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The Impact of Sustainable Materials and Modern Construction Techniques on Energy Efficiency in Residential Buildings in Low-Sunlight Urban Areas

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Abstract

The construction industry is one of the largest consumers of energy worldwide, making the transition toward sustainable and energy-efficient building practices a critical necessity. This study investigates the impact of sustainable and modern construction materials on energy efficiency in residential buildings located in low-sunlight urban areas of England. The research follows an applied–analytical approach, employing both literature review and computer simulation through the Design Builder software to model and analyze residential buildings in the cities of London, Birmingham, and Manchester. The study examines how different wall, roof, and window materials influence heating energy loss under varying climatic conditions. Two scenarios were simulated: one using traditional materials and another employing modern, sustainable alternatives such as double-glazed windows, insulated wall blocks, and rock wool. The comparative analysis revealed that substituting conventional materials with advanced, energy-efficient ones can reduce total energy consumption by up to 46–47%, depending on climatic conditions. Additionally, the use of improved glazing materials allows for a larger window-to-wall ratio, optimizing natural daylight utilization without increasing heat loss. The results emphasize the significant role of material selection in achieving sustainability goals and demonstrate the importance of integrating simulation-based design tools in energy performance evaluation. This research contributes to the growing body of knowledge on sustainable architecture by highlighting practical approaches to reducing energy consumption and carbon emissions in residential buildings, particularly in regions with limited solar exposure.

Keywords: Sustainable Architecture, Energy Efficiency, Building Information Modeling (BIM), Design Builder, Thermal Analysis.

1- Introduction

Articles Given the high level of global energy consumption used by the construction industry, the need to reduce energy consumption in this industry has become very urgent today; therefore, the use of enhanced sensor data and improved computational support for the necessary controls to reduce energy consumption in the construction industry, especially in the field of renovation of public buildings such as service and educational buildings, has become very important and of great interest to researchers today. In this regard, the maximum balance of building energy efficiency and the level of comfort desired by users during and after building renovation, especially educational and service buildings, is very vital and important. [1] In the present era, the important role of sustainable architecture with green architecture in using modern building materials with the approach of exploiting renewable resources instead of non-renewable resources in the earth is important. Sustainable architecture using green and recyclable materials is a logical response to the problems and problems that have arisen in the industrial age. Modern building materials play an important role in sustainability. In fact, what shapes the nature of a building are the materials. [1] Today, with the development of techniques in the fields of materials and construction methods, buildings have been built with higher efficiency, better economy, and also environmentally friendly, and the advancement of technology has led to the provision of new construction materials. These materials are composed of special molecules that perceive and react to their surroundings, and their properties change significantly under the influence of external factors such as light, temperature, humidity, and magnetic effects. Despite such characteristics, they can lead to the optimization of energy consumption and the achievement of sustainable architectural goals. The high potential of modern building materials in the development of functions and forms, as well as their greater adaptation to environmental conditions, has caused a revolution in the field of current architecture, so much so that, according to German architect Axel Ritter, the future will be able to change their color, size, and shape in exchange with the surrounding environment. Future architects will be able to design buildings whose geometry changes according to the weight of the people inside the building. [1] The use of new building materials and resources means the optimal use of energy, natural resources, and materials in order to construct buildings with fewer resources and environmental impacts. This is based on life cycle thinking and includes energy efficiency and material and material efficiency. While energy efficiency considers the ratio of energy consumption to production, the use of new building materials is done in order to save on the use of natural material resources, effectively manage side streams, reduce waste and recycle. Today, natural resources underpin the economic performance of European and global countries and provide quality of life. These resources include raw materials, such as fuels, minerals and metals, as well as food, soil, water, air, biomass and ecosystems, and the building sector is one of the three key sectors of importance. According to research, the use of new building materials in the construction industry in the European Union can reduce final energy consumption by 42%, greenhouse gas emissions by about 35% and more than 50% of total extracted materials. It can also save up to 30% in water consumption. [2] Increasing efficiency in the household sector in Europe accounts for about 25% of total final energy consumption and 29% of total electricity consumption in the European Union. Recent research has estimated that the residential sector could save around 19% of final energy consumption compared to 2020 levels by implementing new energy efficiency policies and removing barriers to the adoption of new technologies. The majority of these savings would come from improved thermal insulation and the use of new sustainable building materials, with around 7% of energy savings coming from the use of household appliances and lighting. In general, policies to reduce energy consumption in buildings include turning off lights when leaving a room, adjusting indoor temperatures at night, reducing heat in unused rooms, using dishwashers and washing machines at full capacity, and increasing the adoption of new and sustainable building technologies to reduce energy consumption in walls, roofs and glazing in residential buildings in European countries, especially in areas with low sunlight. [3] This study attempts to examine the impact of using sustainable materials on reducing energy consumption in residential buildings in European countries and low-light areas.

2- Research literature:

2.1- Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is one of the environmental assessment methods that is used today as one of the standard and widely used methods in the environmental assessment of processes, products and services. In fact, life cycle assessment as one of the environmental assessment methods after technical assessment and economic assessment complements the third side of a sustainable assessment that helps us to act with confidence in terms of the environment in addition to technical and economic dimensions. Therefore, in the discussion of construction, considering the destructive effects of waste, effective waste management and minimizing their destructive effects on the environment and economy are among the most important issues of the current century. Reducing the amount of construction waste and debris is one of the main solutions to prevent environmental pollution and reduce construction costs. [4]

2-2- Research background

Toropoc and et al analyzed two heating systems, chiller and fan coil, for hot water and lighting, in MWh per year. By simulating the heating and cooling systems of chiller and fan coil and comparing them with the VRF air conditioning system, it resulted in an energy saving of about 81.25 MW. [5] Lechtenböhmer and Schüring simulated the thermal quality and costs of building envelope components for new buildings as well as the renovation of existing buildings. Based on the analysis, it was investigated what is needed to accelerate energy savings in the building sector and a more accurate estimate of the potentials that should be targeted by specific policies was provided. The results emphasized the high relevance of accelerating renovation and reinvestment cycles of buildings and, by providing a clear estimate of the full costs associated with the strategy under consideration, will have a significant impact in removing major barriers to the construction and renovation of residential buildings. [6] and et al Sangmesh in a study stated that to meet the demand for construction materials, it is preferable to use alternative indigenous and environmentally friendly building materials. Agricultural wastes were introduced as sustainable alternative materials for use in building construction. In this study, various potential applications of agricultural wastes in building construction were investigated. Also, we presented the relevant physical, thermo-mechanical, methodological and ecological impact assessment. The results showed that the use of agricultural wastes as a commercially viable technological solution for building materials can reduce the detrimental impacts of construction on the environment. [7]

3- Methodology

The type of research in this study is applied-analytical; therefore, in this study, with the help of library research methods, studies, and Design Builder modeling software, their architectural components that are effective in improving the quality of educational spaces in terms of increasing vitality and motivation, increasing social interactions, etc. were extracted, and other research information was also collected through reviewing documents and evidence, sources and documents, and information from internet networks. In this way, as a case study, a residential building with similar specifications and plans in three cities in England, including London, Birmingham, and Manchester, was modeled in accordance with the weather and climate conditions and the amount of sunlight in each city under study, and then the amount of energy loss in each of the models will be compared in two conditions of using traditional materials and modern and sustainable building materials. Finally, an appropriate solution will be presented regarding the maximum use of sunlight in order to provide daylight and the maximum reduction in electricity consumption to provide lighting for the building.

3.1- Weather conditions in the city of London

London has a temperate oceanic climate. Rainfall records have been kept in the city since at least 1697, when records began in Kew. In Kew, the highest rainfall in a single month is 7.4 inches in November 1755, and the lowest is 0 inches in December 1788 and July 1800. The average annual rainfall is around 600 mm, half the annual rainfall of New York City. Despite its relatively low annual rainfall, London has 109.6 rainy days per year with a threshold of 1.0 mm. London is vulnerable to climate change, and there is concern among hydrological experts that households could face water shortages before 2050.[8]

3.2-Weather conditions in Birmingham

Birmingham has a temperate maritime climate, like many of the British Isles, with average maximum temperatures in summer (July) of around 21.3 °C and in winter (January) of around 6.7 °C. Between 1971 and 2000 the warmest day of the year averaged 28.8 °C and the coldest night typically reached -9.0 °C. There were around 11.2 days each year with temperatures reaching 25.1 °C or above, and 51.6 nights with freezing temperatures. Like many other large cities, Birmingham has a significant urban heat island effect. Birmingham is a snow-free city compared to other major areas of the United Kingdom, due to its inland location and relatively high altitude. [9]

3-3- Weather conditions in Manchester

Manchester, like most of the British Isles, has a temperate maritime climate. The city has relatively cool summers and mild winters. The average annual rainfall in the city is 806.6 mm. This compares with the UK average of 0.112 mm, and the average number of rainy days is 4.140 mm per year. Manchester also has relatively high humidity levels, and due to the urban warming effect, snowfall is not a common sight in residential areas. However, the Pennine Woodlands and Rossendale around the eastern and northern edges of the city receive more snow, and roads leading out of the city can be closed due to heavy snowfall. [10] The software used in this study included AUTOCAD software for the architectural design of the building, followed by Design Builder software for the thermal and lighting modelling of the designed building. The modelled building plan is presented below.

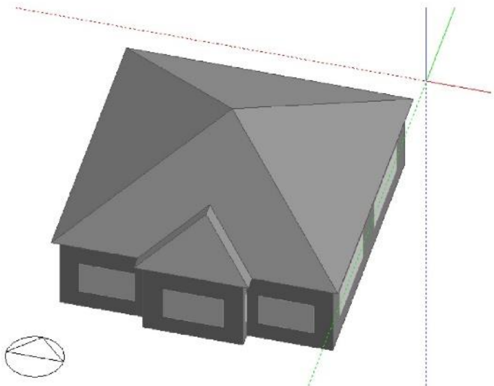

Figure 1 Modeled residential building plan in the cities of London, Birmingham and Manchester.

In this research, after modeling the building in the Design Builder software, introducing the materials used in the external walls, roof and openings, and considering the climatic conditions of the school construction site, thermal and cooling analyses and the amount of energy loss of the building will be carried out, and finally the effect of using different materials in the external shell of the building will be compared. For this purpose, in addition to modifying the consumption pattern, steps can be taken to reduce energy consumption by selecting appropriate materials.

3-4- Introducing materials to modeling software

In the continuation of this research, the definition of the materials used in the school building modeled in the Design Builder software was discussed, and the design and calculation of the amount of energy loss in the summer and winter seasons were examined. For this purpose, the residential building will be calculated with two different details as mentioned in Tables 1 and 2. Also, the heat transfer coefficients of each material are presented.

Table 1. Specifications of materials used in the first modeling

Section	Consumable materials	Thickness (centimeters)	Thermal transfer coefficient (w/m)
External wall	Clay brick	20	1.35
	Cement plaster	2	0.15
	Granite stone	2	2.2
	Gypsum plaster	1	0.56
Floor	Wooden lumber	20	1.05
	suspended ceiling	2	0.72
Single – glazed windows and aluminum frame	Single – glazed windows	0.3	4.8

Table 2. Material specifications used in the second modeling

Section	Consumable materials	Thickness (centimeters)	Thermal transfer coefficient (w/m)
External wall	Double wall of Lika block	20	0.035
	Rock wool	2	0.047
	Refractory brick	2	1
	Gypsum plaster	1	0.56
Floor	Wooden lumber	20	1.05
	suspended ceiling	2	0.72
	Rock wool	2	0.047
Double-glazed window with PVC frame	duble – glazed windows	1.2	3.3

4- Research findings

As mentioned earlier, in recent years, the environmental crisis has been one of the main concerns of mankind. The increase in energy consumption and its impact on the future of the environment has made the design of buildings with a sustainable architectural approach of particular importance. In the meantime, the new construction structures and materials used in buildings, especially in European countries, in order to make greater use of the sun's rays and provide lighting and, as a result, reduce energy consumption, have a significant impact on achieving a livable world. In this regard, the findings of the present study on the use of new construction materials in construction are presented in the following tables.

4.1- Thermal analysis results for the first model in a residential building in the city of Birmingham

According to the studies conducted, the thermal analysis related to the first modeling was obtained based on Tables 1 and 2 according to the diagram below.

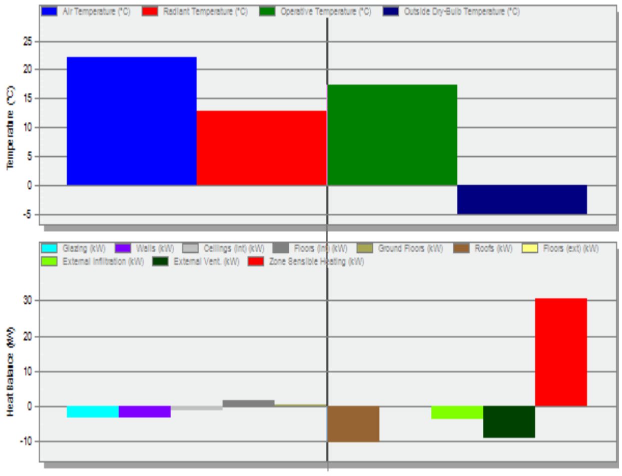

Figure 2. Thermal analysis obtained based on the first modeling

Table 3. the amount of heating energy loss of each building element in kilowatts in the first modeling in the Birmingham city building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	11.83
Operative Temperature (°C)	16.89
Outside Dry-Bulb Temperature (°C)	-5.10
Glazing (kW)	-0.13
Walls (kW)	-0.18
Ceiling (kW)	-0.12
Floors (kW)	0.16
Ground Floors (kW)	0.92
Roofs (kW)	-0.55
Floors (ext) (kW)	-0.47
External Infiltration (kW)	3.45
External Vent (kW)	-4.97
Zone Sensible Heating (kW)	35.03

4.2- Thermal analysis results for the second model in a residential building in the city of Birmingham

According to the studies conducted, the thermal analysis related to the second modeling is presented based on Table 4 and according to the diagram below.

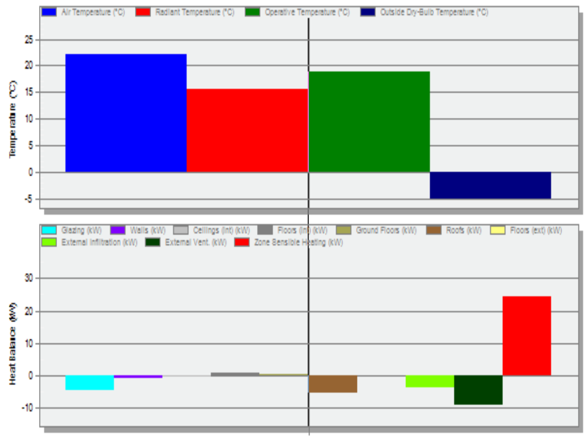

Figure 3. Thermal analysis obtained based on the second modeling

Table 4. The amount of heat energy loss of each building element in kilowatts in the second modeling in the Birmingham city building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	15.48
Operative Temperature (°C)	18.74
Outside Dry-Bulb Temperature (°C)	-3.10
Glazing (kW)	-4.57
Walls (kW)	-3.93
Ceiling (kW)	-0.61
Floors (kW)	0.81
Ground Floors (kW)	0.16
Roofs (kW)	-5.97
Floors (ext) (kW)	-0.58
External Infiltration (kW)	-3.93
External Vent (kW)	4.83
Zone Sensible Heating (kW)	24.22

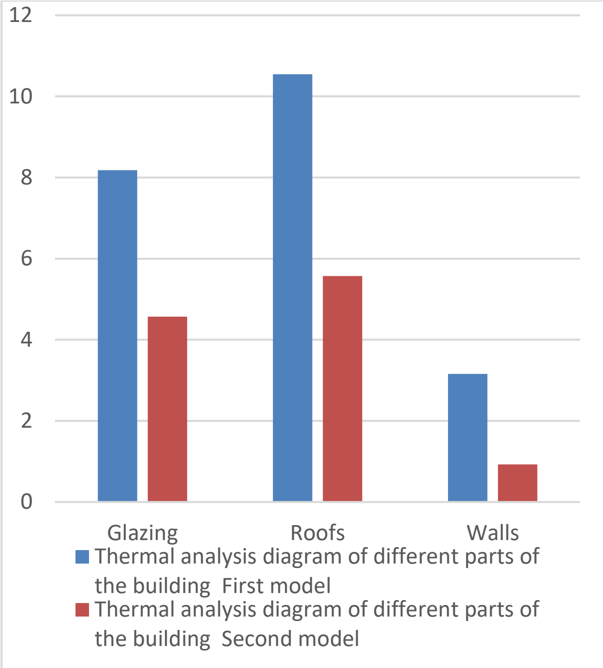

Chart 1. Amount of energy loss from each part of the building in Birmangham

4.1- Thermal analysis results for the first model in a residential building in the city of London

According to the studies conducted, the thermal analysis related to the first modeling was obtained based on Tables 1 and 2 according to the diagram below

4-5- Thermal analysis results for the first model in a residential building in London

According to the studies conducted, the thermal analysis related to the first modeling was obtained based on Table 6 according to the diagram below.

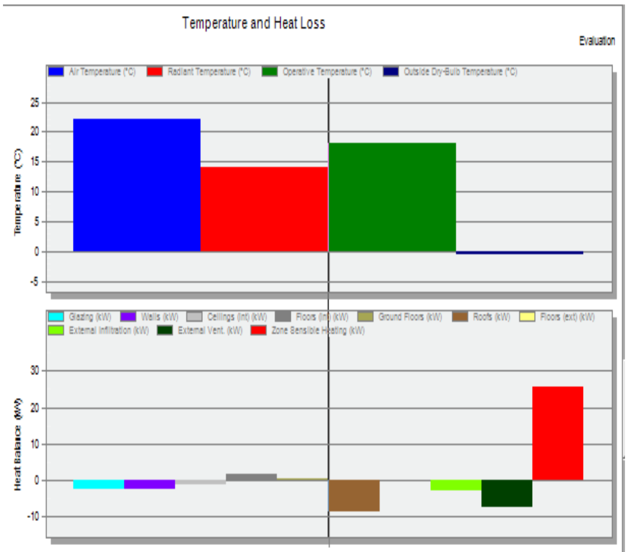

Figure 4. Thermal analysis obtained based on the first modeling of the city of London

Table 5. The amount of heat energy loss of each building element in kilowatts in the first modeling in the London building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	12.83
Operative Temperature (°C)	17.62
Outside Dry-Bulb Temperature (°C)	-4.60
Glazing (kW)	-4.67
Walls (kW)	-3.60
Ceiling (kW)	-0.79
Floors (kW)	0.73
Ground Floors (kW)	0.15
Roofs (kW)	-4.18
Floors (ext) (kW)	-0.75
External Infiltration (kW)	-3.26
External Vent (kW)	4.98
Zone Sensible Heating (kW)	29.92

4-5- Thermal analysis results for the second model in a residential building in London

According to the studies conducted, the thermal analysis related to the first modeling is presented based on Table 7 and according to the diagram below.

Figure 5. Thermal analysis obtained based on the second modeling of the city of London

Table 6. Amount of heat energy loss of each building element in kilowatts in the second modeling in the London building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	16.30
Operative Temperature (°C)	19.15
Outside Dry-Bulb Temperature (°C)	-3.60
Glazing (kW)	-3.77
Walls (kW)	-3.82
Ceiling (kW)	-0.52

Floors (kW)	0.58
Ground Floors (kW)	0.08
Roofs (kW)	-4.66
Floors (ext) (kW)	-1.07
External Infiltration (kW)	-3.24
External Vent (kW)	-2.77
Zone Sensible Heating (kW)	20.26

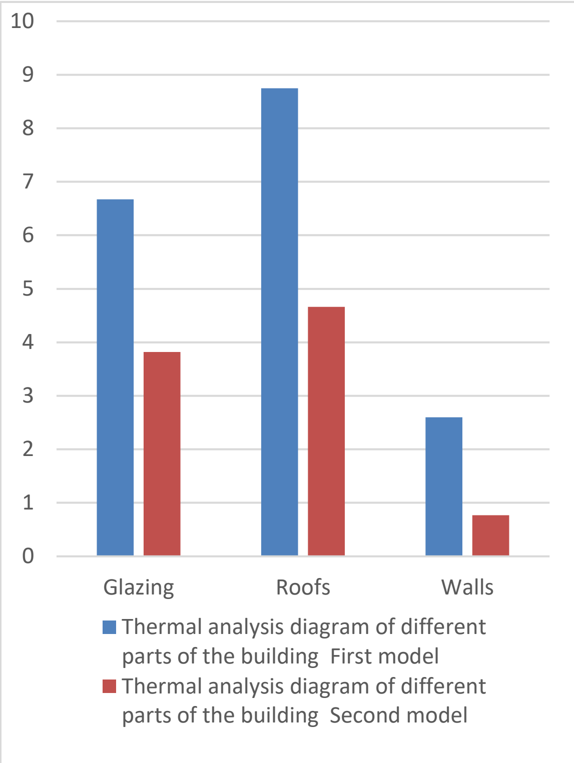

Chart 2. Amount of energy loss from each part of the building in London

4-6- Results of thermal analysis related to the first model in a residential building in Manchester

According to the studies carried out, the thermal analysis related to the first modeling was obtained based on Table 9 and according to the diagram below.

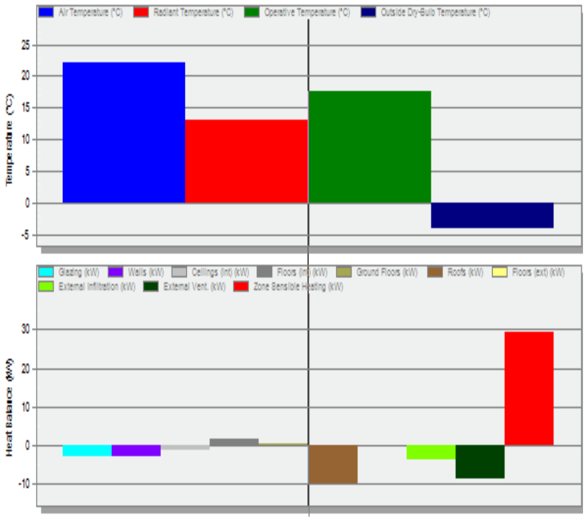

Figure 6. Thermal analysis obtained based on the first modeling of the city of Manchester

Table 7. Table of the amount of heat energy loss of each building element in kilowatts in the first modeling in the Manchester city building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	11.45
Operative Temperature (°C)	16.73
Outside Dry-Bulb Temperature (°C)	-4.10
Glazing (kW)	-3.91
Walls (kW)	-3.84
Ceiling (kW)	-0.87
Floors (kW)	0.14
Ground Floors (kW)	0.81
Roofs (kW)	-10.15
Floors (ext) (kW)	-0.15
External Infiltration (kW)	-3.70
External Vent (kW)	-8.89
Zone Sensible Heating (kW)	33.85

4-8- Thermal analysis results for the second model in a residential building in Manchester

According to the studies carried out, the thermal analysis related to the second modeling was obtained based on Table 10 and according to the diagram below.

Figure 7. Thermal analysis obtained based on the second modeling of the city of Manchester

Table 8. Amount of heat energy loss of each building element in kilowatts in the second modeling in the Manchester building

Air Temperature (°C)	22.00
Radiant Temperature (°C)	15.66
Operative Temperature (°C)	18.83
Outside Dry-Bulb Temperature (°C)	-4.10
Glazing (kW)	-4.44
Walls (kW)	-3.58
Ceiling (kW)	-0.58
Floors (kW)	0.96
Ground Floors (kW)	0.08
Roofs (kW)	-4.05
Floors (ext) (kW)	-0.94
External Infiltration (kW)	-3.78
External Vent (kW)	4.89
Zone Sensible Heating (kW)	23.38

4-9- Results of lighting analysis related to the residential building model designed in the cities of Birmingham, London and Manchester

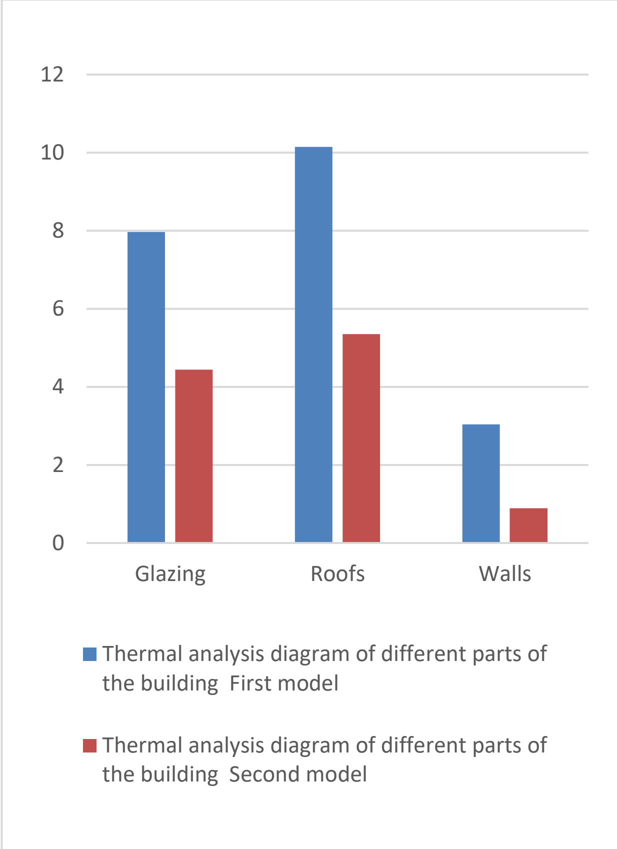

Chart 3. Amount of energy loss from each part of the building in Manchester

According to the modeling carried out in all models, the ratio of the area of windows to the walls of the building is considered a fixed percentage, and the only difference in the models is the material of the frames and glass of the windows. Therefore, it can be examined to what extent, by increasing the area of the windows and at the same time changing the materials in the window openings, the maximum amount of sunlight can be absorbed while reducing the building's heat loss. In this study, the building is modeled based on a 50% window area to wall ratio.

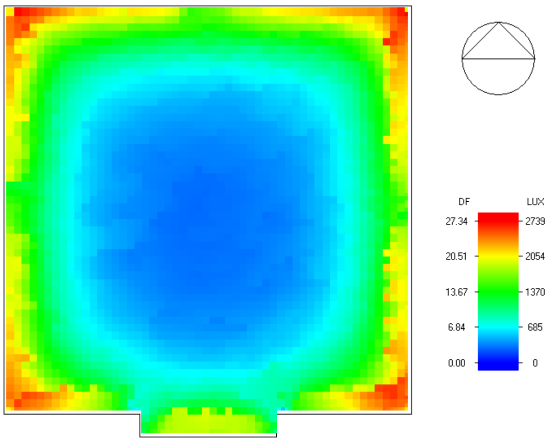

Figure 8. Building illumination and light absorption map in the city of Birmingham

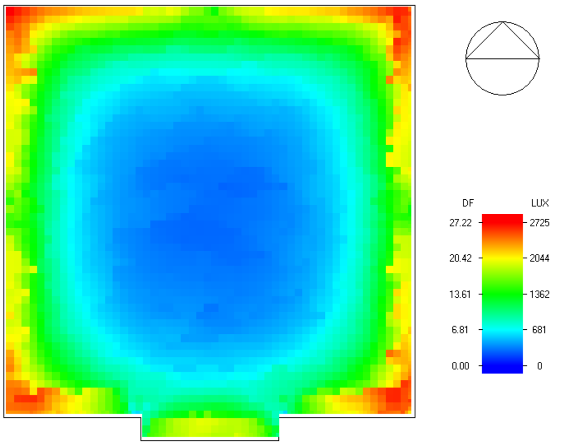

Figure 9. Building illumination and light absorption map in the city of London

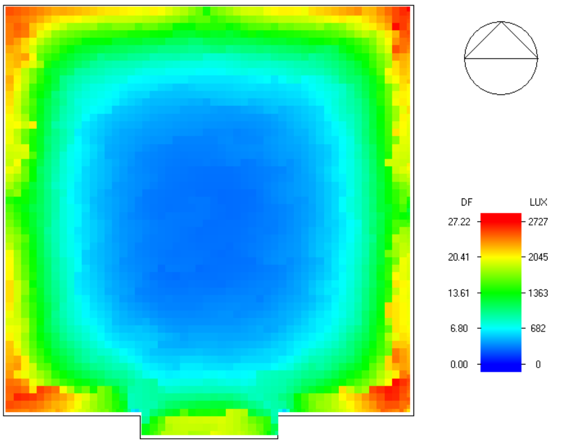

Figure 10. Building illumination and light absorption map in the city of Manchester

Table 9. Birmingham City Lighting Calculation Table

Block	Zone 1	Zone 1	Total
Zone	Block 1	Roof 1	
Floor Area (m2)	120.124	135.319	255.442
Floor Area above Threshold (m2)	120.124	0	120.124
Floor Area above Threshold (%)	100	0	47.03
Reference illuminance (Lux)	55.962	55.952	
Average Daylight Factor (%)	9.8	0	4.61
Minimum Daylight Factor (%)	2.84	0	0
Maximum Daylight Factor (%)	27.34	0	27.34
Uniformity ratio (Min/Avg)	0.29	0	
Uniformity ratio (Min/Max)	0.1	0	
Min illuminance	284.55	0	0
Max illuminance	2739.04	0	2739.04
Adequately lit	116.65	0	

Table 10. Building lighting calculation table in the city of London

Block	Zone 1	Zone 1	Total
Zone	Block 1	Roof 1	
Floor Area (m2)	120.124	135.319	255.442
Floor Area above Threshold (m2)	120.124	0	120.124
Floor Area above Threshold (%)	100	0	47.03
Reference illuminance (Lux)	55.966	55.938	
Average Daylight Factor (%)	9.79	0	4.61
Minimum Daylight Factor (%)	2.9	0	0
Maximum Daylight Factor (%)	27.22	0	27.22
Uniformity ratio (Min/Avg)	0.3	0	
Uniformity ratio (Min/Max)	0.11	0	
Min illuminance	290.73	0	0
Max illuminance	2726.51	0	2726.51
Adequately lit	116.65	0	

Table 11. Building lighting calculation table in Manchester

Block	Zone 1	Zone 1	Total
Zone	Block 1	Roof 1	

Floor Area (m2)	120.124	135.319	255.442
Floor Area above Threshold (m2)	120.124	0	120.124
Floor Area above Threshold (%)	100	0	47.03
Reference illuminance (Lux)	55.915	55.884	
Average Daylight Factor (%)	9.82	0	4.62
Minimum Daylight Factor (%)	2.69	0	0
Maximum Daylight Factor (%)	27.22	0	27.22
Uniformity ratio (Min/ Avg)	0.27	0	
Uniformity ratio (Min/ Max)	0.1	0	
Min illuminance	269.27	0	0
Max illuminance	2724.84	0	2724.84
Adequately lit	116.65	0	

Conclusions

Based on the analyses obtained from modeling residential buildings in the cities of Birmingham, London, and Manchester, as well as replacing traditional materials with modern construction materials to reduce energy consumption, especially in low-light areas, the following table is presented to summarize the results.

Table 12. Summary table of results and percentage reduction in energy consumption

City: Birmingham

Model number	**Walls**	**Windows**	**Roof**	**Max illuminance**	**Average energy consumption reduction**
1	3.18	3.86	10.18	2731.64	48%
2	0.97	4.57	5.57	2731.64	
Percentage reduction in thermal energy waste	31%	55%	45%		

City: London

Model number	**Walls**	**Windows**	**Roof**	**Max illuminance**	**Average energy consumption reduction**
1	2.6	6.67	8.05	2121.18	47%
2	1.7	3.82	5.87	2121.18	
Percentage reduction in thermal energy waste	30%	57%	51%		

City: Manchester

Model number	**Walls**	**Windows**	**Roof**	**Max illuminance**	**Average energy consumption reduction**
1	3.84	7.94	10.15	2761.51	49%
2	3.04	5.27	7.13	2761.51	
Percentage reduction in thermal energy waste	21%	56%	47%		

Based on the results obtained, it was determined that using new construction materials in the walls, windows, and roofs of residential buildings in the studied cities was effective in reducing energy consumption by 46% in Birmingham, 47% in London, and 46% in Manchester. On the other hand, by modifying the materials used in the windows, the surface area of existing windows can be increased without increasing energy loss, and therefore, we can get the most benefit from absorbing sunlight in the building.

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