sustainability

MDPI

Article

Retrofitting Existing Buildings to Improve Energy Performance

Sunil Kumar Sharma [1], Swati Mohapatra [2], Rakesh Chandmal Sharma [3], Sinem Alturjman [4], Chadi Altrjman [4], Leonardo Mostarda [5] and Thompson Stephan [6,*]

[1] School of Engineering & Applied Science, National Rail and Transportation Institute, Vadodara 390004, Gujarat, India; sk.sharma@nrti.edu.in
[2] School of Science, Gujarat State Fertilizers and Chemicals University, Vadodara 391750, Gujarat, India; swatimohapatraiitr@gmail.com
[3] Mechanical Engineering Department, Maharishi Markandeshwar, Mullana 133207, Haryana, India; drrcsharma@mmumullana.org
[4] Artificial Intelligence Engineering Department, Research Center for AI and IoT, AI and Robotics Institute, Near East University, Mersin 10-99138, Turkey; sinem.alturjman@neu.edu.tr (S.A.); altrjmanc@gmail.com (C.A.)
[5] Computer Science Division, Camerino University, 62032 Camerino, Italy; leonardo.mostarda@unicam.it
[6] Department of Computer Science and Engineering, M. S. Ramaiah University of Applied Sciences, Bengaluru 560054, Karnataka, India
* Correspondence: thompsoncse@gmail.com

Abstract: Energy-efficient retrofits embrace enhancement of the building envelope through climate control strategies, employment of building-integrated renewable energy technologies, and insulation for a sustainable city. Building envelope improvements with insulation is a common approach, yet decision-making plays an important role in determining the most appropriate envelope retrofit strategy. In this paper, the main objective is to evaluate different retrofit strategies (RS) through a calibrated simulation approach. Based on an energy performance audit and monitoring, an existing building is evaluated on performance levels and improvement potentials with basic energy conservation measures. The considered building is experimentally monitored for a full year, and monitoring data are used in calibrating the simulation model. The validation of the base model is done by comparing the simulation analysis with the experimental investigation, and good agreement is found. Three different retrofit strategies based on Intervention of minor (RS1), Moderate (RS2), and Major (RS3) are analyzed and juxtaposed with the base model to identify the optimal strategy of minimizing energy consumption. The result shows that total energy intensity in terms of the percentage reduction index is about 16.7% for RS1, 19.87 for RS2, and 24.12% for RS3. Hence, RS3 is considered the optimal retrofit strategy and is further simulated for a reduction in carbon dioxide (CO_2) emissions and payback investigation. It was found that the annual reduction in CO_2 emissions of the building was 18.56%, and the payback period for the investment was 10.6 years.

Keywords: energy management; energy saving; load management; energy efficiency; sustainable city

check for updates

Citation: Sharma, S.K.; Mohapatra, S.; Sharma, R.C.; Alturjman, S.; Altrjman, C.; Mostarda, L.; Stephan, T. Retrofitting Existing Buildings to Improve Energy Performance. *Sustainability* **2022**, *14*, 666. https://doi.org/10.3390/su14020666

Academic Editor: Antonio Caggiano

Received: 18 November 2021
Accepted: 22 December 2021
Published: 7 January 2022

1. Introduction

The need to 'retrofit' or re-engineering existing buildings has gained growing popularity in recent years. On a worldwide scale, the expanding concentration of our growing human population in urban areas has focused emphasis on cities' role in mitigating and adapting to climate change, as well as accomplishing larger sustainable development goals. Although cities are considered the cause of many severe environmental and resource degradation problems, cities can also provide solutions with ingenuity such as the Internet of Things [1] and creative potential [2,3].

In recent decades, rapid industrialization and technical advancement have resulted in a massive increase in fossil fuel use. The majority of energy consumption is derived from nonrenewable energy sources, which are harmful to the environment. As a result, there is a greater emphasis on reducing nonrenewable energy consumption (EC) on a global scale [4,5]. The need to minimise fossil fuel use and CO_2 emissions can lead to improved energy efficiency in existing structures, as well as new building designs. These initiatives might be expanded into energy performance evaluation and monitoring of existing buildings, as well as retrofit techniques [6].

The net-zero energy building (NZEB) [7,8] concept has gained popularity over the last decade as a way to improve energy efficiency within the building sector and as a model for creating sustainable cities. In India, considering the significant element of their high EC, it is preferable to incorporate the NZEB idea into commercial retrofit, as this will assist both the conservation of embodied construction energy and the decrease of operating energy. Overall performance may be improved by updating and refurbishing existing buildings, which opens up new opportunities to revitalize the huge inventory of buildings and benefit local economies in the long term [9–11]. Typically, achieving NZEB entails improving building enclosures, lighting reduction, electric loads, Heating, Ventilation, and Air Conditioning (HVAC) systems and, passive layout approaches, allowing for the needed energy balance to be balanced with renewable energy sources such as wind turbines or solar photovoltaics.

Achieving net-zero energy objectives for an existing structure is a more motivating aim than new construction because of more constraints imposed on existing buildings. In most nations across the world, total EC for the building industry is about 40%. With the introduction of new technologies, operational challenges have increased, and it has become necessary to select the best plans and devise methods to reduce EC in the building sector [12]. On the other hand, the interplay among layout factors, HVAC systems, weather changes, distinct users, etc., is very complex and can be observed best by simulating all elements interfering in building energy performance. This can be achieved by using software applications but many different types of software applications have emerged in this area, and they must be carefully chosen [13–15].

In a dry and cold region, Saffari et al. [16] employed an energy plus tool to model the heating and cooling loads of a building. When the results were compared to the real data, it was discovered that the difference in cooling and heating loads was 5% and 3%, respectively. Furthermore, Saffari et al. [17] performed a critical analysis on the cooling system of a building under various climatic circumstances for energy and comfort assessment. Daemei et al. [18] investigated natural ventilators with a home construction design function in Rasht, Iran, and discovered that natural wind ventilation may be utilized with appropriate architecture.

The practical challenge of existing building retrofit is regarded as one of the most important problems for reducing energy consumption and greenhouse gas emissions. It also plays a critical role in enhancing a nation's energy security, reducing vulnerability to energy prices, and increasing human comfort. Above and beyond these uncertainties, changes in climate, services, human behaviour, government legislation, and so on, have an indirect or direct impact on the selection of retrofit technology [19]. Other problems that create interruptions in operations include financial constraints, extended payback periods, and building owners' willingness to pay for retrofits. Retrofitting or modifying existing buildings not only meets functional requirements but also significantly reduces costs, energy consumption, occupant well-being, and environmental effects.

Appropriate long-term decisions for building retrofit and effectiveness can significantly increase thermal performance and hence reduce energy usage [20]. The effects of supply air flow rate and temperature on the performance of a bed-based task/ambient air conditioning system are also investigated in other research. Furthermore, certain specialised places within a hospital complex need air-conditioning. In the operating room, for example, air cooling is widely acknowledged to be vital. In this context, air-conditioning refers to the capacity to manage the temperature both below and above the ambient temperature, as well as the humidity and sterile filtration. Air conditioning is also required in other departments, including as critical care, birth rooms, recovery rooms, radiology, and nuclear medicine, due to the hot, humid environment in most regions of a nation [21,22].

Buildings are complex and one-of-a-kind systems with a diverse range of physical, functional, and environmental properties. Considering this level of complexity, a holistic approach is essential, which employs methodologies combined with national and international standards. Therefore, in this paper, an analysis is done to demonstrate a systematic approach for the optimization of an energy-efficient retrofit strategy. A case building in the campus area of Motilal Nehru national institute of technology (MNNIT) Allahabad is monitored for one full year, including on-site climatic data, indoor temperature and humidity, energy consumption, and CO_2 emissions. Hence, this research aims to utilize a building energy simulation tool to replicate the base-case energy performance of the existing building and propose energy conservation measures targeting the improvement of the building envelope.

2. Methodology

The case study under consideration comes from the city of Allahabad in India. The highest cooling load occurs in June, when summer temperatures are at their highest, and the lowest load occurs in January, when winter temperatures are at their lowest. In comparison to November and December, the months from April through October have a significant cooling load. The flow chart of the methodology is given in Figure 1.

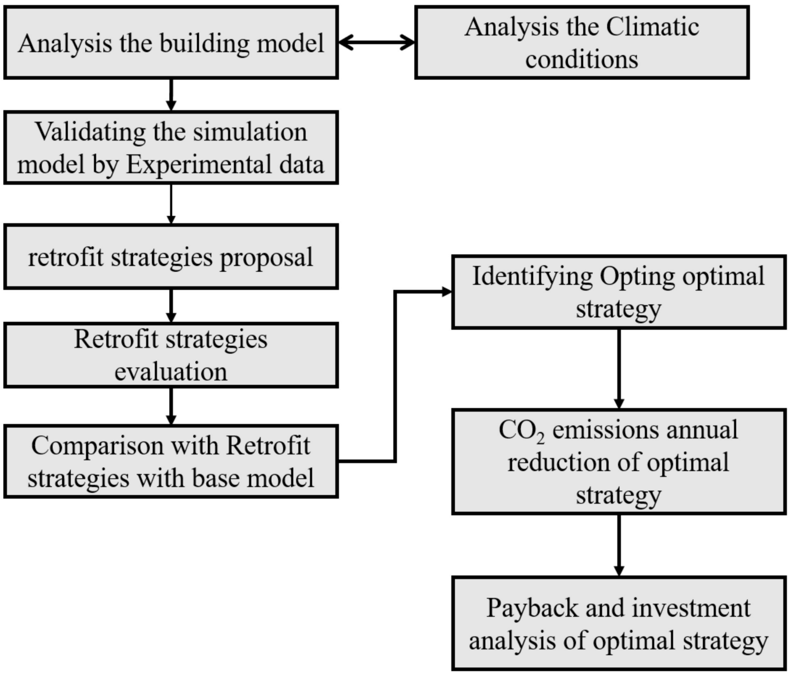

Figure 1. Flow chart of the methodology.

2.1. Multipurpose Building Audit

The building attributes such as orientation, location, comfort ranges, occupancy, and installed technology are acquired through building audits. The MNNIT Case Building (see Figure 2) is primarily used for multi-purpose events. The building detail information is given in Table 1. Cooling, heating, and ventilation systems are considered to maintain indoor air quality and to acclimatize the indoor environment.

Figure 2. MNNIT, Allahabad Multipurpose (MP) Hall.

Table 1. Building information.

No of floors	1
Total Area	1355 m^2
Floor Height	7.4 m
External Walls	228.20 mm brickwork, outer leaf 12.70 mm of plaster inside and outside, 12.70 hardboard (standard) inside with U-value of 2.176 W/m^2 K.
Internal Walls	228.20 mm brickwork, outer leaf 2.70 mm of plaster inside and outside with U-value of 0.831 W/m^2 K.
Roof	19 mm cement plaster, sand aggregate, 200 mm RCC 12.70 plaster (dense), and hardboard at an inner surface with a U-value of 1.233 W/m^2 K.
Window Area	20%
Floors	Concrete floor on ground of 463.5 mm with U-value of 0.953 W/m^2 K.
Glazing	6 mm sgl clr 5.788 W/m^2 K
Infiltration Rate(ac/h)	0.7 AC/H [23]
HVAC	Central (175 tons)
Set Point Temperature	(25–27 °C) Summer and (21–23 °C) Winter
Occupancy	2.2 m^2/person

2.2. Allahabad Climatic Conditions

The building is located at latitude 25.43° N and longitude 81.84° E, which is usually hot in summer and cold in winter. Figure 3a–d shows the mean minimum and maximum temperatures, average monthly total hours of sunshine, mean monthly relative humidity, and mean monthly wind speed, respectively.

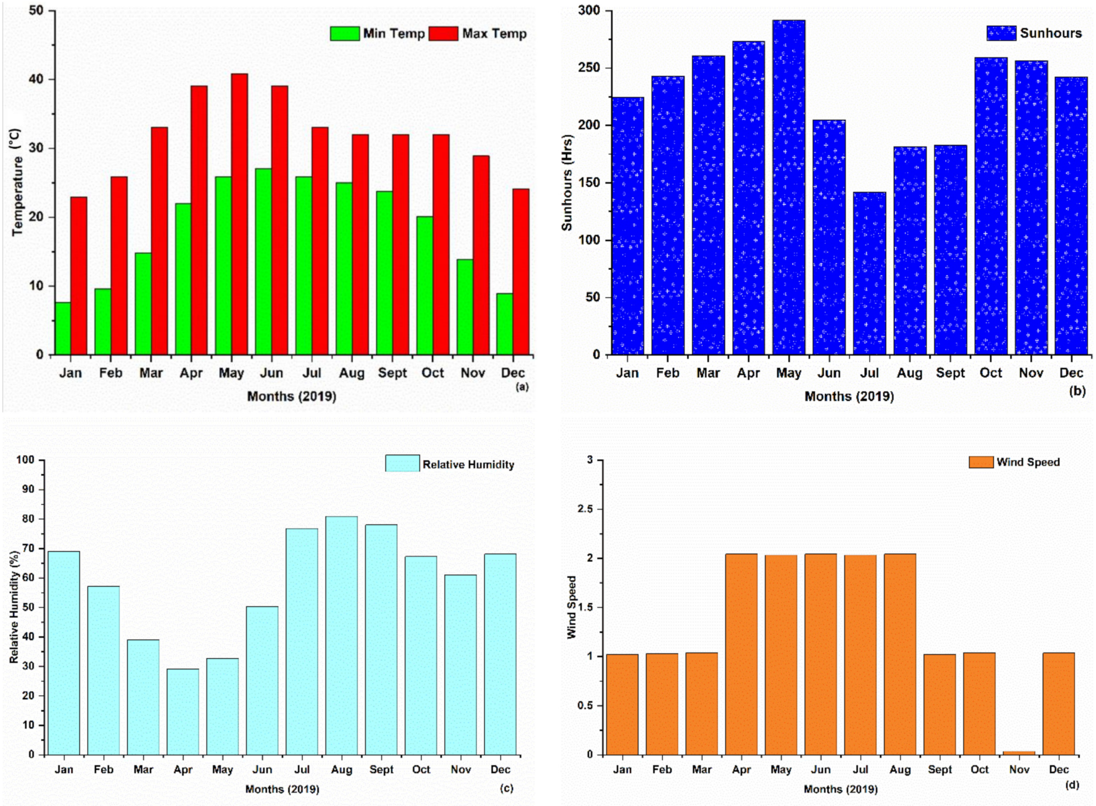

Figure 3. Climatic condition of Allahabad month wise (**a**) mean minimum and maximum temperatures, (**b**) average total hours of sunshine, (**c**) mean relative humidity, (**d**) mean wind speed.

2.3. Energy Performance Simulation Modelling

Building performance is simulated using the design builder simulation tool [24]. It is one of the most extensive user interfaces for dynamic thermal and energy simulation engine. In the design information, the lighting requirements and the appropriate lighting intensity levels for each building zone were included, so it was fairly trivial to enter these data into the model to provide the specific lighting performance. The lighting performance design level was updated to meet with the design builder requirement to identify lighting units. Because lighting in the building is primarily controlled by zone occupancy, it was assumed that lighting activity patterns were closely linked with building occupancy schedules. Both of these were estimated based on energy consumption data, which appear to be some extent indicative of building occupancy and occupant behaviour.

The HVAC system was modelled in the design builder using the basic mode. This decreases the model's complexity by eliminating the need to characterise every facet of the HVAC system. The basic mode, on the other hand, employs an idealised technique of load computation based on constant performance factors set by the modeler. Pump and fan energy, which may be monitored using building management systems energy data, can each be defined individually. Because the basic mode is employed, the energy model for HVAC is not expected to be as dependable as other components of the model. However, relative changes in energy use should be constant across model outputs because the HVAC model specification will be consistent. Figure 4 depicts the MP Hall design builder model.

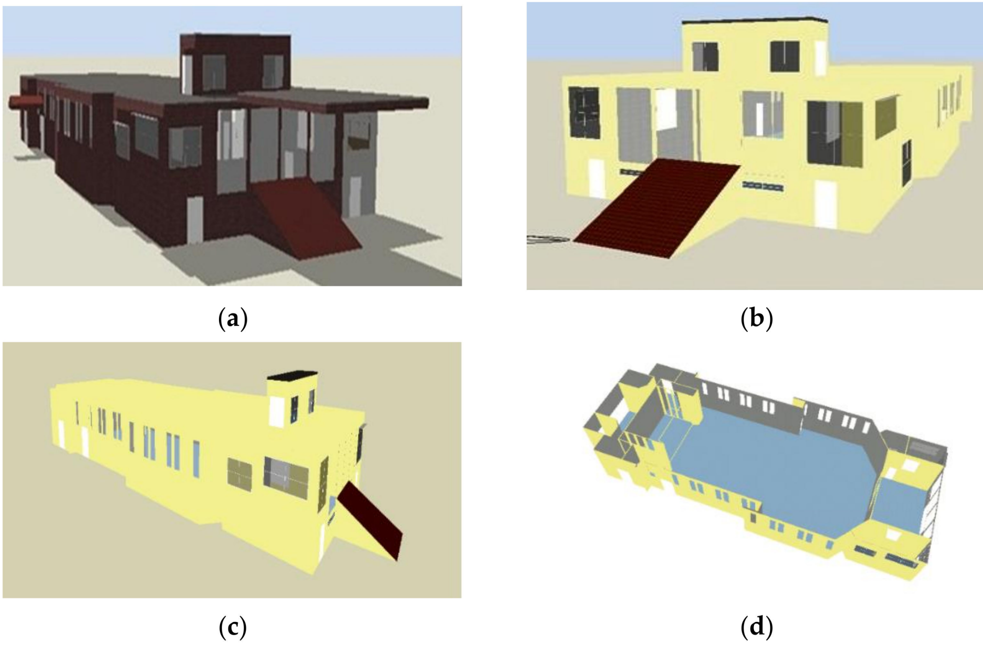

Figure 4. MP hall building modeled in design builder (**a**) Isometric view (**b**) Front view (**c**) Left side view (**d**) Internal view.

Extensive and continuous measurements of interior and outside data are required to achieve good findings for assessing indoor thermal profiles. Temperature and humidity measurements of sample volumes, greenhouse gas emissions, fuel consumption, energy usage, microclimate data, and of the building's heating infrastructure were all tracked for one full year in 2019.

3. Model Validation Methodology

Adequate testing and validation are necessary to verify that construction models are an accurate depiction of reality and that their data outputs are dependable enough to draw useful conclusions about the buildings. By comparing the data produced by the models with analogue data measured from real buildings and coupling this with a weather file in the model generated from actual measured data from a site near the building, errors in the model can be detected and tuned to the point where the building model can be said to be a satisfactory representation of the real building. Moreover, as input to the model, the internal gain/energy load input from occupancy, equipment, lighting is given in Figure 5.

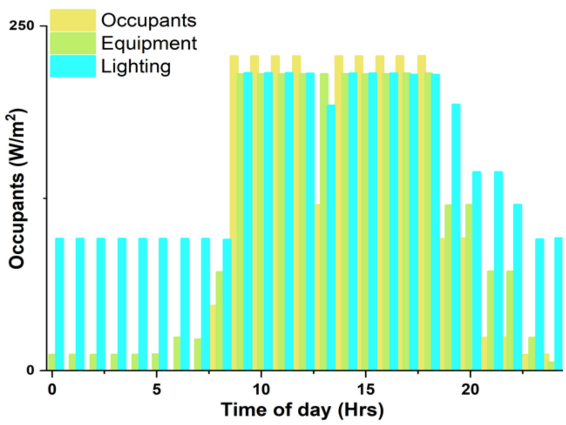

Figure 5. Internal heat gain profiles for lighting, equipment, and occupancy in a building.

During the validation process, errors associated with random events and actions in the building must be detected and discounted. It is quite difficult for the model to accept these random events; thus, care should be made to ensure that they do not impact the validation process. This may result in the building being optimized for the specific behavior seen during the validation time, but then the model will cease to be properly representative outside the validation period. The goal is to create a model that can accurately portray the building throughout any given year. To evaluate a building model, several components of it need be compared to actual data gathered from the structure.

Model validation was performed in this article using interior temperature profiles and the regular energy use of varied loads. By comparing the facts supplied by the models with comparable evidence estimated from real buildings and combining this with a weather file in the model created by actual measured data from a site near the building, errors in the model may be detected.

3.1. Temperature Profiles for Building Modes

Data were collected experimentally and simulations were carried out for the year 2019; historical periods reflecting the building modes (natural ventilation, heating, and cooling) were chosen. Compared with that created by the simulation, the actual indoor temperature profile was compared. An indicator of how well the model reflects the thermal efficiency of the real building should be given by a match between the measured temperature profile and that of the model.

3.2. Energy Usage

Due to stochastic problems such as occupancy, which are difficult to accurately model, it is impossible that the energy consumption of building components such as lighting can fit actual building use profiles over a short period. A properly tagged model, however, should exhibit comparable daily energy consumption compared to the calculated energy usage of the buildings. For periods wherever information from the building was available, regular lighting and IT masses were compared to the model.

3.3. Error Quantification

Error quantification for temperature profiles was evaluated using the percentage reduction index [25,26] (PRI) (Equation (1)) and the coefficient of determination, R^2. The performance of retrofit strategies was compared with the base model in terms of total energy intensity. A PRI of 15% was chosen as satisfactorily accurate for the validation of the simulation model. It was selected as this resembles an average residual of around 1–2 °C, which is within the margin associated with measurement error such as position or calibration measurement.

$$\mathrm{PRI} = \frac{\left(y_{\mathrm{measured}} - y_{\mathrm{modeled}}\right)}{y_{\mathrm{measured}}} \times 100 \tag{1}$$

4. Experimental–Numerical Validation

The period chosen for validation of temperature profiles was 6 August 19 to 12 August 19. This was chosen firstly, as it was the week with the most complete weather dataset and temperature data, but it is conjointly a decent illustration of an operating week. Figure 6a shows the comparison between the measured temperature and simulated temperature for the office. It can be seen that the internal temperature varied from 13 °C to 24 °C. A closer look reveals that the effect of sol–air temperature is more predominant for the roof as it receives direct insolation of the sun without any provision of shading. Besides, the dark grey rough surface of the rooftop further welcomes the sun. It is not surprising to see that east and west directions have a higher value of sol–air temperature and hence constitute a greater heat transfer rate for the same wall area and U-value. Between the two profiles, a sound match is established. The model tends to overestimate the room's peak temperatures over the two days of the weekend where no HVAC works in space.

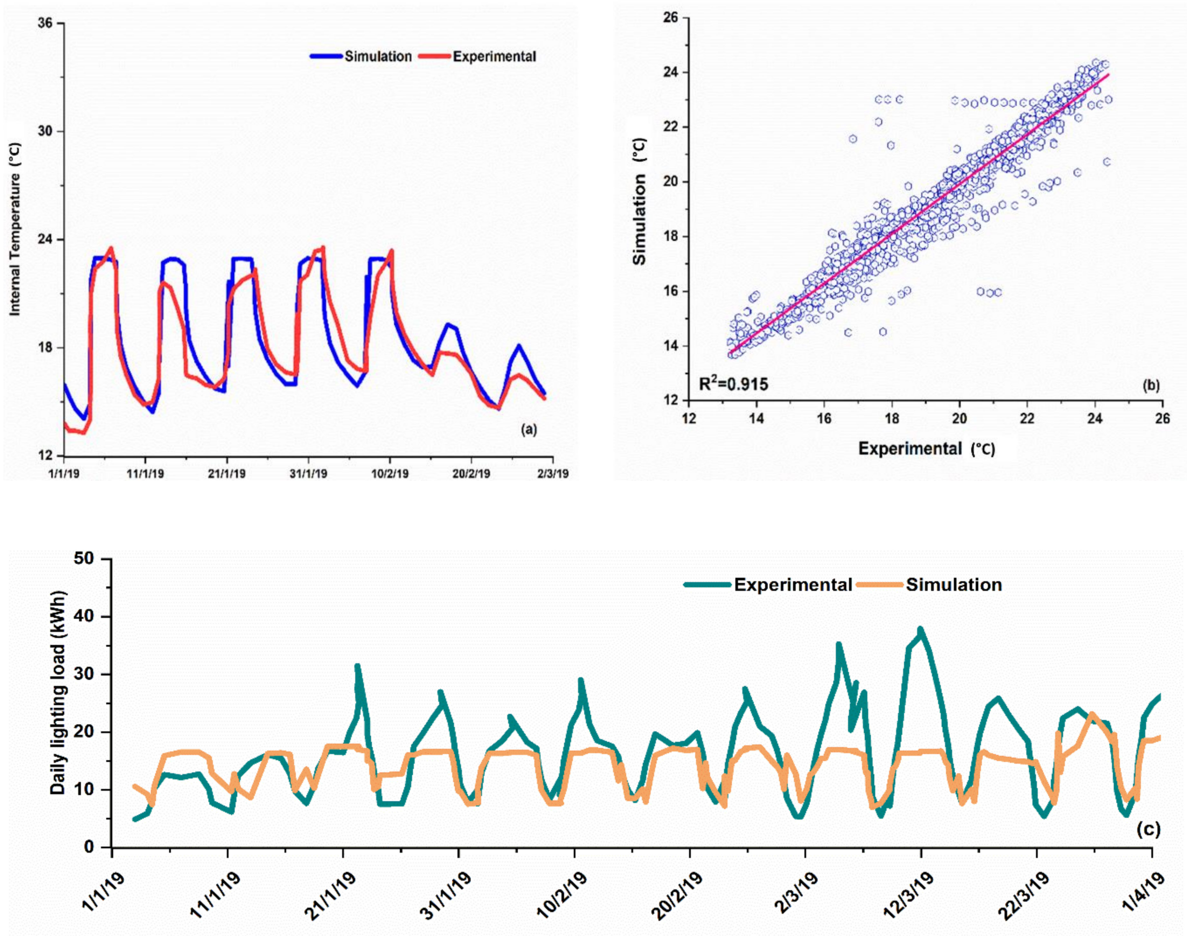

Figure 6. Office room temperature profile (**a**) comparison (**b**) R^2 (**c**) lighting electrical use comparison.

The PRI is calculated as −1.76%. The negative sign shows that the model over-predicts the temperature on average, by a magnitude of 1.76%, In the mornings, the highest levels of error are found where HVAC does not start running at the same time as in the model. An error can be more easily discounted during this stage of the day as the factors causing it (variations in occupancy-driven HVAC operation) are difficult to foresee and therefore to incorporate into the model. By matching simulation schedules to occupancy data, this error can be reduced; however, this will significantly increase modeling time and complexity, and in all cases could never be accurate enough to fit energy/temperature profiles exactly. As can be seen, the behavior of the model correlates well during these times to that of the real house. The coefficient of determination will indicate how well the model matches the measured data, having plotted the model values and measured values on a scatter graph. Errors occur because of the influence of variations in occupancy driven by HVAC operation and infiltration.

Buildings are never airtight due to the gaps between the frames of doors and windows and shutters. Therefore, the air infiltrates from surroundings at higher pressure into the room. This causes an increase in the cooling load. Similarly, if the room is maintained at a pressure higher than that of the surroundings, the cool air leaks out of the room. No sooner doors are opened than the cool air being heavier than the warm air of surroundings leaks out of the conditioned space. The flow of cool air from freezers and household refrigerators into surroundings is a well-known situation and falls under the latter category of infiltration. The increase in cooling load is due to this type of loss of cool air. The exact estimation of the leakage of air through apertures (the small gap between frame and shutter of a window or door) is extremely difficult. However, approximate values have been tabulated in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals and Equipment report. Similarly, the leakage of air due to door openings and through shutters is also based on practical experience in terms of room sizes. The volume of air infiltration is related to the volume of a room for different usages: average usage, long usage, and heavy usage, and it is difficult to calculate.

A decent correlation is observed showing an R^2 of 0.915 (Figure 6b), which means 91.5% of the variance is explained by the model. The horizontal streak of off-trend information points on the higher aspect is due to the model heating the building in a perfect manner, i.e., the temperature within the zone is the command at precisely the heating setpoint. This may not be true of the real building that varies within the comfort band and in some cases, heating is not a gift in the slightest degree in the real building over the sample validation period. The second stage of validating the model was a comparison of energy use. Figure 6c shows the comparison of lighting electrical EC in the first three months of 2019. The PRI was calculated as 11.35%, which is in the range of acceptable error. The monthly comparison of heating and cooling energy consumption for simulation and experimental are shown in Figure 7.

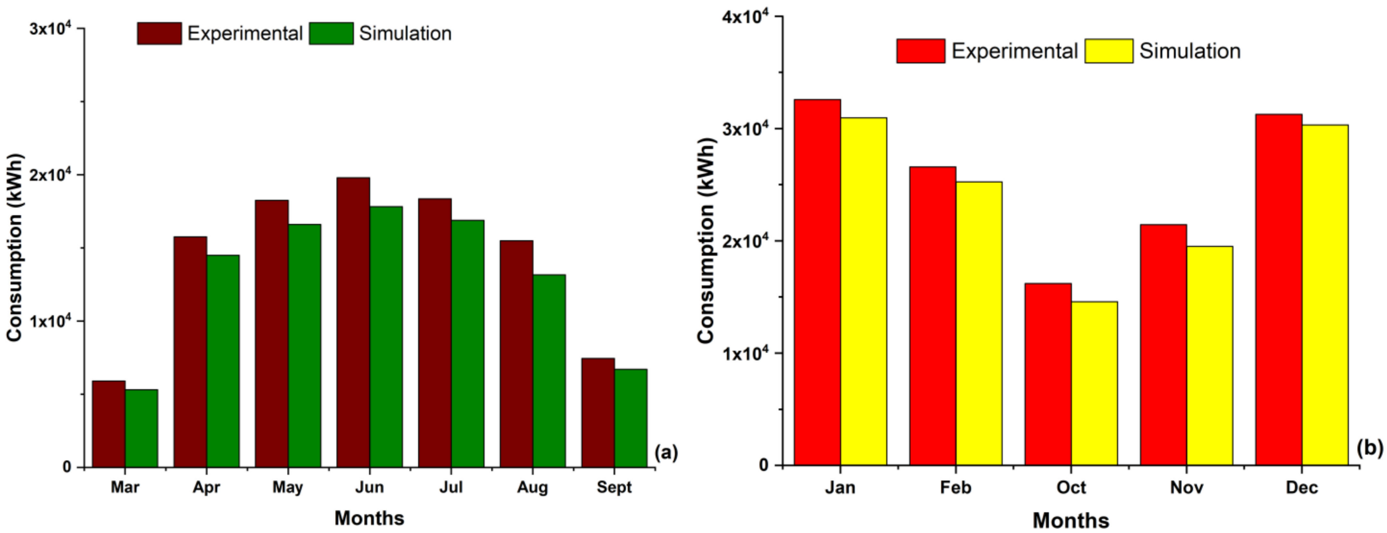

Figure 7. Monthly comparison of energy consumption for simulation and experimental (**a**) cooling and (**b**) heating.

5. Result and Discussion

As a result of a measured control cycle base-case model, retrofit strategies to enhance a building's energy efficiency and indoor environmental quality are suggested. It is stressed in the literature that an effective building envelope retrofit scenario requires one, a combination, or both of the following thermal characteristics to be controlled: (a) a reduction in ventilation and infiltration losses, (b) reduction in propagation, and (c) an increase or decrease in solar gains as a thermal feature of the envelope [27–29]. Retrofit plans include decisive requirements based on insufficiencies found by a building efficiency assessment or current building review. Additionally, due to the various alternatives where the primary concern is to determine the strategies that are supposed to be useful in the long term, an approach to producing retrofit strategies must be identified. With a broad variety of possibilities for retrofit solutions, environmental, energy, financial, and social considerations need to be weighed to achieve the most reliable approach.

5.1. Proposal of Retrofit Strategies

Three separate retrofit techniques were considered in this paper to increase the energy efficiency and internal environmental consistency of a building, i.e., small, medium, and large stages of intercession, such as RS1, RS2, and RS3, respectively. In compliance with pre-defined qualitative and quantitative requirements, retrofit techniques are recommended and include thermal insulation of opaque components, enhancement of the window insulation quality, reduction of intrusion rate, use of mass or ventilated walls, etc. For the least intrusion in the workplace to preserve the efficiency of building tenants, qualitative requirements are considered. For the estimation of the insulation thickness for each retrofit technique, objective parameters based on the measurement of the optimum insulation thickness are used. The criteria determined by a method for deciding the optimal insulation thickness for building components are the type of insulation content, insulation thickness, cost of insulation material, and cost of energy used for heating and cooling. Optimization is based on the estimation of micro-climatic weather by degree days, cost analysis of insulation products, and energy usage via a calibrated base-case model; retrofit techniques are applied to determine their effects on indoor environmental parameters and annual energy usage for room heating and cooling.

XPS is used as the insulation medium for external opaque envelope components for these three distinct techniques, as it has a lower thermal conductivity of 0.030 W/m K and has optimum payback times and lower thickness savings. Regarding optimal thickness analysis, each wall assembly is given an insulation thickness. The outer brick wall is insulated with an XPS board of 40 mm and is completed with a brick cladding of 30 mm for the RS1 intercession. The exterior concrete wall is supplied with XPS insulation of 50 mm thickness and is coated with 10 mm insulating plaster. Exterior concrete wall steps are kept the same for RS2 intercession, but the external brick wall assembly is changed with a ventilated cavity and 30 mm thick XPS insulation, completed with 6 mm wooden facade cladding. For the previous technique, RS3 intercession retains the proposed brick wall assembly but integrates a comparable assembly to the concrete wall with 40 mm XPS dimensions, 30 mm ventilated cavity, and 6 mm wooden facade cladding. This technique involves strengthening the concrete floor on the ground with 30 mm thick XPS insulation. For the 1st strategy, a glazing upgrade is recommended due to the substitution of the current glass panes with Low-E (RS1). The 2nd and 3rd strategies (RS2 and RS3) retain Low-E substitute interference, which requires the substitution of vinyl frames with 1.4 W/m^2 K U-values.

5.2. Retrofit Strategy Evaluation

Through the calibrated model, retrofit strategies are simulated by incorporating different RS into envelope components. The outcomes are calculated according to the frequency of hours beyond the comfort range and the annual heating and cooling energy usage. For the heating and cooling seasons, frequency analysis is used to assess the percentage of hours beyond the comfort range. Building comfort temperatures range between 22 °C for winter and 24 °C for summer; assessment temperature ranges between a minimum of 21 °C and maximum of 25 °C. For this study, conditioned rooms are measured, covering occupancy hours for the entire year. Retrofit strategies are applied through a regulated base-case model with the purpose to assess their effects on indoor environmental parameters and annual EC for space heating and cooling. Figure 8 show the total energy intensity comparison month wise for all the retrofit strategies.. Table 2 shows the retrofit strategies have better total energy intensity attenuation ability than the base model system for all RS.

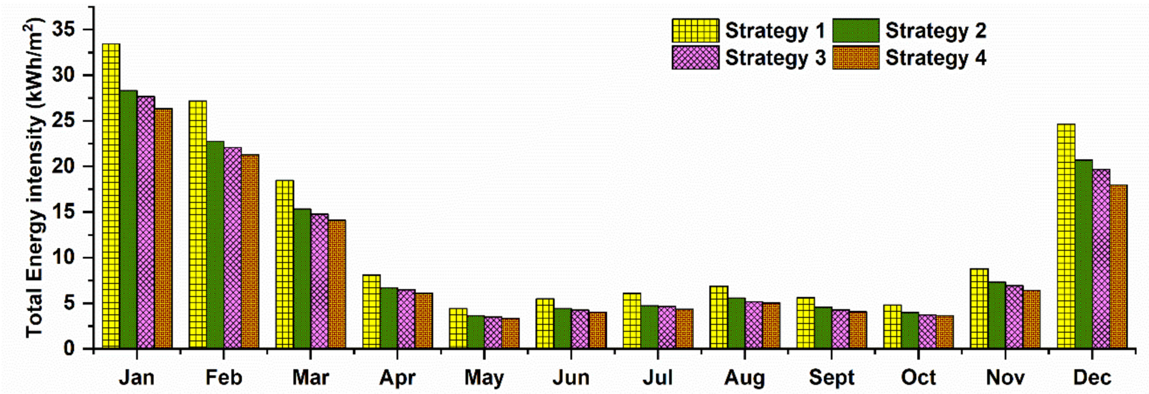

Figure 8. Comparison of simulated total energy intensity with all retrofit strategies.

Table 2. Total energy intensity (kWh/m^2) and PRI for different retrofit strategies for the year 2019.

	Month	January	February	March	April	May	June	
Total energy intensity	Base model	33.45	27.17	18.47	8.12	4.45	5.51	
	RS1	28.33	22.76	15.35	6.71	3.64	4.43	
	RS2	27.66	22.1	14.78	6.5	3.51	4.26	
	RS3	26.35	21.3	14.1	6.12	3.36	4.02	
% PRI	RS1	15.32	16.23	16.9	17.32	18.23	19.65	
	RS2	17.32	18.65	19.98	20.01	21.02	22.65	
	RS3	21.23	21.59	23.65	24.65	24.48	27.04	
	Month	**July**	**August**	**September**	**October**	**November**	**December**	**Total**
Total energy intensity	Base model	6.09	6.86	5.61	4.83	8.8	24.65	154.02
	RS1	4.74	5.59	4.6	4	7.32	20.71	128.17
	RS2	4.66	5.18	4.3	3.74	6.93	19.67	123.42
	RS3	4.34	5.06	4.08	3.66	6.44	17.97	116.87
% PRI	RS1	22.23	18.56	17.98	17.21	16.78	16.01	16.78
	RS2	23.54	24.56	23.32	22.65	21.23	20.2	19.87
	RS3	28.77	26.24	27.17	24.37	26.85	27.13	24.12

According to the results of simulated retrofit strategies, it can be observed that PRI has an improvement in total energy intensity of about 16.7% for RS1, 19.87 for RS2, and 24.12% for RS3. The EC can further be reduced, by using double-paned glass with an air gap, as air in a confined space serves as a very good insulator; usage of overhangs leads to minimization of the effect of incident solar radiation and hence reduces the effect of sol–air temperature and using sun-ban reflective glasses, which reflect solar heat, while allowing light to come through for illuminating purposes. This will also reduce electrical demand for lighting during the daytime. But as per investigation, the maximum total energy intensity was found in RS3. Hence, RS3 is considered the optimal retrofit strategy and was further simulated for a reduction in CO_2 emissions and payback investigation.

5.3. Reduction in Annual CO_2 Emissions

The simulation results for the optimum plan suggest an annual reduction of the building's CO_2 emissions at a value of 18.56% relative to the base case scenario. Reduced EC heating results in a 15.69 percent reduction in CO_2 emissions due to fuel combustion. Space cooling consumption emissions decrease by 22.96 percent annually (Figure 9).

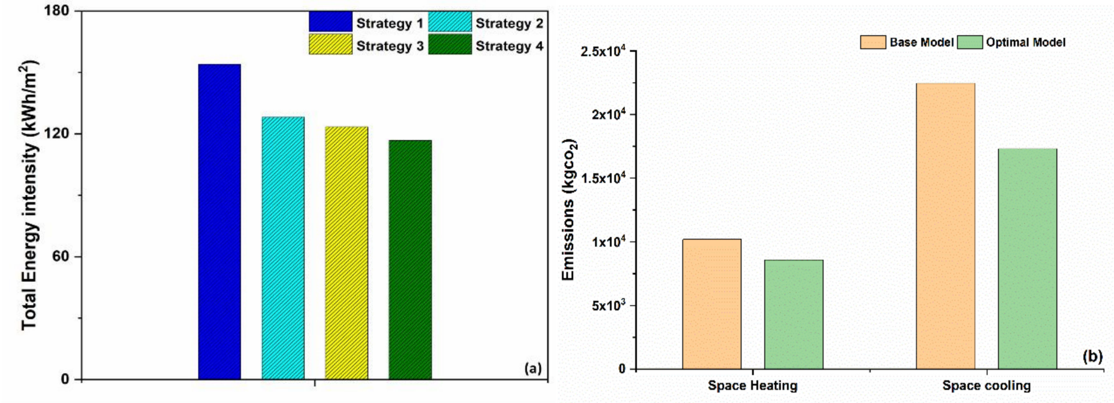

Figure 9. (**a**) Total energy intensity yearly for different retrofit strategies (**b**) annual reduction in CO_2 emissions for the optimal strategy.

5.4. Payback and Investment Analysis of the Optimal Strategy

The payback time for the project is estimated at 10.6 years, according to the current valuation calculation of the investment and savings (Figure 10). Energy-efficiency upgrades to the construction envelope are typically costly measures, and payback times are lengthy for holistic improvements. However, in contrast to energy efficiency, changes in the indoor environment, elimination of CO_2 emissions, etc., lengthy payback times and high investment costs can be considered reasonable. The retrofit steps are expected to have a lifecycle of 25–30 years in this analysis. In this context, it can be argued that the outcome of the payback period for an optimal retrofit strategy is positive and similar to parallel studies.

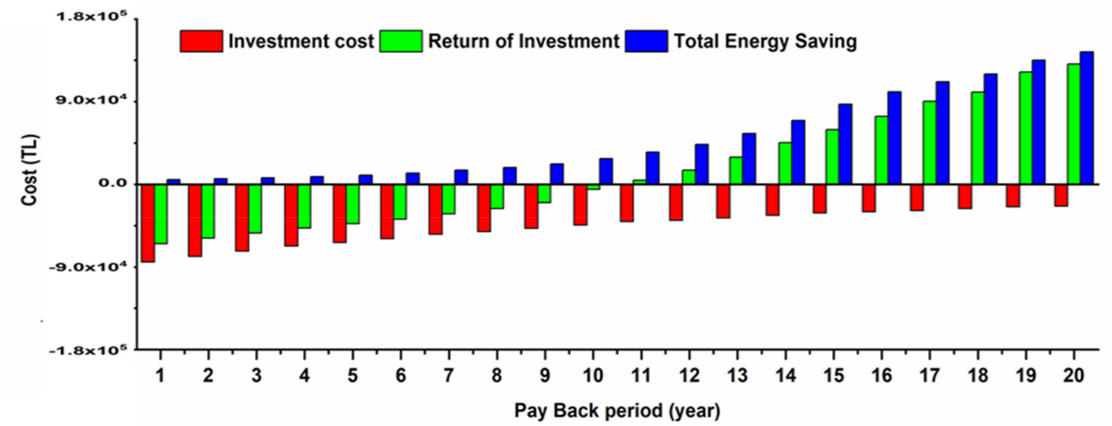

Figure 10. Return on investment analysis for the optimized retrofit strategy.

6. Conclusions

In this paper, an approach is presented to demonstrate the use of energy performance monitoring and a calibrated dynamic simulation approach to be utilized in defining energy-efficient envelope retrofit measures. Conscious decision-making for retrofit strategies is critical, especially when investment costs are high and payback periods for these improvements are long. As a result, the study's primary focus is to conduct a detailed energy performance monitoring process, evaluate any retrofit measures using dynamic assessment methodology, preferably validated simulation models, and assess an optimised retrofit strategy to improve the energy performance of existing building envelopes.

The results show that, following sufficient design manipulations, this existing building can minimize energy usage. In this analysis, a multipurpose building was examined for annual EC in 2019 using a design builder, and validation was done using experimental analysis. The error in comparison was about 1.76%, showing good agreement between numerical and experimental analyses. To minimize the EC, RS1, RS2, and RS3 strategies were investigated, and it was found out that PRI had an improvement of about 16.7% for RS1, 19.87% for RS2, and 24.12% for RS3 for total energy intensity. RS3 as an optimal strategy was further investigated for an annual reduction in CO_2 and investment/payback analysis. It was found that the annual reduction in CO_2 emissions of the building was 18.56%, and the payback period for the investment was 10.6 years.

Author Contributions: S.K.S., S.M. and R.C.S. prepared the inspection system for the simulation and performed the simulation presented in this research. S.A. conceived the original idea. C.A. and L.M. designed the methodology, gave guidance, and helped to improve the quality of the manuscript. S.K.S. wrote the original draft preparation in consultation with T.S., who reviewed and edited the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zahmatkesh, H.; Al-Turjman, F. Fog computing for sustainable smart cities in the IoT era: Caching techniques and enabling technologies—An overview. *Sustain. Cities Soc.* **2020**, *59*, 102139. [CrossRef]
2. Chithaluru, P.; Al-Turjman, F.; Kumar, M.; Stephan, T. I-AREOR: An energy-balanced clustering protocol for implementing green IoT in smart cities. *Sustain. Cities Soc.* **2020**, *61*, 102254. [CrossRef]
3. Deebak, B.D.; Al-Turjman, F. A novel community-based trust aware recommender systems for big data cloud service networks. *Sustain. Cities Soc.* **2020**, *61*, 102274. [CrossRef]
4. Dhalluin, A.; Bozonnet, E. Urban heat islands and sensitive building design—A study in some French cities' context. *Sustain. Cities Soc.* **2015**, *19*, 292–299. [CrossRef]
5. Zune, M.; Pantua, C.A.J.; Rodrigues, L.; Gillott, M. A review of traditional multistage roofs design and performance in vernacular buildings in Myanmar. *Sustain. Cities Soc.* **2020**, *60*, 102240. [CrossRef]
6. Kwon, S.-J. Effect of mineral admixture on CO_2 emissions and absorption in relation to service life and varying CO_2 concentrations. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 165–173. [CrossRef]
7. Kwon, S.-J. Service life variation in RC columns exposed to chloride attack: A time-dependent deterministic and probabilistic examination. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 184–197. [CrossRef]
8. Parrish, K.; Singh, R.; Chien, S.-C. The role of international institutional partnerships in delivering low-energy building design: A case study. *Sustain. Cities Soc.* **2015**, *14*, 383–389. [CrossRef]
9. Wang, Z.; Jiang, D.; Wang, F.; Lv, Z.; Nowak, R. A polymorphic heterogeneous security architecture for edge-enabled smart grids. *Sustain. Cities Soc.* **2021**, *67*, 102661. [CrossRef]
10. Zavadskas, E.K.; Turskis, Z.; Šliogerienė, J.; Vilutienė, T. An integrated assessment of the municipal buildings' use including sustainability criteria. *Sustain. Cities Soc.* **2021**, *67*, 102708. [CrossRef]
11. Buck, K.D.; Summers, J.K.; Smith, L.M. Investigating the relationship between environmental quality, socio-spatial segregation and the social dimension of sustainability in US urban areas. *Sustain. Cities Soc.* **2021**, *67*, 102732. [CrossRef]
12. Da Cruz, R.B.C.; de Castro Marins, K.R.; Kurokawa, F.A. Multicriteria methodological-rational model to evaluated urban areas: A case study of the São Paulo City/Brazil. *Sustain. Cities Soc.* **2021**, *67*, 102718. [CrossRef]
13. Guo, Y.; Qian, H.; Sun, Z.; Cao, J.; Liu, F.; Luo, X.; Ling, R.; Weschler, L.B.; Mo, J.; Zhang, Y. Assessing and controlling infection risk with Wells-Riley model and spatial flow impact factor (SFIF). *Sustain. Cities Soc.* **2021**, *67*, 102719. [CrossRef]
14. Torkayesh, A.E.; Hashemkhani Zolfani, S.; Kahvand, M.; Khazaelpour, P. Landfill location selection for healthcare waste of urban areas using hybrid BWM-grey MARCOS model based on GIS. *Sustain. Cities Soc.* **2021**, *67*, 102712. [CrossRef]
15. Azunre, G.A.; Amponsah, O.; Takyi, S.A.; Mensah, H. Informality-sustainable city nexus: The place of informality in advancing sustainable Ghanaian cities. *Sustain. Cities Soc.* **2021**, *67*, 102707. [CrossRef]
16. Saffari, M.; de Gracia, A.; Ushak, S.; Cabeza, L.F. Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1239–1255. [CrossRef]
17. Saffari, A.; Silver, M.J.; Zavattari, P.; Moi, L.; Columbano, A.; Meaburn, E.L.; Dudbridge, F. Estimation of a significance threshold for epigenome-wide association studies. *Genet. Epidemiol.* **2018**, *42*, 20–33. [CrossRef]
18. Baghaei Daemei, A.; Khotbehsara, E.M.; Nobarani, E.M.; Bahrami, P. Study on wind aerodynamic and flow characteristics of triangular-shaped tall buildings and CFD simulation in order to assess drag coefficient. *Ain Shams Eng. J.* **2019**, *10*, 541–548. [CrossRef]

19. Pluchinotta, I.; Pagano, A.; Vilcan, T.; Ahilan, S.; Kapetas, L.; Maskrey, S.; Krivtsov, V.; Thorne, C.; O'Donnell, E. A participatory system dynamics model to investigate sustainable urban water management in Ebbsfleet Garden City. *Sustain. Cities Soc.* **2021**, *67*, 102709. [CrossRef]
20. Aboelata, A. Reducing outdoor air temperature, improving thermal comfort, and saving buildings' cooling energy demand in arid cities—Cool paving utilization. *Sustain. Cities Soc.* **2021**, *68*, 102762. [CrossRef]
21. Sharif, A.A. Sustainable architecture, interactions and mutual relations: A case study of residential building facades. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 146–152. [CrossRef]
22. Kwon, C.W.; Lee, K.J. Investigation of the environmental performance of a transitional space in a UK nursery school. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 153–164. [CrossRef]
23. Akhter, S. Impact of solar passives architecture on thermal loads of a building. *Motilal Nehru Natl. Inst. Technol.* **2011**, 1–65.
24. Design-Builder. 2021. Available online: https://designbuilder.co.uk/ (accessed on 15 November 2021).
25. Sharma, S.K.; Kumar, A. Ride comfort of a higher speed rail vehicle using a magnetorheological suspension system. *Proc. Inst. Mech. Eng. Part K J. Multi-body Dyn.* **2018**, *232*, 32–48. [CrossRef]
26. Sharma, S.K.; Kumar, A. Disturbance rejection and force-tracking controller of nonlinear lateral vibrations in passenger rail vehicle using magnetorheological fluid damper. *J. Intell. Mater. Syst. Struct.* **2018**, *29*, 279–297. [CrossRef]
27. Hestnes, A.G.; Kofoed, N.U. Effective retrofitting scenarios for energy efficiency and comfort: Results of the design and evaluation activities within the OFFICE project. *Build. Environ.* **2002**, *37*, 569–574. [CrossRef]
28. Dascalaki, E.; Santamouris, M. On the potential of retrofitting scenarios for offices. *Build. Environ.* **2002**, *37*, 557–567. [CrossRef]
29. Güçyeter, B.; Günaydın, H.M. Optimization of an envelope retrofit strategy for an existing office building. *Energy Build.* **2012**, *55*, 647–659. [CrossRef]