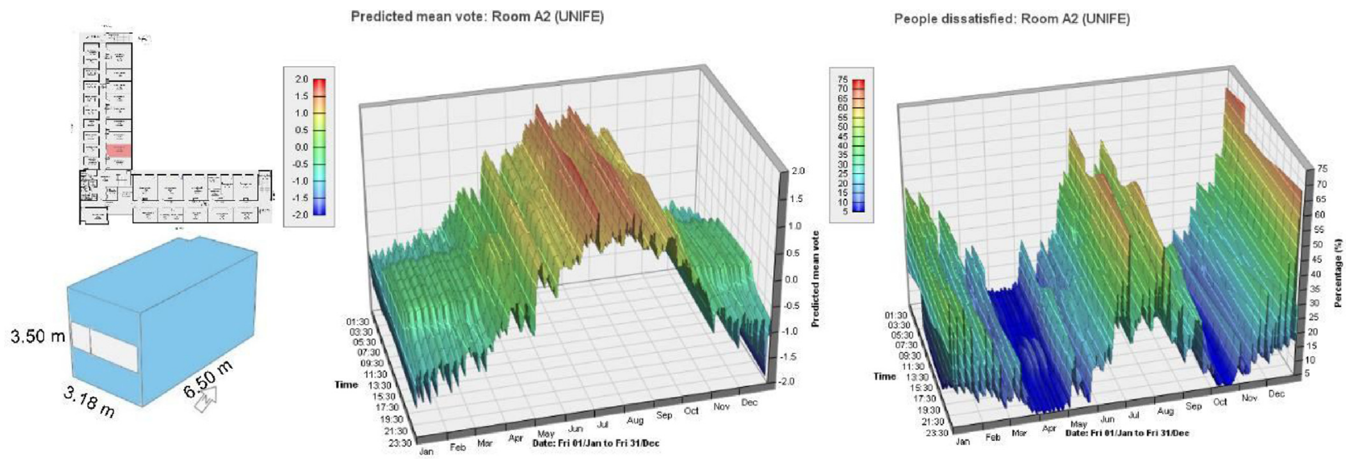


Fig. 12. PMV-PPD values (linked with solar radiation) for room A2.

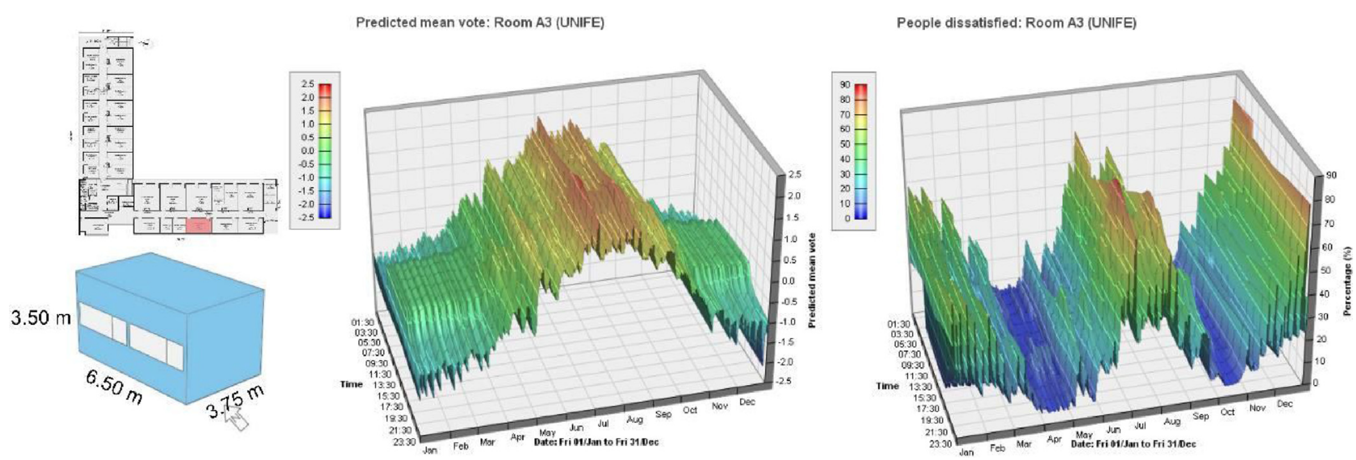


Fig. 13. PMV-PPD values (linked with solar radiation) for room A3.

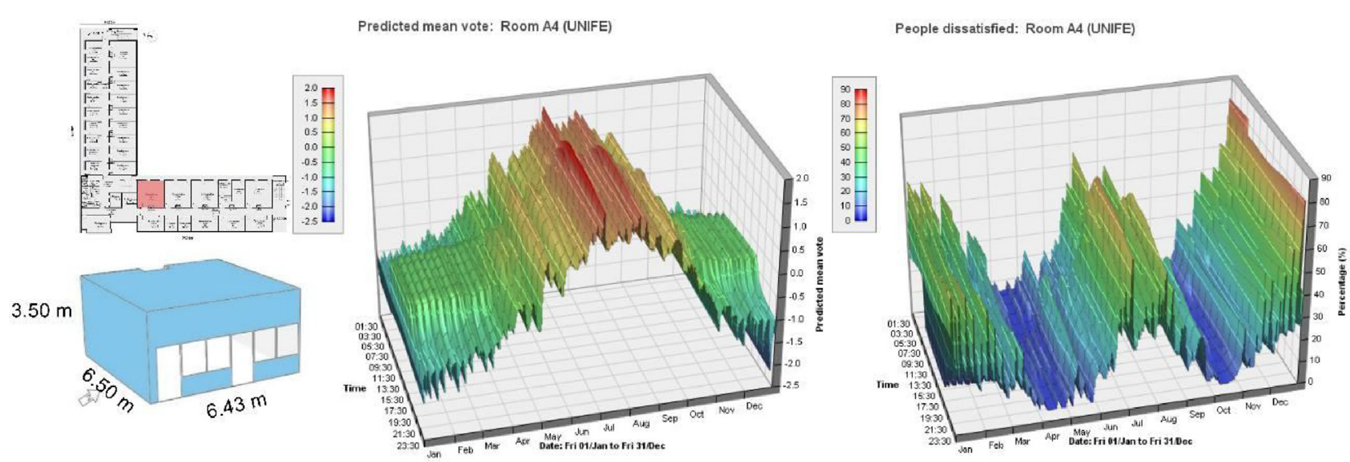


Fig. 14. PMV-PPD values (linked with solar radiation) for room A4.

Fan coil units were used to provide heating, cooling or both in the building. Heating and cooling set points were 20° C and 25° C respectively in order to maintain thermal comfort (between 20° C and 25° C). Thermal zones used the same operating schedules (lighting, occupancy, and equipment). Public areas such as entryways, corridors, restrooms, stairways and entrances were stimulated by different temperature schedule and set points. In the first step SunCast was used to analyze the effect of sunlight and shadow on thermal behavior of rooms as shown in the following figures. It was performed under solar radiation conditions in the diffuse sky. The next step was to simulate airflows within the building by using MacroFlo component which is used to investigate the effectiveness of natural ventilation (e.g. windows and doors) (Figs. 11–14).

It is important to note that the simulation results were only considered for the occupied periods of 07.00 a.m. to 18.00 p.m. for case

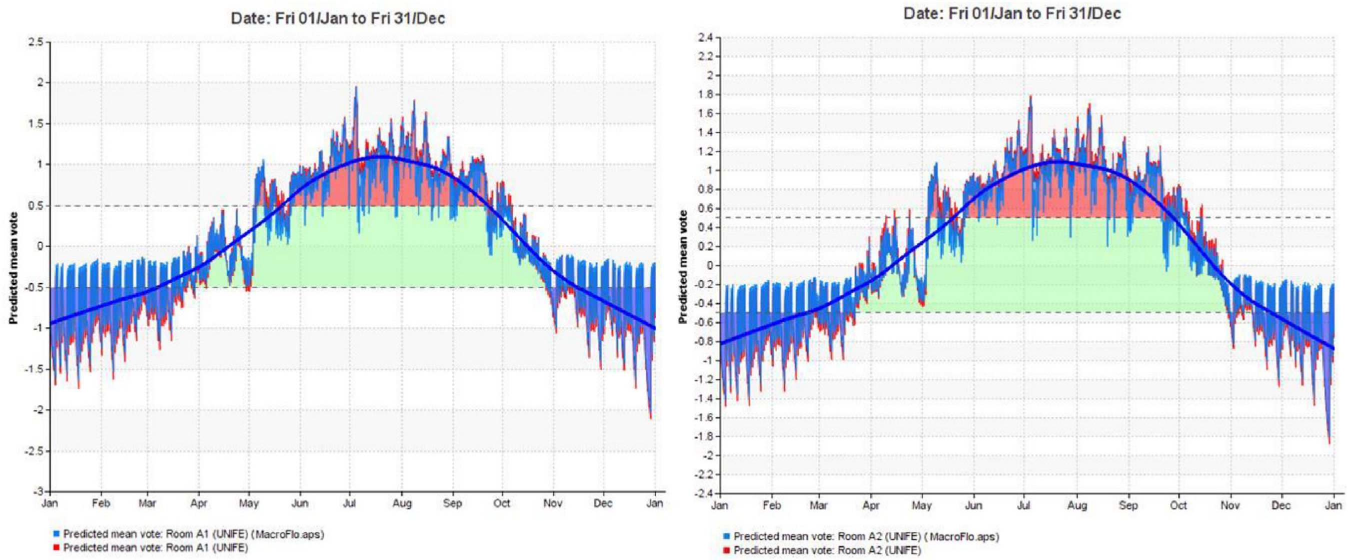


Fig. 15. PMV values in naturally ventilated: room A1 (left) and room A2 (right).

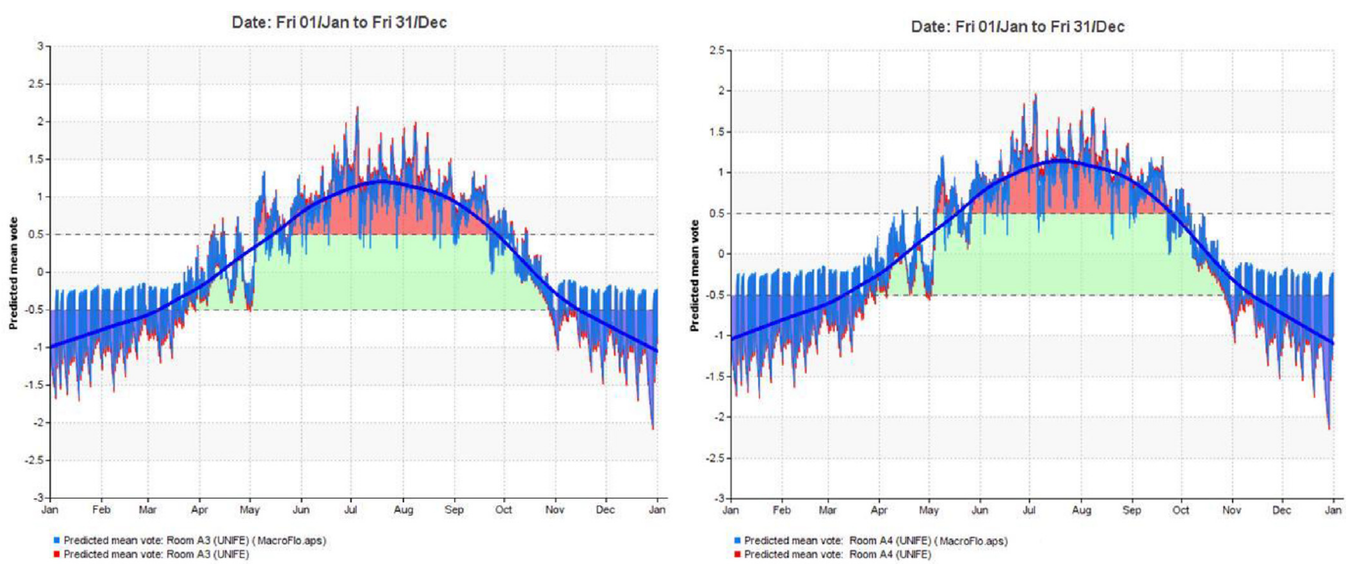


Fig. 16. PMV values in naturally ventilated: room A3 (left) and room A4 (right).

Table 5
Maximum and minimum PMV values for reference room zones.

Model	PMV values			
	Maximum	Month	Minimum	Month
Room A1	1.67–1.96	July	−1.96 to −2.00	December
Room A2	1.60–1.79	July	−1.72 to −1.78	December
Room A3	1.80–2.19	July	−1.95 to −2.00	December
Room A4	1.70–1.97	July	−2.00 to −2.05	December

study. It is worth nothing that in the IES-VE software the default comfort settings are 0.69 clo for clothing and 0.9 met for activity (1 met = 58 W/m^2; 1 clo = 0.155 m^2K/W). In this respect, users are expected to be wearing the same type of clothes across all months and working at the same activity level throughout the year. A summary of simulation results is presented in Table 5. A comparison between simulated data and comfort requirements can be used to evaluate indoor thermal comfort conditions.

The recommended criterion in ASHRAE-55 standard, is to limit the PMV to between −0.5 and 0.5 and a dissatisfaction rate of less than 10%. The simulation results showed that the values of PMV in the rooms are not always within an acceptable range defined by ASHRAE-55 in the occupied periods (07.00 a.m. to 18.00 p.m.). According to the simulation results in Table 5, room A3 has the maximum PMV values during July compared to other rooms. This is because room A3 receives maximum sunlight as it is situated at the west side of the building. The room A2 has minimum PMV (between −1.72 to −1.78) values during December.

Natural ventilation is one of the key environmental factors that plays the significant role in putting forward sustainability principles for buildings. The key purpose of natural ventilation is to provide fresh air and moving heat from indoor environment. Natural ventilation is one of significant methods to achieve the adaptive thermal comfort by users and can improve indoor environmental quality.

A study [26] has stated that mechanical ventilation has been preferred to natural ventilation, as it can provide stable air con-

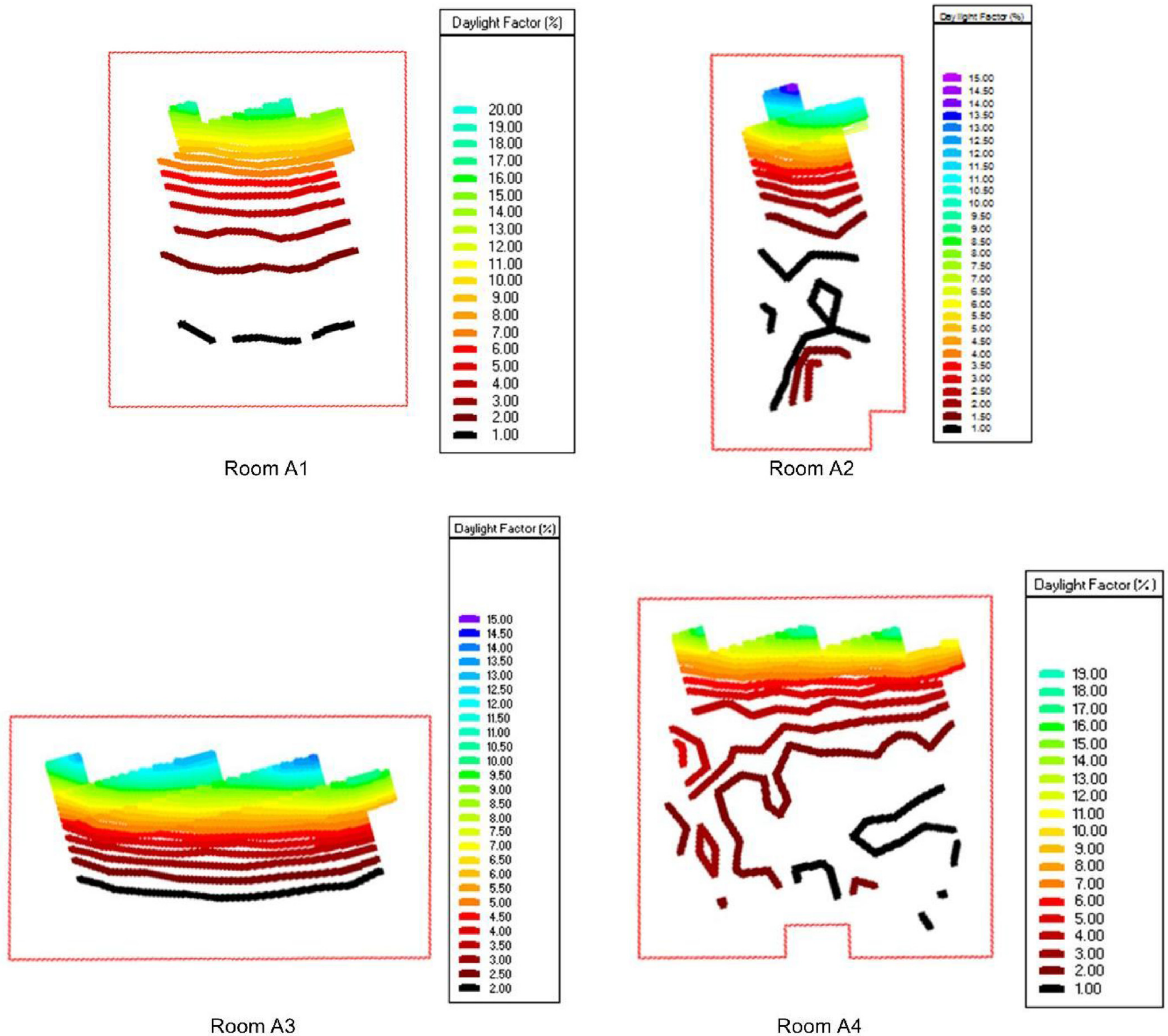


Fig. 17. Daylight factors in rooms A1, A2, A3, and A4 (performed in IES-VE).

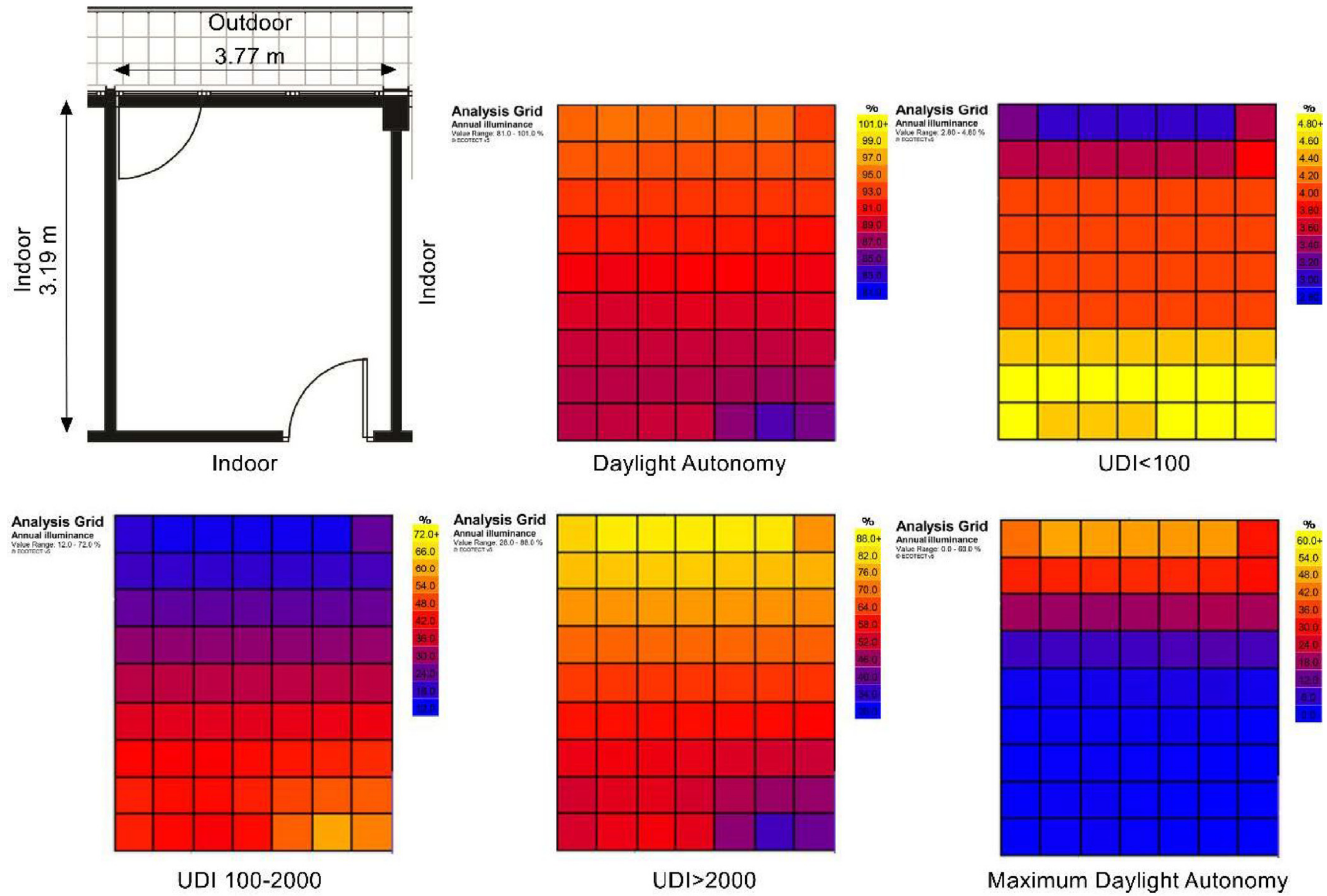


Fig. 18. Daysim simulation results of room A1: Useful Daylight Index.

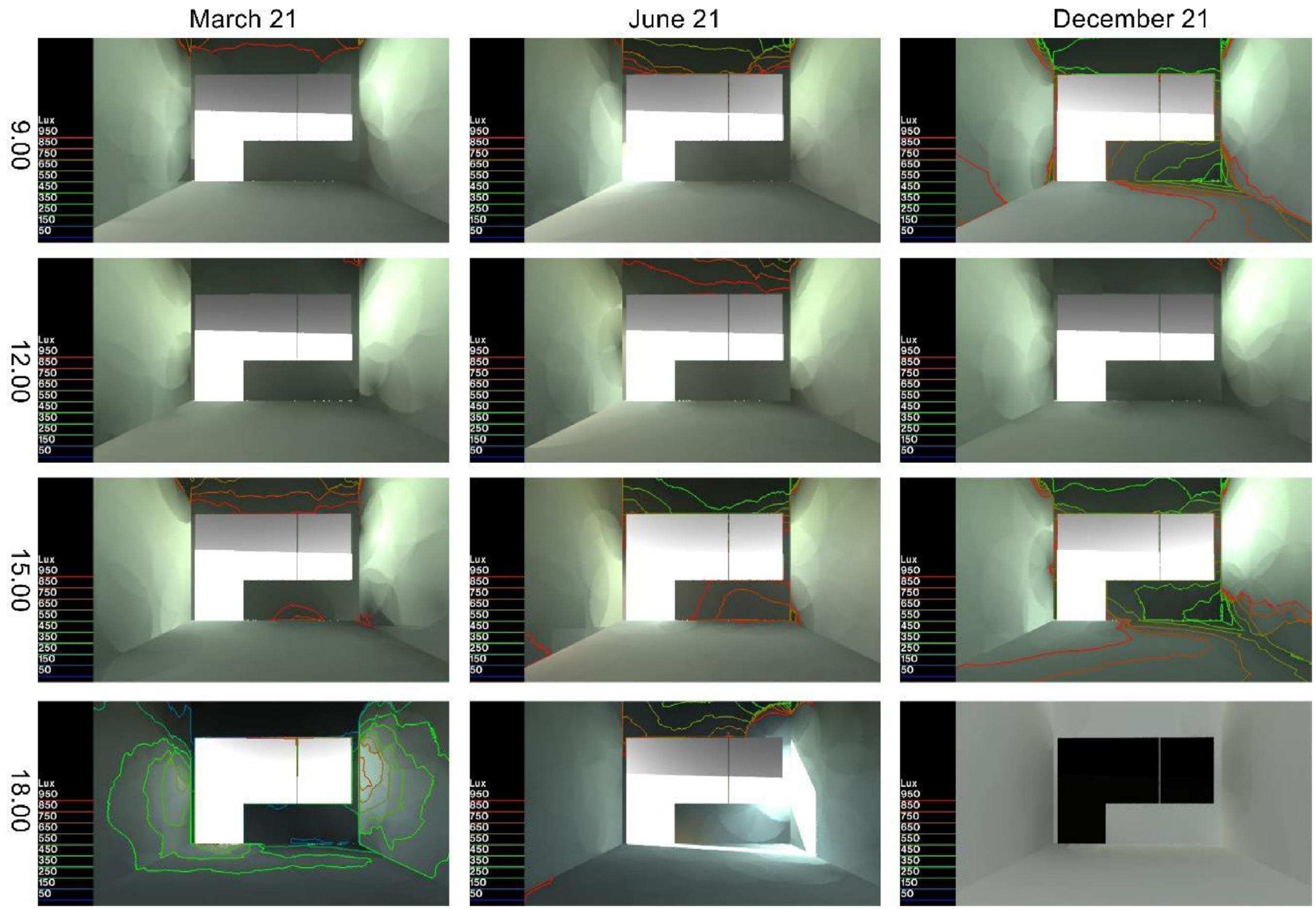


Fig. 19. Radiance simulation results of room A1: Illuminance.

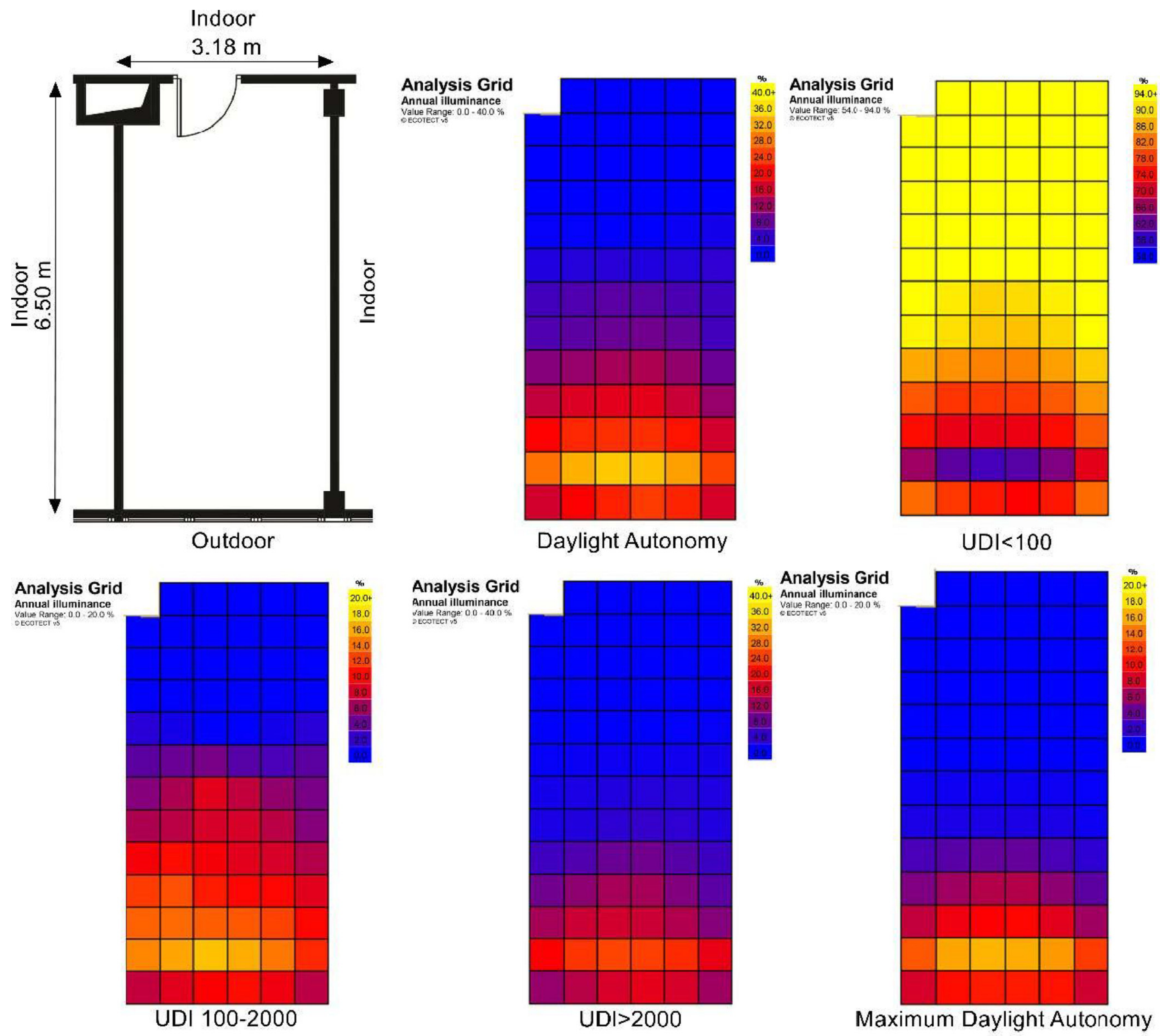


Fig. 20. Daysim simulation results of room A2: Useful Daylight Index.

ditions and resolve airflow problems triggered by inadequacies in design. Nevertheless, heating, ventilation and air conditioning systems (HVAC) are complex and need a large number of components to operate. Furthermore, this kind of technology consumes a great amount of energy, whilst not always managing to deliver the desired indoor climate [27].

It is clear that users, when the inside temperature is higher than the outside temperature, are willing to open windows. Natural ventilation can be considered as an efficient method to reduce mechanical ventilation consumption. For example, the HVAC system can be shut down in a space when a window is open. In this respect, users have a greater role in opening windows and controlling air conditioners.

The hybrid ventilation (mixed mode) systems combine user controlled natural ventilation with mechanical ventilation systems. They have significant advantages compared to conventional mechanical systems and offer possibilities to improve indoor environmental quality. Hybrid ventilation relies on natural driving forces to provide the desired (design) flow rate. It uses mechanical ventilation when the natural ventilation flow rate is too low [28]. To evaluate the performance of selected rooms with reference to natural ventilation, a detailed analysis of indoor airflow distributions was performed. In this context, the simulations were conducted with the aim of evaluating the benefits of natural ventilation. IES-MarcoFlo (for natural ventilation analysis) was used to determine impacts of natural ventilation on the baseline rooms. In the case study buildings, ventilation occurs through open able windows and doors.

The main aim of analysis was to determine the number of months that natural ventilation can improve indoor environmental conditions within comfort limits ($-0.5 < PMV < +0.5$). In this regard, the simulations were carried out under two conditions (with and without natural ventilation), and the results obtained are shown in Figs. 15 and 16. The waved blue and red lines represent with and without natural ventilation conditions respectively.

It is a fact that there is more natural ventilation in the warmer months. According to the above figures, the desired PMV values were found between May and November. It can also be seen from the figures that natural ventilation can result in the lower PMV values. For example, the maximum PMV values of rooms A1, A2,

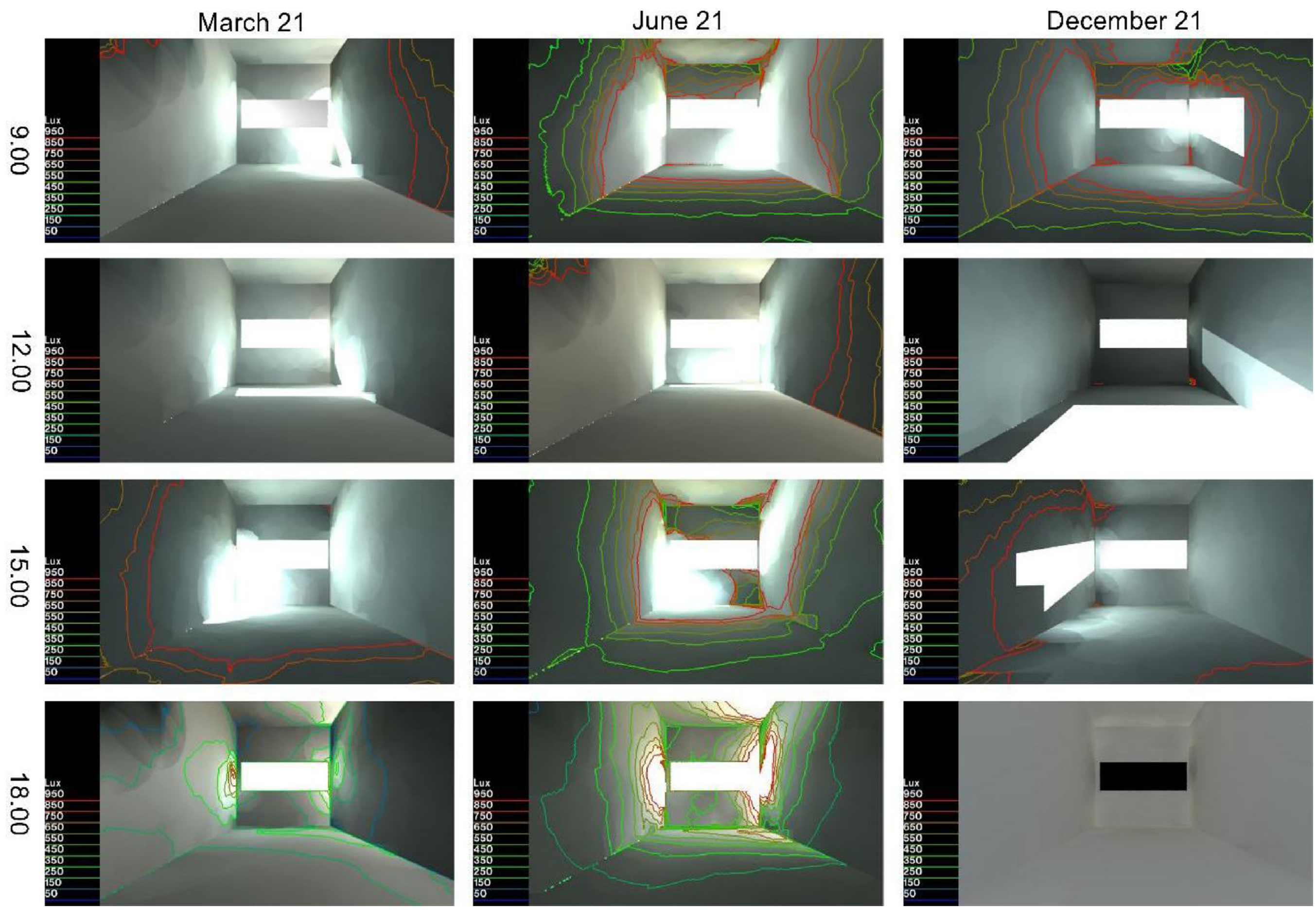


Fig. 21. Radiance simulation results of room A2: Illuminance.

A3, and A4 have been reduced from 1.96, 1.79, 2.19, and 1.97–1.94, 1.74, 2.12, and 1.94 respectively.

2.2.2. Daylight performance

The use of natural daylight is considered as one of the most important strategies for establishing a comfortable and efficient environment. It can contribute to reduce energy use from artificial lighting in the buildings. It is, therefore, important to gain maximum benefits from natural lighting. Several methods are used to evaluate daylight availability in buildings. Daylight factor (DF) is one of the most commonly applied methods used in evaluating daylight performance. Moreover, useful daylight illuminance (UDI) and daylight autonomy (DA) metrics are considered to provide a more detailed and realistic understanding of the annual daylight availability within indoor climate. The study [29] provided a review of recommended static and dynamic daylight performance metrics.

In order to evaluate the daylighting inside case study, the simulations were performed with IES-VE (Fig. 17), Radiance and Daysim (Figs. 18–25) at working planes height of 0.8 m from January 1 st to December 31 st under overcast sky conditions. The minimum illuminance required for a room is 500 lx. Furthermore, simulations were carried out for the solar analysis characteristics days, i.e. the spring equinox (March 21st), the summer and winter solstices (June 21st, December 21st). The reference rooms were considered without dynamic shading device. The results obtained in the simulations are shown in the following figures.

The above graphic results show that rooms have different daylight factor distributions. Daylight factor contours in room A2 and A3 show a high uniformity of light distribution compared to other rooms. As mentioned before, rooms with daylight factor between 5% and 10% are considered to be good quality daylight. The simulation results show that floor area of the rooms receive under 2% of daylight factor. It can also be observed that there are high daylight factors near view windows. It is important to note that due to the evaluation of daylight factors under overcast conditions, the measurements are not affected by factors related to time and window orientation (location of room).

2.2.3. Acoustic performance

Evaluation of acoustic comfort is a necessary step in order to provide a comfortable environment. It can include measurements such as sound insulation, reverberation time, speech intelligibility, etc. In this context, it is important to determine the major factors influencing acoustic performance and the causes of noise in the built environment. Acoustic performances of building elements are the most important criteria in the design and refurbishment of buildings. They should, therefore, be taken into consideration when designing a comfortable environment.

The main sources of noise are air, road and rail traffic, and industrial activities. Road traffic noise is the major contributor to environmental pollution. It is a significant source of noise which affects building user comfort and satisfaction.

The reverberation time (RT) is one of the most significant parameters for evaluating acoustical performance. It has an important impact on speech intelligibility and is controlled by using sound absorption. There are three methods to calculate the reverberation time (RT) in rooms as follows: Sabine, Eyring and Millington-Sette. According to Sabine's formula, the reverberation time is defined as

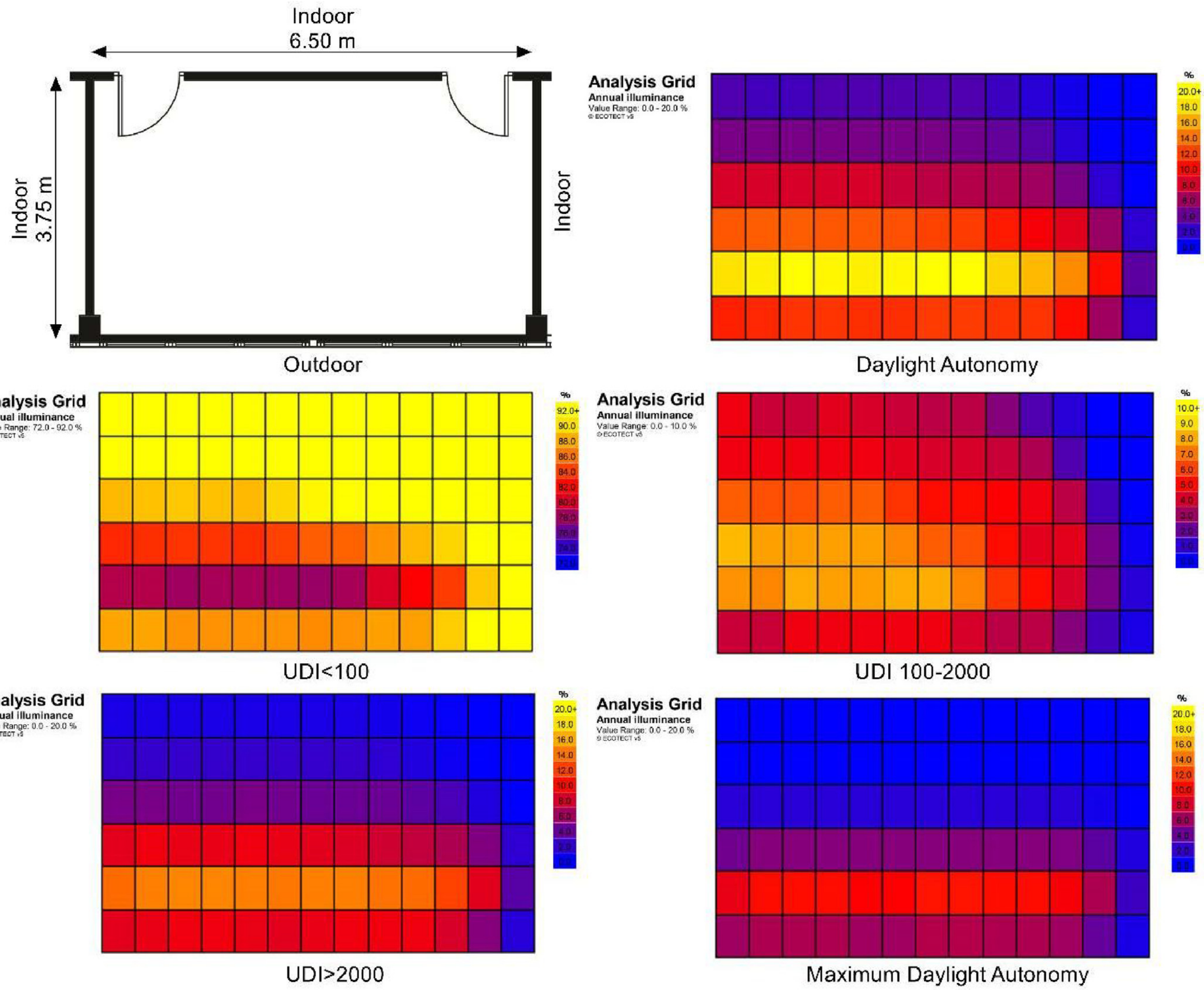


Fig. 22. Daysim simulation results of room A3: Useful Daylight Index.

the time it takes for the SPL (sound pressure level) to decay 60 dB after the sound's source has stopped. The reverberation time (RT) varies depending on enclosure volume and the degree of exposed sound absorbing surfaces.

Reverberation times is affected by various factors such as materials, building shape and dimensions insulators. It determines the distribution of sound in a space. Although long reverberation time in the concert hall can be excellent, it is less desirable in the workplace. The basis of acoustical comfort in the office buildings is the privacy index (PI). However, proper reverberation time is a very important consideration for each enclosed room. Optimum reverberation time for a room is 0.5 s. Recommended reverberation times for private and open plan office are between 0.6–0.8 and 0.8–1.2 s respectively. In the context of acoustic performance, noise measurement and calculation are usually determined in octave or third-octave band frequency range 100–3150Hz.

To calculate some simple statistical reverberation times of reference rooms, computational simulations were carried out with Ecotect (Fig. 26).

The above figure shows the results of reverberation time for A1, A2, A3 and A4 rooms in 63 Hz to 16000 Hz region. According to the results, only room A1 has zero reverberation time while room A4 has a longer reverberation time. From the results it can clearly be seen that reverberation time is directly proportional to the volume of the room. For example, room A1 has minimum volume (42.04 m^3) and A4 has maximum volume (151.83 m^3).

3. Data/Results

The overall results showed that the main indoor environmental parameters (thermal, visual, acoustic and air quality) affect users' comfort and satisfaction. It can be seen that indoor environmental parameters have an important role in the process of evaluating buildings.

BIM has the potential to play a vital role in facilitating more visibility and interaction in the process of scenario development. It provides enhanced communication and interaction between end-users and buildings. In order to predict the behavior of building systems, it can be useful to create a clearer connection between BIM and improved strategies.

It is important to define basic principles for the validation of a method. Process validation can provide documentary evidence that a method is capable of being used for a particular use. It also can be used as a process enforcement tool.

The development of energy management systems is an attractive and increasingly feasible option for several smart buildings. However, designing highly efficient micro scale energy management systems requires an in-depth understanding of various

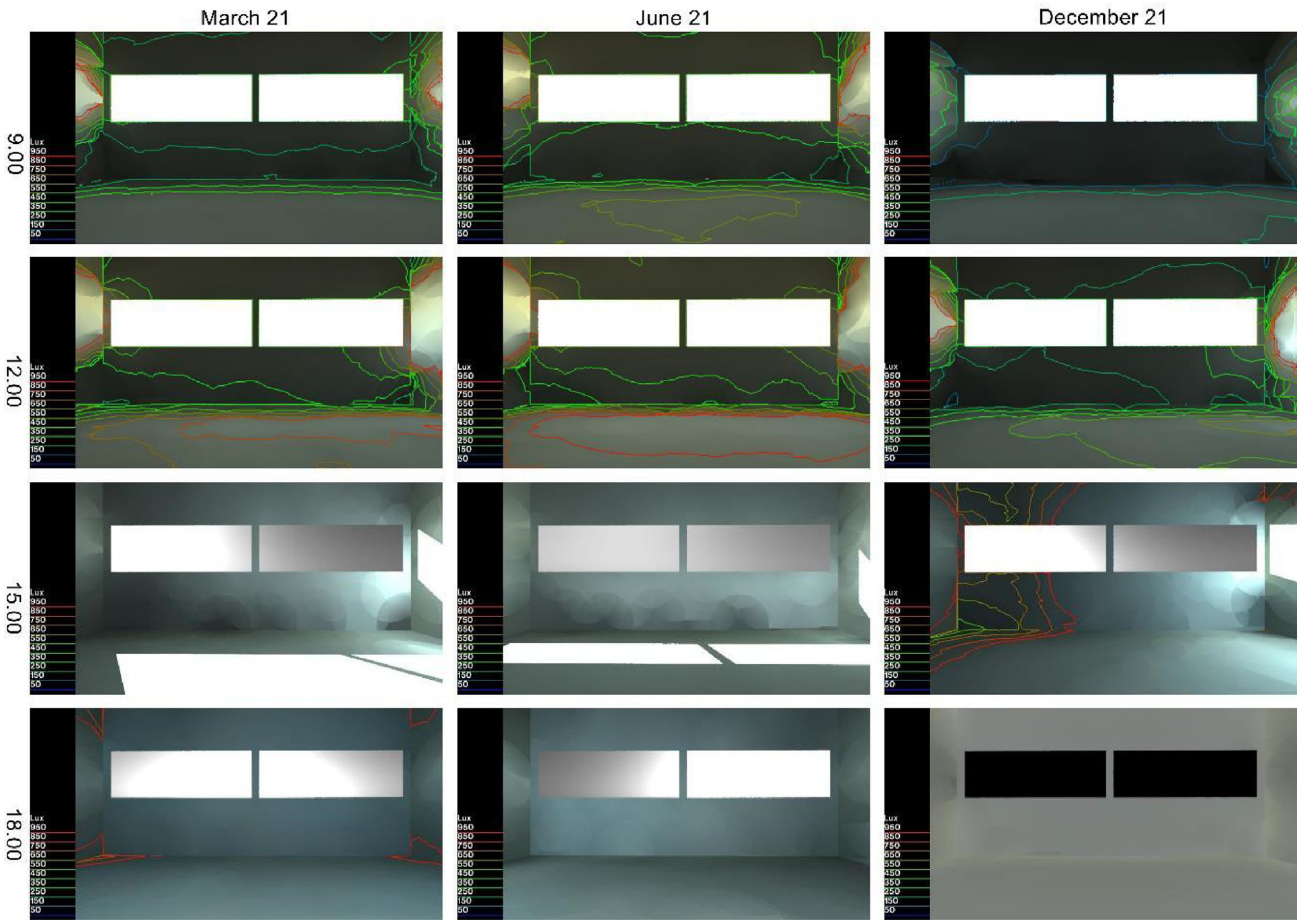


Fig. 23. Radiance simulation results of room A3: Illuminance.

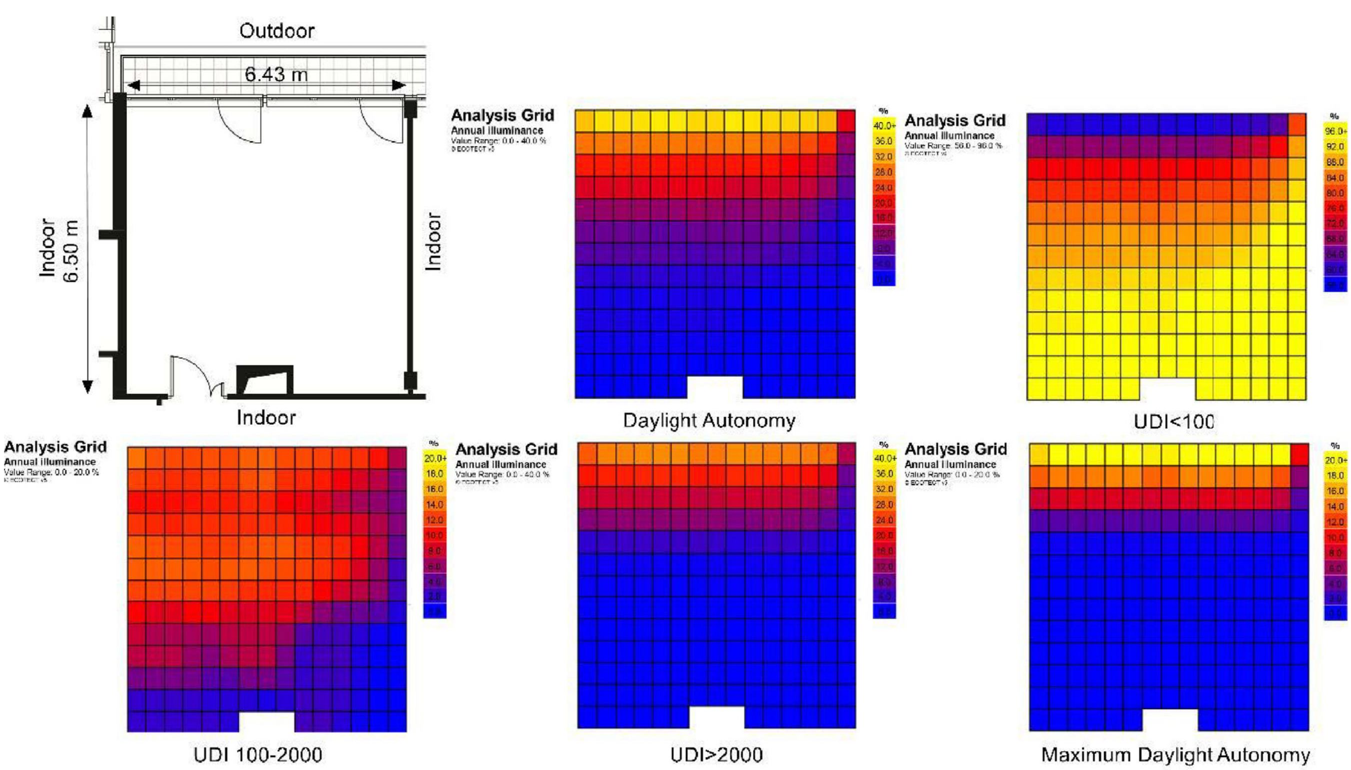


Fig. 24. Daysim simulation results of room A4: Useful Daylight Index.

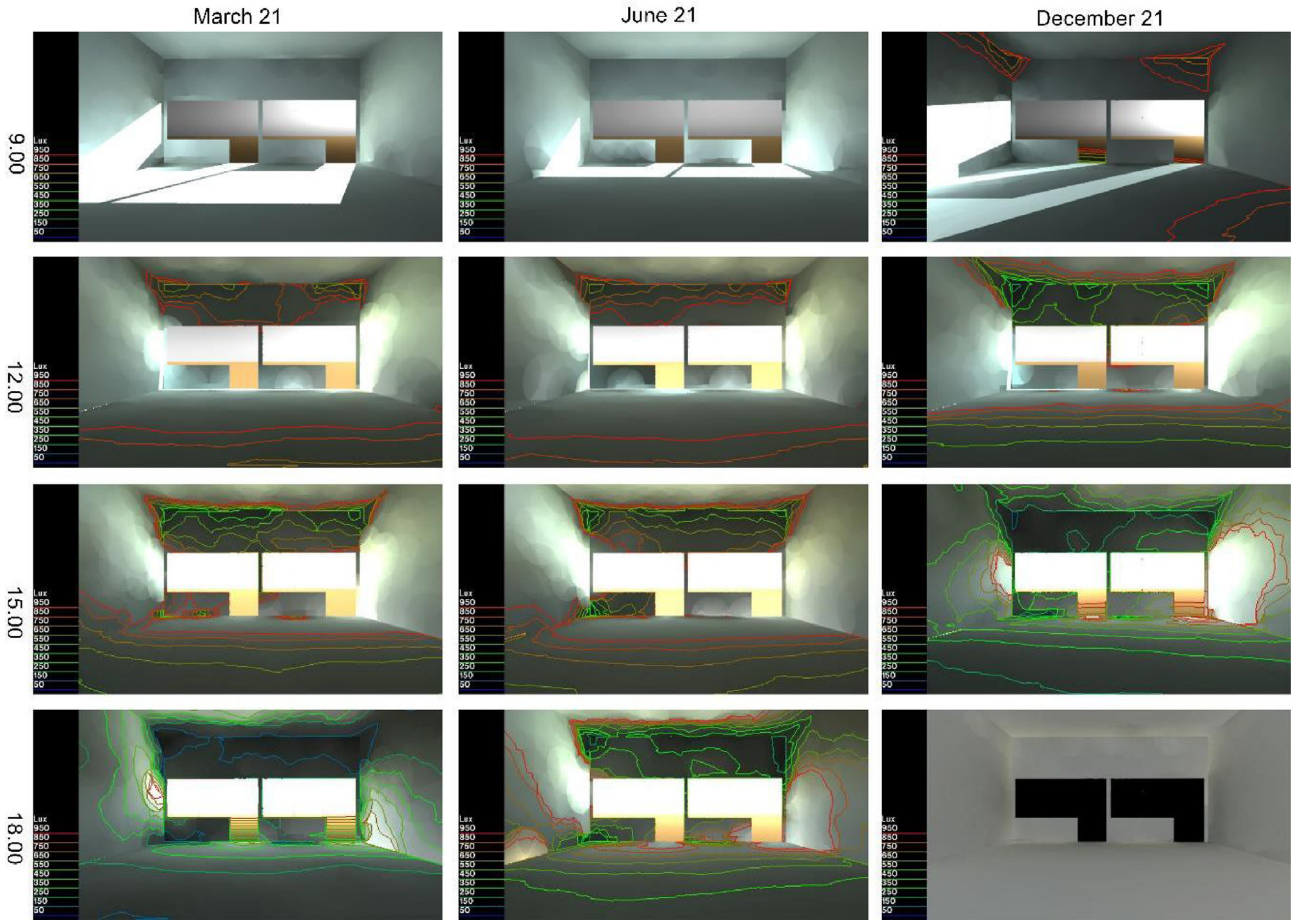


Fig. 25. Radiance simulation results of room A4: Illuminance.

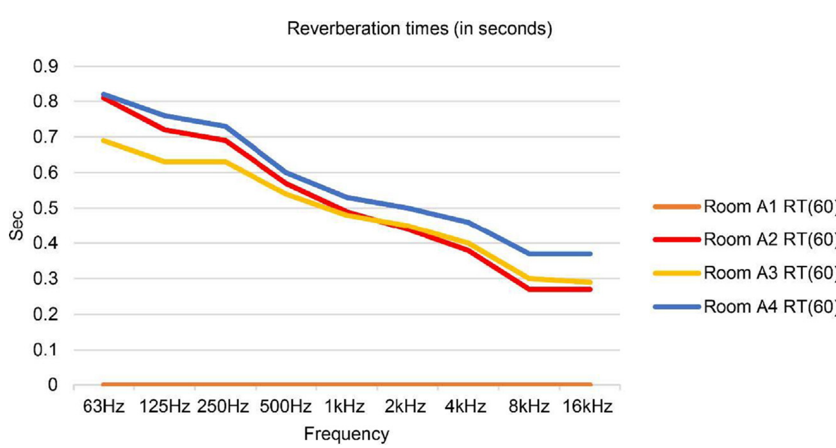


Fig. 26. The results of reverberation time for A1, A2, A3 and A4 rooms (Ecotect).

Table 6
Thermal and optical factors of In-flector insulator [31].

In-flector	Solar transmittance	Solar reflectance	Solar absorbance	Visible transmittance
Silver side	0.253	0.496	0.251	0.22
Black side	0.253	0.083	0.664	0.22

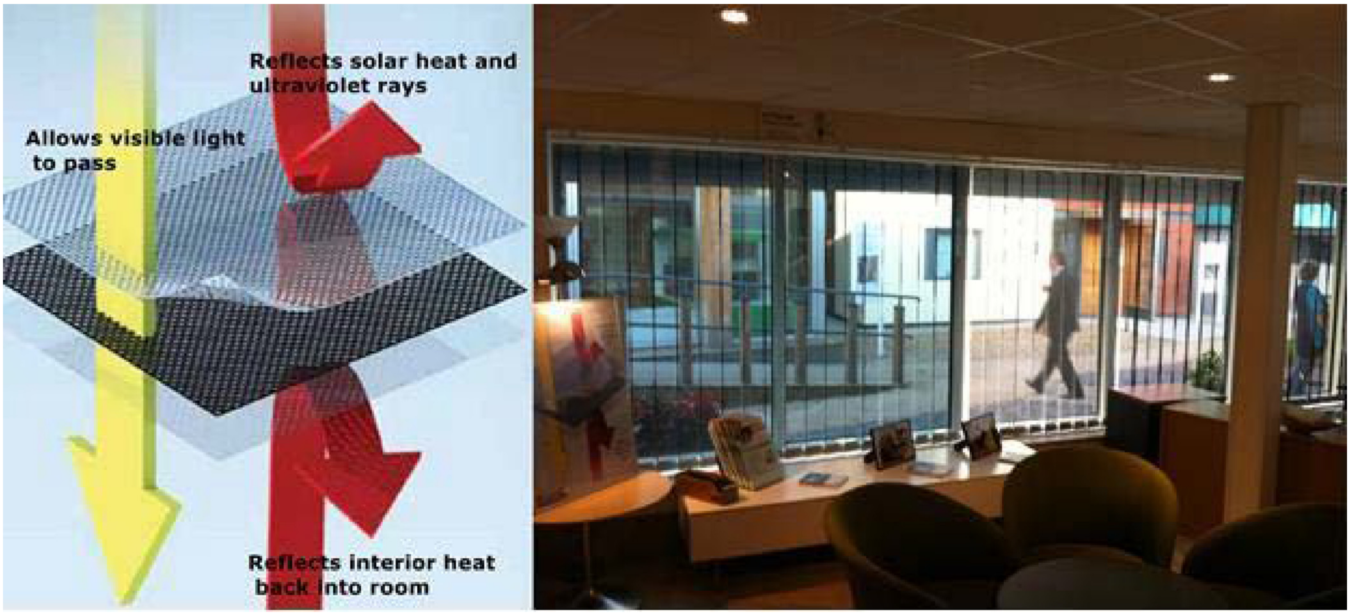


Fig. 27. Illustration of In-flector insulators in the Building Research Establishment (BRE), Innovation Park Watford, UK [31].

Table 7
Comparison of reverberation times measured by In-flector [31].

Test orientation	Measured reverberation times (sec)				
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz
Existing glazing test area without insulator	0.75	0.91	0.84	0.56	0.53
Existing glazing test area with In-flector insulator	0.61	0.56	0.76	0.54	0.54

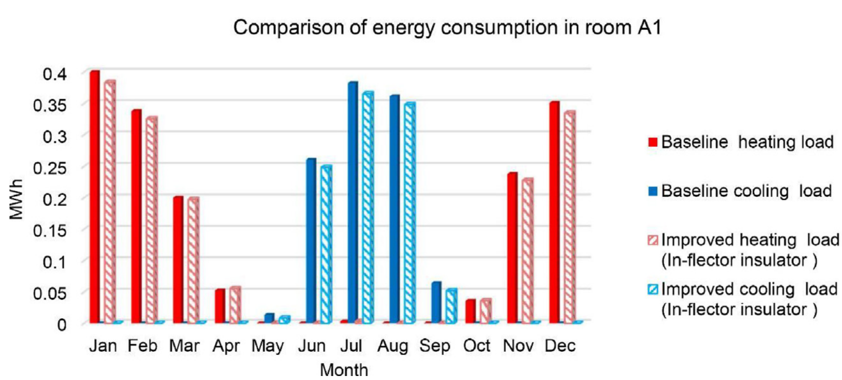


Fig. 28. Comparison of energy consumption in room A1.

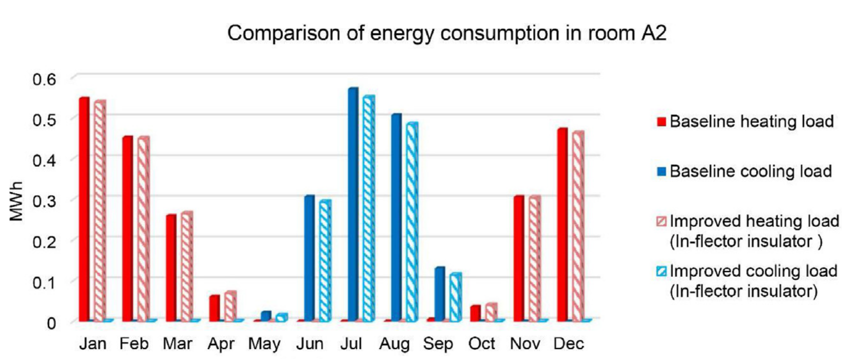


Fig. 29. Comparison of energy consumption in room A2.

Table 8
Comparison of baseline and improved energy consumption.

Model	Total baseline heating (MWh)	Total improved heating (MWh)	Reduction (%)	Total baseline cooling (MWh)	Total improved cooling (MWh)	Reduction (%)
Room A1	1.6183	1.5648	~1	1.0821	1.0226	~1
Room A2	2.1385	2.1286	~1	1.5369	1.4561	~1
Room A3	2.7658	2.7088	~1	1.9675	1.8476	~1
Room A4	4.5824	4.5132	~1	3.2365	3.0533	~1

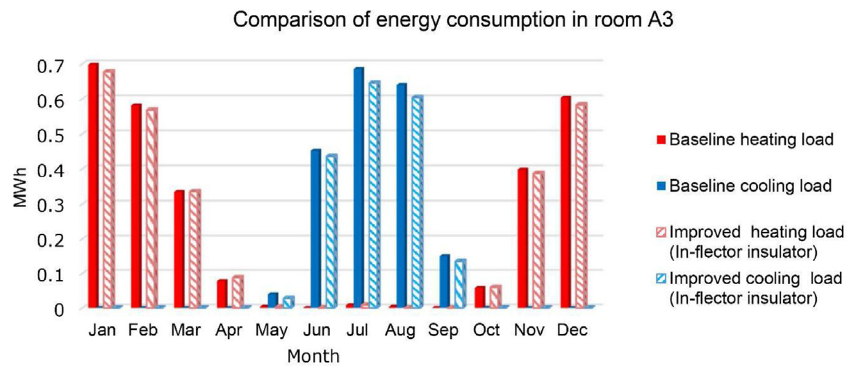


Fig. 30. Comparison of energy consumption in room A3.

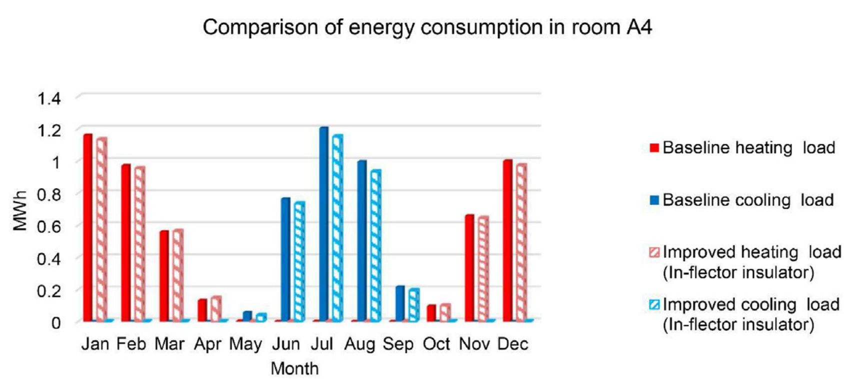


Fig. 31. Comparison of energy consumption in room A4.

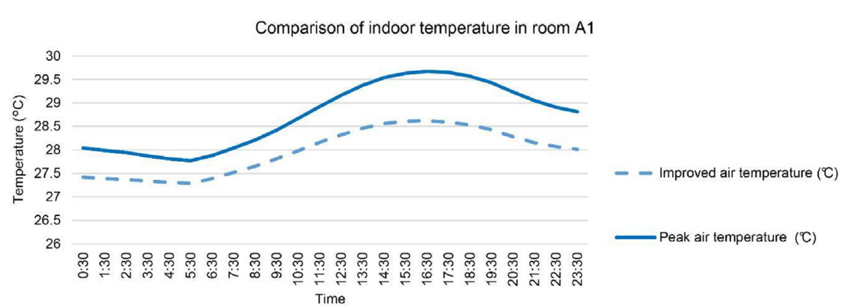


Fig. 32. Comparison of indoor temperature in room A1 (04 July).

building systems and user behaviors. An investigation with a focus on interior shading devices is carried out to determine the effect of developed building systems on building control and management systems.

A recent study by O'Brien and Gunay [29] showed that users are fairly inactive when operating manual roller shades. Furthermore, Reinhart and Voss [30] indicated that users overrode 45% of all automated blind movements and 88% of the times that the blinds were automatically.

In buildings unwanted heat and the loss of heat through windows are the two main issue that directly affect energy efficiency. In-flector is a flexible material designed for use as window insulation and solar shading product (Fig. 27). It maintains interior comfort in the building by reflecting the transfer of heat back into the room before it can be lost through the window during winter, and reflects the heat back out through the window during the summer (Table 6). It also has possibilities for noise reduction (Table 7). In-flector blinds are effectively climate control. They can be installed to either protect from the sun, prevent heat gain from sun rays, or reduce glare massively [31].

To illustrate the impact of In-flector on energy efficiency and indoor environmental, simulations were carried out in the IES-VE software. Four rooms (case study) were chosen to carry out a heating and cooling load analysis with In-flector insulator (as internal

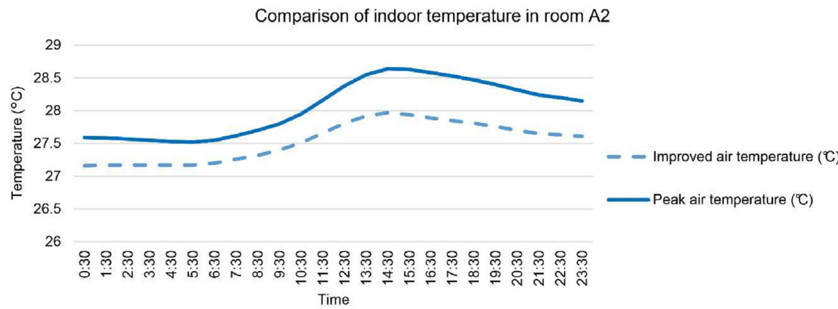


Fig. 33. Comparison of indoor temperature in room A2 (04 July).

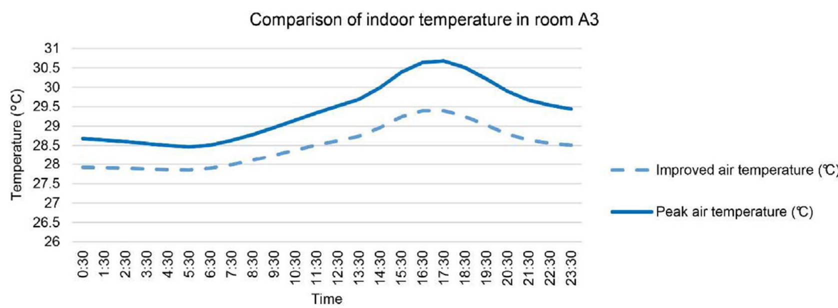


Fig. 34. Comparison of indoor temperature in room A3 (04 July).

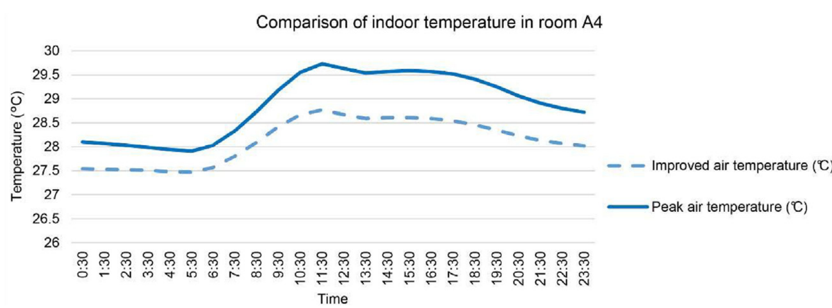


Fig. 35. Comparison of indoor temperature in room A4 (04 July).

Table 9
Comparison of indoor temperature in rooms.

Model	Peak air temperature (°C)	Improved air temperature (°C)	Temperature reduction(°C)
Room A1	29.67	28.62	~1
Room A2	28.63	27.94	~1
Room A3	30.68	29.4	~1
Room A4	29.73	28.77	~1

shading device). Furthermore, the peak indoor environmental temperature in each room was analyzed under In-flector insulator. In the following figures a comparison between the results obtained by In-flector insulator and existing condition for each room is presented (Fig. 28–31).

Monthly energy consumption for each room obtained by IES-VE. This process can help in understanding the highest demand during each month. From the above figures, it can be seen that there is high demand for heating during winter months and the largest cumulative cooling loads occur in summer months such as Jun, July, and August. Furthermore, a comparison of the performance of In-flector insulator is presented (Tables 8–9) (Figs. 32–35).

According to the above results, In-flector insulator proved to be an effective internal shading device. It is important to note that internal shading devices can be part of a comprehensive energy management system. In this context, building users should be considered as the most important determinants of comfort. To achieve better comfort conditions, it can be useful to gain maximum benefits of outdoor comfort such as natural ventilation and solar gains which can assist in reducing energy consumption in both summer and winter months.

4. Conclusion

BIM has been shown to have considerable benefits for a better understanding of existing environmental conditions (e.g. thermal, lighting, and acoustic). Although BIM is unable to simulate actual user behavior in buildings, it is a very effective and efficient process for design evaluation and construction.

The present work aimed to frame implementation of BIM in order to gain a detailed insight into existing environmental conditions and make energy efficiency improvement strategies for buildings. The simulation results showed that users can take advantage of natural environment and passive design strategies. In order to fulfill these objectives, users need to monitor and control both outdoor and indoor environmental parameters in real-time.

The benefits of such BIM and BPS tools are greater particularly during monitoring and optimizing environmental factors. The findings of this work showed that there are direct links between BIM and BPS tools. Although BIM and BPS tools have been developed with different perspectives, they can become interoperable to facilitate energy-efficient building retrofits and design. Therefore, it is important to develop methods to integrate them for building performance analysis during the design, construction and refurbishment.

This work also presented the development and validation of a retrofit strategy on internal shading elements through BIM-based building performance analysis. As part of this work, BIM with architectural data (e.g. location data, building geometry, and materials) can be used as a framework for promoting collaborative design development and optimization. It can also contribute to advances in building performance simulation and energy efficiency. It is important to note that the vision of the future BIM tools should focus beyond visualization and coordination.

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