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Original Article

Towards more sustainable residential buildings in New Cairo, Egypt: A case study assessment using energy efficiency simulations

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CO_2 emissions, energy efficiency, energy consumption, sustainability, thermal comfort

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Abstract
Globally, there is an increase in the severe climatic events that are happening, such as the increase in global temperature, flooding, wildland fires, and sea level rise. This necessitates the need to adopt sustainable design principles and solutions to develop better and healthier future cities. The Egyptian government in corporation with civil society in recent years, through many attempts, tried to implement the notion in the local society. Thus, the paper will explore multiple solutions that can achieve three main parameters that correlate with each other: thermal comfort, energy consumption reduction, and carbon dioxide (CO_2) emissions decrease. This will be discussed for the residential sector and by using New Cairo in Egypt as the research case study. The study will reveal several significant findings on two levels; Level one is the building's footprint which includes building form in relation to orientation mainly in the early design stages. Where it was found that the rectangle with the courtyard had the best results among the six simulated forms. And level two is the building design that explored the building envelope; façade and roof in relation to Indoor Environmental Quality especially when retrofitting the research case study. Where it was found that green roofs are a better strategy for enhanced sustainable results in a hot arid climate than the Phase Changing Material (PCM). This will be achieved throughout adopting a systematic analysis with the help of the Energy Plus (Design-Builder) simulation tool.

I. INTRODUCTION

Continuing urbanization in developing countries is increasing the energy demand, yet the supply is inadequate, non-existent, or facing future challenges. Egypt has a hot arid climate in general and, like many other developing countries, is facing a series of challenges related to the limitation of natural resources concerning its population size and economic growth. That is reflected in the rapidly increasing energy costs, with a strong impact on urban development and planning. Additionally, Egypt's future urban development plans for 2050 aim at developing over 40% of Egypt's area to use available natural resources and support around 20 million job opportunities[1]. However, this means more burden to the already existing ones, if the built environment did not consider the users' need for internal thermal comfort with less energy consumption and less dependent on heating, ventilation, and air condition (HVAC) Systems[2], and the mitigation of the increased CO_2 emissions.

Globally, many approaches to sustainability in urban development and planning were developed. They include creating for example Eco-cities and Liveable cities. Each approach focuses on particular sustainability-related challenges[3]. Eco-cities are outlined as cities working to minimize their negative effects on the environment through waste reduction, increased recycling, decreased emissions, increased housing density while expanding open space, and encouraging the growth of sustainable local enterprises[4]. Thus, a new city master plan must strive to achieve sustainability in various fields. Such as:

- Urban, Land Use, and Architecture Sustainability Indicators.
- Infrastructure and public facilities Sustainability Indicators.
- Economic Sustainability Indicator.
- Environmental Sustainability Indicator[5].

The International Energy Agency IEA's with its latest report in 2021 provides detailed information and statistics on energy and its efficiency while keeping track of renewable energy transitions. It stated that in 2020 although global CO_2 emissions fell by 5.8%, however, global energy-related CO_2 emissions remained the same in the atmosphere[6]. Thus, previous studies demonstrated the need to reduce buildings' energy use and emissions, for both new constructions and retrofit ones to develop a more sustainable built environment. By optimizing the geometry, Adriana Ciardiello *et al* (2020) succeeded in decreasing the annual energy consumption by 60% and the annual energy cost by 23% when the geometry was fixed by using passive and active strategies. Many studies worked on the concept of multi-objective optimization of buildings throughout developing genetic algorithm (GA), where the framework of Harlequin which deals with commercial buildings is considered the most comprehensive by some[7]. Another study by Abdollah *et al* (2021) achieved a 40% average reduction in the cooling energy demands and CO_2 emissions of residential affordable buildings in Egypt among three cities; Cairo, Hurghada and Aswan. The study analysed each city's weather and used weather data files using Hadley center's global climate model predictions[8]. On the other hand, Fahmey *et al* (2022) in their research, investigated reforming the Arabic free-planning court-yarded housing typology in Egypt. It was transformed into a neighbourhood urban form instead of single parcel division urban planning. The authors chose performance indicators to illustrate socioeconomic and environmental sustainability aspects, comparing them among several scenarios to show the recommended design. ENVI-met was used to simulate surface-plant-air interactions for various cases, and Radiance was utilized to conduct a radiation analysis where the Ladybug Tools plugin for a Grasshopper was used to calculate the annual radiation (kWh/m^2 -year) falling on all buildings' façades and roofs. It was found that combining urban, building, material, and renewables (UBMR) solutions demonstrated improved comfortable outdoor areas by 47.8% during an intense summer afternoon, and the energy-efficient envelope allowed cooling energy consumption to be decreased by 28.9%[9]. Furthermore, another study by Fahmy *et al* (2021) looked at the development of a sustainable climate-responsive urban design strategy and energy efficiency in hot and arid areas. It investigated how urban patterns (geometry) affected outdoor thermal conditions. It demonstrated some methods that were used to study urban microclimate examples in Egypt, presenting the urban microclimate gaps and what may be applied in Egypt to create new housing typologies responsive to climate. The study recommended the use of the Tripling Evaluation Methodology (TEM), and the need for the emergence of a code for sustainable city design[10]. Additionally, orientation, wind and housing clustering are examples of urban passive design solutions that have been shown to improve Indoor Environmental Quality (IEQ) in buildings while lowering annual carbon emissions .

Hence, this research will focus on studying several varied factors, using Egypt's hot arid climate, to enhance the residential buildings' Indoor Environmental quality by improving thermal comfort while decreasing energy consumption costs and CO_2 emissions. They will be discussed while classifying them on two levels. Level one will be the building's footprint which will work with building forms and orientation. While level two will be the building design, which will include the building façade and roof, and Indoor Environmental Quality.

2. Research Objective and Methodology

The research's main aim is to create efficient sustainable residential buildings from thermal comfort, CO_2 emissions, and energy consumption point of view, in a hot arid climate, in relation to the building footprint and design. Thus, the paper studied the building on two levels in both its theoretical and practical sections. The first level is the building footprint, which included studying the thermal comfort, CO_2 emissions, and energy consumption footprint of 6 basic geometrical building forms, in addition to discussing the orientation factor. Since the research also aims at emphasizing the importance of environmental computer software, thus the 6 shapes analysis was conducted using the design-builder software, as illustrated in figure (1). This tool was selected for use since the study focuses only on Internal Environmental Quality and not the outdoor environment. The second level of study was the building design which included discussing various techniques and strategies for the façade and roof (building envelope) and the Indoor Environmental Quality. This part will mainly illustrate the importance of early design stages in relation to form and orientation toward achieving the research aim. Additionally, it illustrated some solutions that could be planned from the early design stage of the building envelope design or as retrofitting measures, such as the re-roofing techniques, for the practical part of the research.

In the practical part, the study used New Cairo city in Egypt, as its case study. Again, the two levels were discussed. The building was analyzed on level one; its footprint, and then it was compared with the results of the previously discussed basic shapes. In the case study building analyses, the envelope design parameters like the fenestration geometry and materials were included in the simulation. Then only two techniques; the Phase Changing Material (PCM) and Green Roofs were selected to apply on the building for level two; the building design, while comparing their results. This part illustrates again the importance of early design stages in relation to form and location, and the result of retrofitting the building envelope; façade, and roof using the two techniques.

Furthermore, the research reached a detailed level in its analysis by monitoring the energy consumption of a residential unit and comparing it with the results of the design-builder software to evaluate the effect on actual costs and the variations between actual results and software results. The model was drawn with full details and used an updated data file for 2021 the period under study for the weather information; temperature and humidity included. All data was inserted for the simulation including the HVAC information. Then a single analysis was conducted regarding the total energy consumption alone and its reflection on costs. The study worked with the whole building calibrated simulation approach which includes the use of a computer simulation tool to generate a model of mainly energy use. The model at the unit level will be calibrated against actual measured energy use from utility bills. The calibrated results can be used to better enhance the simulation tools in predicting future scenarios[11]. However, it must be acknowledged that non-calibrated models, due to several internal and external uncertainties, might provide over- or under-estimations for energy consumption and costs. Finally, the research adopted the inductive analytical approach with the help of computer software to develop its findings. The Energy Plus (E+) simulation tool, version 8.2, with an interface to the software modelling tool Design Builder (DB), version 6.2 and the Ladybug weather data file (EGY_ QH_Cairo. Intl.AP.623660_TMYx.2007-2021.epw) were used[12]. Additionally, the qualitative approach was partially used in comparing the results.

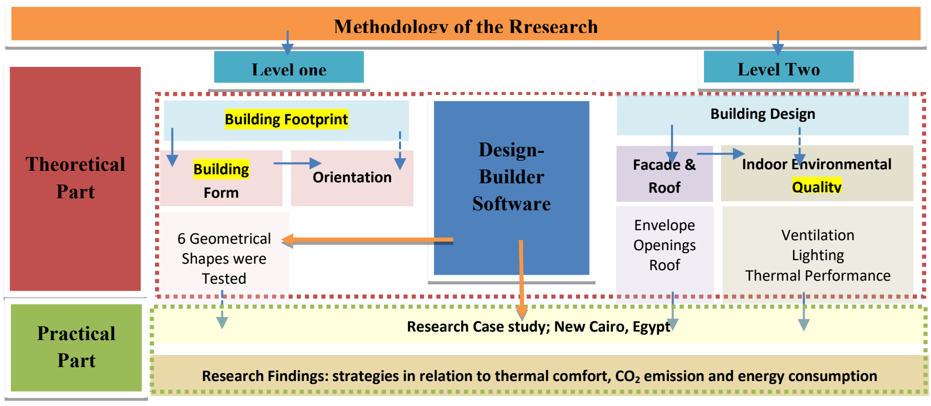
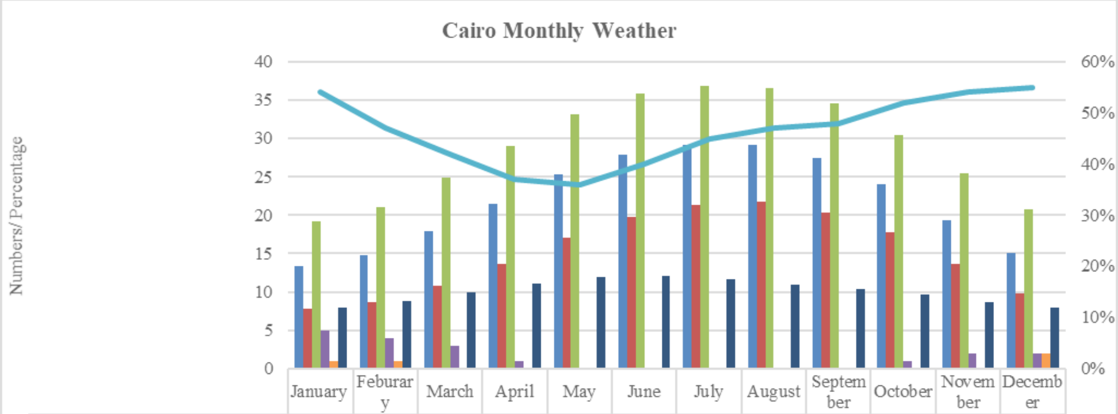


Fig. 1: The Research proposed methodology

3. Egypt Overview

3.1. Climate Analysis

Egypt is in the northern hemisphere and is specified with a hot arid climate. As for Cairo, it is considered a desert climate, which has long hot summers that starts at the end of June and ends in September, and cool dry winters[13], with a hot semi-arid climate as a general according to Koppen-Geiger climate classification. August is being the hottest month of the year with an average of 29.2 °C | 84.6 °F, while January has the lowest average temperature around 13.4 °C | 56.1 °F, which gives an average annual temperature of 22.1 °C | 71.7 °F. December is the month with the highest relative humidity at 55.29 % and May has the lowest relative humidity at 36.44 %. As for the rain range, there is very rare rainfall during the year, January has the highest number of rainy days equals to (1.30 days) and the lowest is Tune with (0.07 days), where precipitation is around 18 mm | 0.7 inches per year as illustrated in figure 2.



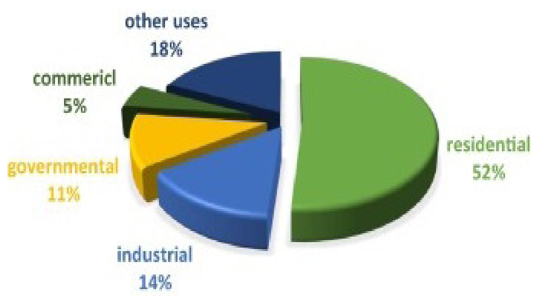
	January	Feburary	March	April	May	June	July	August	September	October	November	December
Avg. Temperature °C	13.4	14.8	17.9	21.4	25.3	27.9	29.1	29.2	27.4	24	19.4	15.1
Min. Temperature °C	7.8	8.7	10.8	13.6	17.1	19.7	21.3	21.8	20.3	17.7	13.7	9.8
Max. Temperature °C	19.2	21.1	24.9	29	33.1	35.8	36.8	36.6	34.5	30.4	25.5	20.8
Precipitation / Rainfall mm	5	4	3	1	0	0	0	0	0	1	2	2
Rainy days (d)	1	1	0	0	0	0	0	0	0	0	0	2
Avg. Sun hours (hours)	7.9	8.8	10	11.1	11.9	12.1	11.6	10.9	10.3	9.6	8.6	7.9
Humidity (%)	54%	47%	42%	37%	36%	40%	45%	47%	48%	52%	54%	55%

Fig. 2: The weather by month for Cairo, Data: 1991 - 2021 Avg. Temperature °C, Min. Temperature °C, Max. Temperature °C, Precipitation / Rainfall mm, Rainy days, Humidity %, Data: 1999 - 2019: avg. Sun hours[13].

The Energy Plus weather data file was found to be for the year 2009 with an update for 2017. Thus, the data file supported by Climate.One Building.org for 2007-2021 was used in this study simulation for Cairo climate conditions. The weather data file used in this study is (EGY_ QH_Cairo. Intl.AP.623660_TMYx.2007-2021.epw) as previously mentioned. Moreover, a previous study showed that weather datasets used from different periods can lead to a difference in annual energy consumption currently and in the future. Additionally, it demonstrated the obsolescence of the used Egyptian Typical Meteorological Years (ETMY - 2003) because the energy simulation readings significantly differ from the TMYx- 2018 datasets[14].

3.2. Energy Analysis

The Egyptian government wants to achieve energy efficiency by filling the gap between supply and demand over mainly electricity. Energy conservation is a potent tool for creating economic and environmental advantages such as increased economic competitiveness, energy security, and environmental benefits. The energy efficiency aim is to supply what is needed without misusing the available resources. Both energy efficiency and savings can be achieved by providing architectural solutions for building designs. Additionally, electricity request has grown significantly- because of socioeconomic development, whereas the peak demand increased by more than 200%[15].



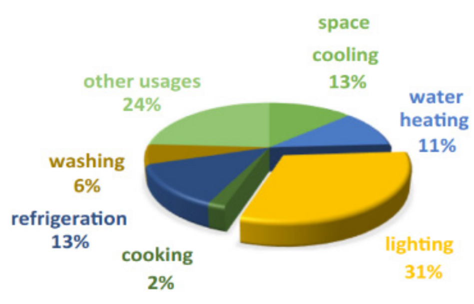


Fig. 3: a) On the left is; Energy distribution, b) On the right is; Sectorial Electricity Consumption Pattern[16,17].

As illustrated in Figure (3) Egypt's energy consumption demands rated around 52% for the residential sector alone. Additionally, around 32% of the residential building's energy consumption is used for lighting, while 13% is for space cooling and 11% is for water heating. It's clear that by decreasing energy consumption in the residential sector and the huge load on energy, total consumption rates will be simultaneously decreased.

Additionally, due to climate change globally, the Egyptian climate is changing drastically, creating a further burden on the energy sector to reach the desired thermal comfort for residents in their houses. As, for CO2 emissions, there is a national notion now 2022 called "Be Prepared for Greening", sponsored by the presidency itself. This call includes enhancing CO_2 emissions as part of its agenda. Thus, Egypt was selected as the research case study[18].

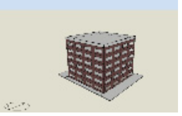
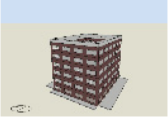
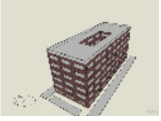
4. Level one; Building Footprint

Designing buildings that can enhance the users' thermal comfort, energy consumption levels, and CO_2 emissions start from their footprint on their environment. Given that there is a significant correlation between the Indoor Environmental Quality of buildings and the outdoor urban thermal performance. This includes many variables; however, the study will only focus on buildings' forms with their implication on orientation. Since it was observed that despite their great importance, these two factors take sometimes back seats to other elements when residential buildings are designed.

4.1. Building Form Analysis

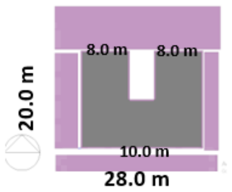
The building form is the first step in reaching thermal comfort and energy efficiency and decreasing CO_2 emissions, thus, simultaneously decreasing its footprint on its environment. Hence, this part is dedicated to analyzing the effect of the different building geometrical forms on all three elements. Various building forms were simulated using Design-Builder software and the weather data file. It would have been difficult to simulate all available building forms, thus only six basic building shapes were investigated, which are considered the most commonly used. The shapes used are Square, Rectangle, L-shape, U-shape, Square with courtyard, and Rectangle with courtyard shapes. All forms in the simulation had a unified area, Window-to-Wall Ratio, thermal mass, insulation, type of glazing, and shading devices as illustrated in Table 1. Additionally, Table 1 shows the summary of the input data for the design-builder simulation; it illustrated the lighting, opening, HVAC system, and activity chosen in the case study. These shapes were evaluated as freestanding (isolated) structures with building areas of 400 m2 and using brick walls. The impact of the building forms was investigated and analysed in relation to thermal comfort, energy consumption (internal gain) as demonstrated in Table 2, and CO_2 emissions as illustrated in Table 3. Orientation in the simulation was fixed, where the main elevation of the form was facing the north.

Table1: Fundamental facts about the investigated basic forms

	Square	Rectangle	L-shape	U-shape	Square with Courtyard	Rectangle with Courtyard
Basic Forms of the Study						
Window-to-Wall Ratio (WWR)	45%					
Thermal mass	Brickwork single-leaf construction light plaster					
U-Value (W/m2-K)	1.949 W/m2-K					
Insulation / U-Value (W/m2-K)	EPS insulation					
Number of panes	2 panes					
Type of glazing	Clear single 3mm					
Shading	Without shading device					
Number of Floors	Six Floors					
Lighting	18 fluorescent lamps have a standard intensity of 550 lux Lighting energy = 0.4 W/m2 Radiant fraction = 0.37 Visible fraction = 0.18					
Openings	Based on electricity from the grid U-Value = 5.77 Total Solar Transamination = 0.819					
HVAC	Split no fresh AC Air with COP = 2.2 Based on electricity from the grid Natural Ventilation = through the opening					
Activity	The density of 0.2 people/m2 Metabolic factor = 0.9 Clothing = 0.3 clo					

Six optimization runs were carried out, one for each form. Table 2 demonstrates the simulation parameters, options and results analysis of the six runs, where the analysed factors are differentiated by a specific colour in the generated charts demonstrated in the appendices section; Appendix A, Appendix B, and Appendix C. For thermal comfort, the X-axis shows the months while the Y-axis represents various factors such as Air Temperature °C, Operative temperature °C, Relative Humidity%, and Fanger Predicted Mean Vote (PMV). As for the internal gain analyses, the X-axis shows the months while the Y-axis represents the operational energy consumption. This includes room electricity, lighting, cooling, Domestic Hot Water (DHW), and heating. And finally, the carbon emission was determined based on the building's fuel usage for the HVAC system and the working of other activities such as lights and computer equipment as illustrated in Table 3. The X-axis shows the months while the Y-axis represents the CO_2 emissions in Kg.

Table 2: Simulation parameters, options and results analysis of the six forms

Basic Forms / Dimensions	Software Results Analysis (Summer and Winter)	
	Thermal Comfort (Comfort Range factors: Air Temperature °C / Operative Temperature °C / Relative Humidity% / Fanger PMV)	Internal Gain (Gain Range factors: Room Electricity/ Lighting / Heating (Electricity) / Cooling (Electricity) / DHW (Electricity))
U-Shape 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 °C • Operative Temperature: 37.75 °C • Relative Humidity: 41.26 % • Fanger PMV: + 4.5 Analysis (2): Average Annual Fanger PMV: + 2.12	Analysis (1): Highest / Average values achieved are: • Lighting: 4626.689 kWh / 4539.62 kWh • Cooling: 38345.19 kWh / 16293.67 kWh • DHW: 1364.341 kWh / 1338.67 kWh Analysis (2): Total Annual Fuel • Electricity: 24862.21 kWh

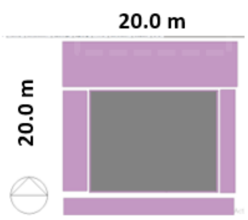
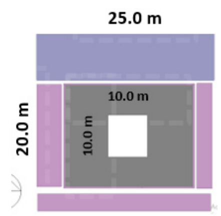
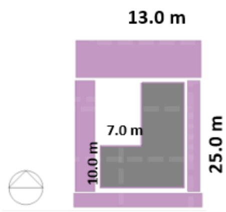
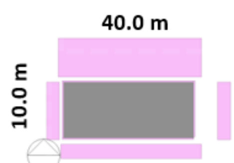
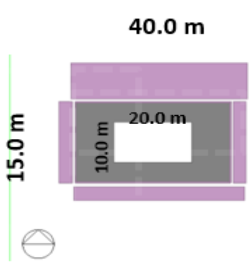
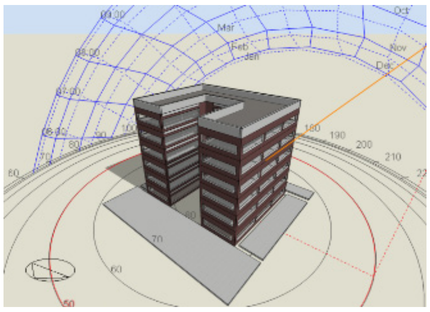
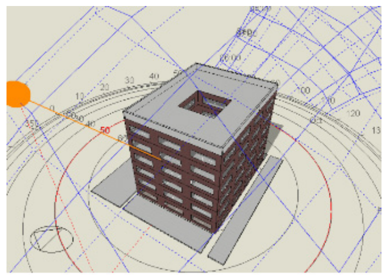
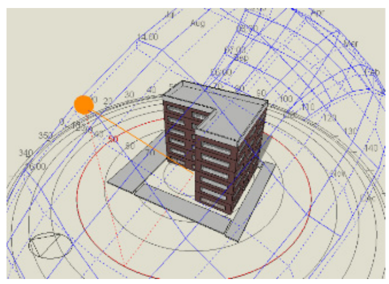
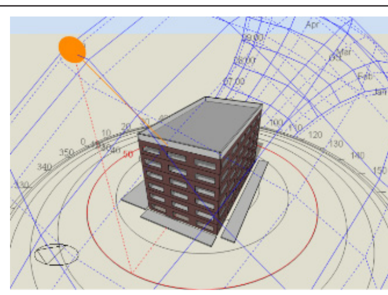
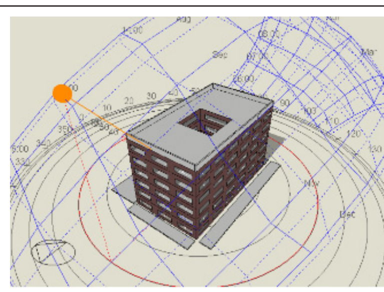
Square-Shape 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 ºC • Operative Temperature: 32.36 ºC • Relative Humidity: 53.65% • Fanger PMV: + 2.36 Analysis (2): Average Annual Fanger PMV: + 0.98	Analysis (1): Highest / Average values achieved are: • Lighting: 3121.87 kWh / 2979.20 kWh • Cooling: 23162.78 kWh / 6624. 41 kWh • DHW: 1021.19 kWh / 970.68 kWh Analysis (2): Total Annual Fuel • Electricity: 13884.16 kWh
Square with Courtyard 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 ºC • Operative Temperature: 32.35 ºC • Relative Humidity: 53.47% • Fanger PMV: + 2.31 Analysis (2): Average Annual Fanger PMV:+ 0.93	Analysis (1): Highest / Average values achieved are: • Lighting: 3314.52 kWh / 3163.05 kWh • Cooling: 27070.39 kWh / 8436.79 kWh • DHW: 1084.21 kWh / 1030.58 kWh Analysis (2): Total Annual Fuel: • Electricity: 15840.29 kWh
L-Shape 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 ºC • Operative Temperature: 32.57 ºC • Relative Humidity: 53.22% • Fanger PMV: +2.42 Analysis (2): Average Annual Fanger PMV: +1.0	Analysis (1): Highest / Average values achieved are: • Lighting: 3636.77 kWh / 3470.57 kWh • Cooling: 27979.21 kWh / 8069.66 kWh • DHW: 1189.62 kWh / 1130.78 kWh Analysis (2): Total Annual Fuel: • Electricity: 16687.72 kWh
Rectangle 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 ºC • Operative Temperature: 37.27 ºC • Relative Humidity: 53.74% • Fanger PMV: +4.44 Analysis (2): Average Annual Fanger PMV: +2.56	Analysis (1): Highest / Average values achieved are: • Lighting: 3590.73 kWh / 3432.78 kWh • Cooling: 26556.69 kWh / 7482.27 kWh • DHW: 1174.56 kWh / 1116.47 kWh Analysis (2): Total Annual Fuel: • Electricity: 15704.85 kWh
Rectangle with Courtyard 	Analysis (1): Highest values achieved are in August • Air Temperature: 29.2 ºC • Operative Temperature: 34.83 ºC • Relative Humidity: 53.13% • Fanger PMV: +1.57 Analysis (2): Average Annual Fanger PMV: +0.70	Analysis (1): Highest / Average values achieved are: • Lighting: 2691.32 kWh / 2568.33 kWh • Cooling: 24311.28 kWh / 7008.29 kWh • DHW: 880.35 kWh / 836.81 kWh Analysis (2): Total Annual Fuel: • Electricity: 13745.77 kWh

Table 3: CO_2 emissions analysis of the six forms

Basic Forms	Software Results Analysis (Summer and Winter)	
	Models Pictures	Analysis
U-Shape		• Highest value achieved for CO_2 emissions was in August by 28403.23 kg. • The annual average is CO_2 emissions 15066.49 kg.

Square		• Highest value achieved for CO_2 emissions was in August by 15806.43 kg. • The annual average CO_2 emissions is 7825.56 kg.
Square with Courtyard		• Highest value achieved for CO_2 emissions was in August by 18279.98 kg. • The annual average CO_2 emissions is 8101.05 kg.
L-Shape		• Highest value achieved for CO_2 emissions was in August by 19017.08 kg. • The annual average CO_2 emissions is 9427.5 kg.
Rectangle		• Highest value achieved for CO_2 emissions was in August by 18128.93 kg. • The annual average CO_2 emissions is 8840.55 kg.
Rectangle With Courtyard		• Highest value achieved for CO_2 emissions was in August by 16258.34 kg. • The annual average CO_2 emissions is 7822.82 kg.

4.2. Building Form Results

4.2.1. Thermal Comfort

A metric scale called the predictive mean value (PMV) is used to assess the level of thermal comfort attained in a given area[19]. The value of this metric should fall between 1 and -1 to attain the comfort zone, with zero being the ideal situation, according to the Egyptian code for energy [20]. It was discovered during the simulation that the design-builder calculations of the air temperature, relative humidity, and operative temperature were significantly influenced by the meteorological data file input. The results obtained when using the weather data from the energy-plus (2009), varied substantially after using the file from One Building Design (2019), which reflects the actual change in climate during the 10 years difference. It was found that the best forms in achieving thermal comfort using PMV were the rectangle with courtyard (annual average PMV; +0.70), square with courtyard (annual average PMV; +0.93), and simple square (annual average PMV; +0.98) whether when analyzing the average annual thermal comfort or thermal comfort peak points (August). The worst shape was the U-shaped form when analyzing the peak month (August PMV; +4.5) and the rectangle shape when analyzing the average annual thermal comfort (PMV; +2.56) as demonstrated in Figure (4).

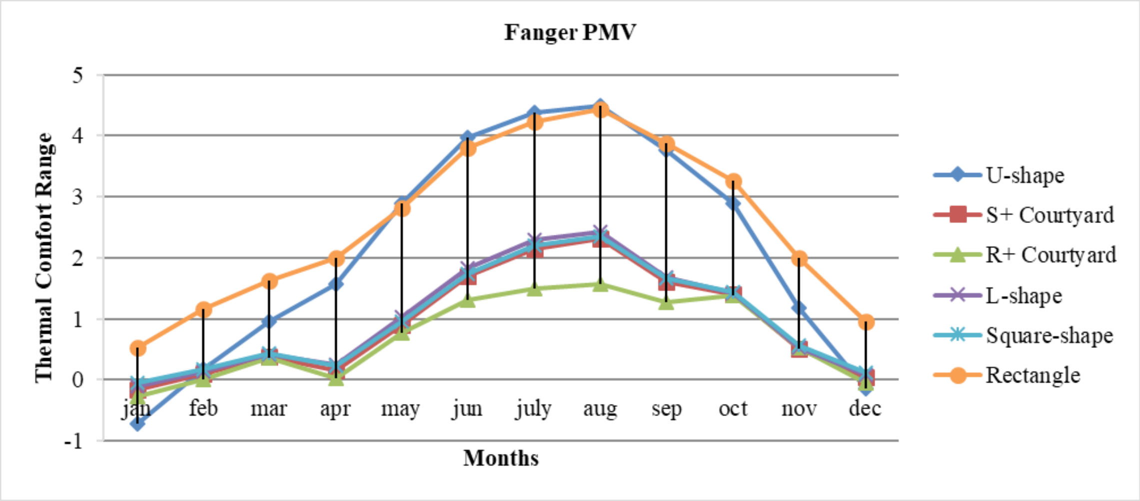


Fig. 4: Thermal comfort analyses results of the various shapes

4.2.2. Energy Consumption (Internal Gain)

The energy consumption rates depended on the internal gain analyses conducted by the design-builder including room electricity, lighting, cooling, Domestic Hot Water DHW, and heating. Where DHW represents the water heating energy required depending on the number of bedrooms and dwelling units, water heater type, distribution system, fuel type, and conditioned floor area. When analyzing the highest month in energy consumption as demonstrated in the Fuel breakdown charts, contrary to the thermal comfort, the highest months vary in relation to whether it is the lighting consumption or cooling, etc as illustrated in Table 2. That is understandable since for example, lighting consumption is higher in winter than summer while cooling is higher in summer than winter, and so on. Thus, the monthly fuel breakdown charts in the design-builder were used for the comparative analyses between the various shapes as illustrated in Figure (5. a). some figures were incomprehensible within the internal gain; however, they were deemed insignificant in the scope of the overall results. Thus, the tests conducted demonstrated that the rectangle with a courtyard shape consumed the least energy (13745.77 kWh), followed by the square shape (13884.16 kWh) with minor differences. On the other hand, the U-Shape had the highest consumption rate (24862.21 kWh) with an obvious difference as shown in Figure (5. b).

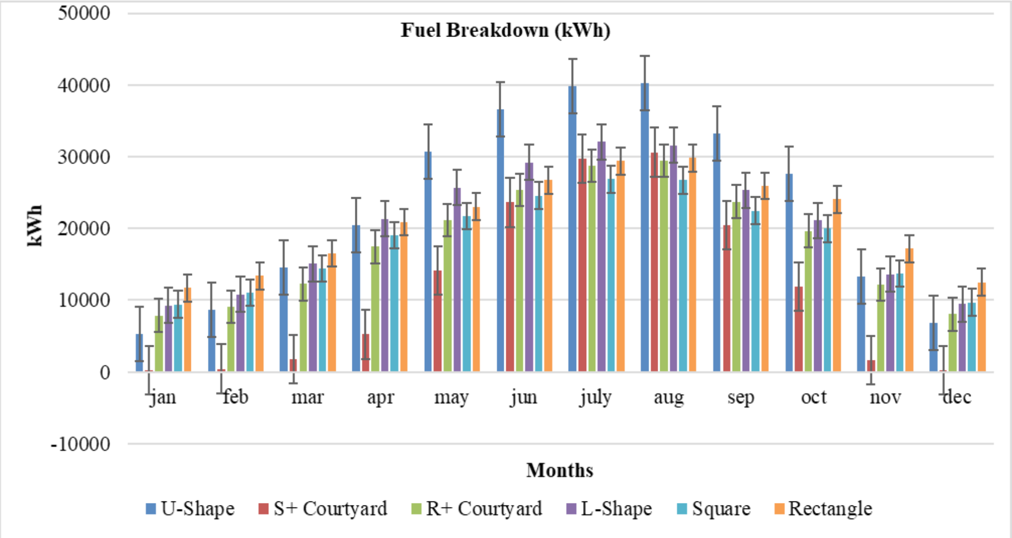


Fig. 5. a: Energy consumption and savings analyses results of the various shapes during the year

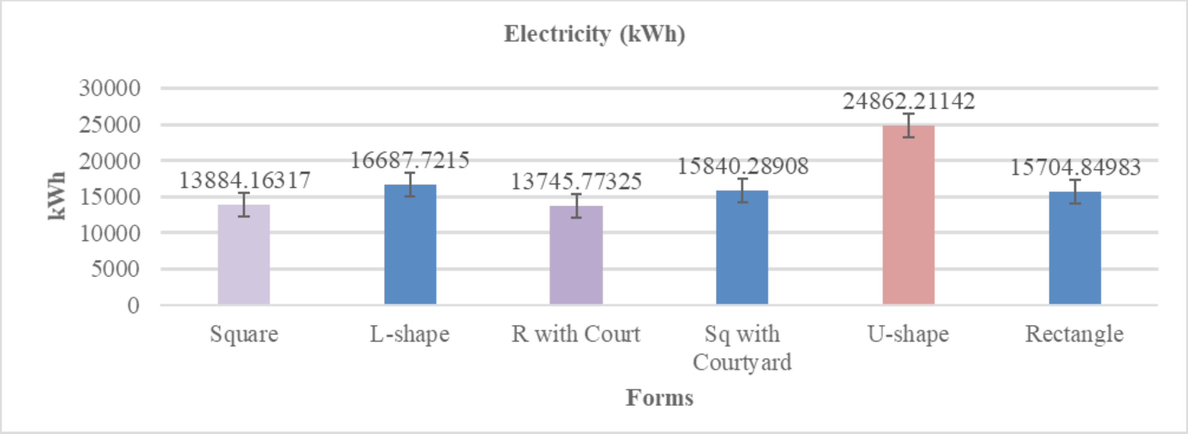


Fig. 5. b: Electricity total average annual consumption analyses results of the various forms

4.2.3. CO_2 Emissions

Based on the building's fuel consumption for the HVAC system and the operation of other activities like running lights and computer equipment, a carbon dioxide analysis has been done for the six forms of the study. When analyzing both the highest emitting month and the annual average, it was found that the lowest emitting shapes are the Square and the Rectangle with a courtyard. On the other hand, the highest emitting shape was the U-shaped as illustrated in Figure (6).

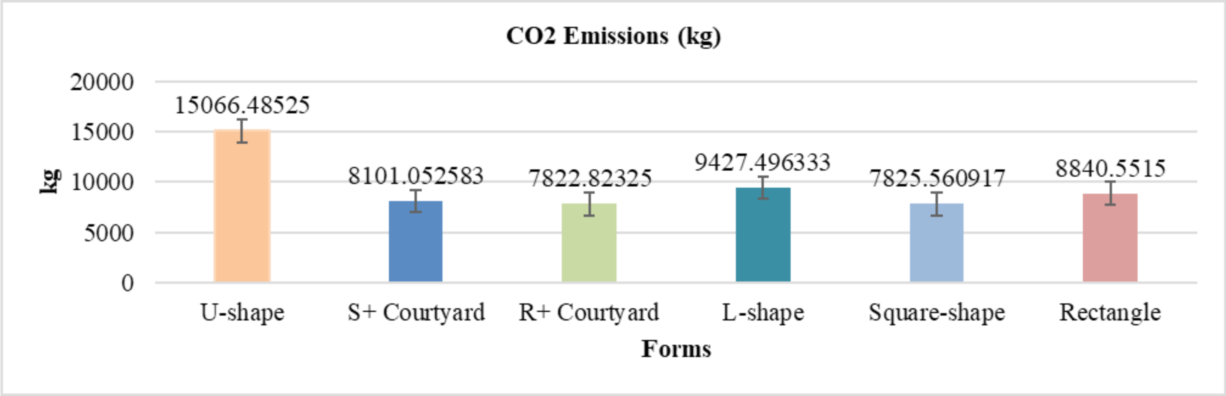


Fig. 6: CO_2 analyses results of the various forms

4.3. Building Orientation

The building orientation is one of the most important elements affecting energy consumption and thermal comfort, due to the thermal loads that the buildings will be subjected to because of their orientation in the layout, and simultaneously the building footprint on its environment. Thus, in the form analysis part, the paper fixed the six buildings' forms' orientation when conducting the simulations for calibration. As previously mentioned, the research fixed the main building elevation to face the north orientation. The main elevation in the rectangle shape was considered to be the long side, hence, it was parallel to the east-west axis facing the north. While in the U-shaped and L-shaped forms, their elevations with openings were considered to be the main ones, hence, the U and L openings faced the north direction. However, for future research, it is recommended to compare different orientations for the same forms to further investigate the relation and effect of orientation on them.

5. Level Two; Building Design

In this part, the study will discuss the building design while highlighting the characteristics of the sustainable envelope and other various design elements that could be used to achieve the three research goals: thermal comfort, energy consumption, and carbon dioxide emissions. Thus, the building façade and roof design and the Indoor Environmental Quality were discussed.

5.1. Facade and Roof Design

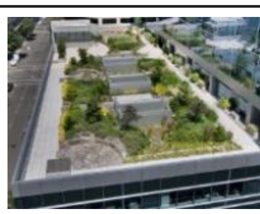
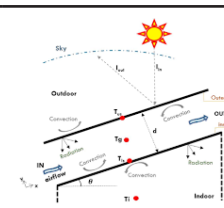
There are multiple effective design characteristics for the residential building that affect the users' thermal comfort, energy performance, and CO_2 emissions. They include building envelope, openings, and roof in addition to their parameters as detailed in Table 4[21]. The main goals of façade design are achieving thermal comfort, providing good views outside of the building, protecting from outdoor noise, good natural air ventilation, and minimizing energy loads. Nowadays, decreasing CO_2 emissions through the façade design is also sought throughout using, for example, Green Walls, Eco-Material, and Hybrid Ventilation[22].

Table 4: Facade and Roof Design parameters concerning thermal comfort, energy consumption, and CO_2 Emissions[23,24].

	Envelope	Openings	Roof
Thermal Comfort Energy Consumption	• Thermal Insulation: (Coating Materials / Phase Changing Material (PCM)/ etc.) • Double Skin • Green Wall • Eco-Material • Hybrid Ventilation	• Sun Protection (Sun Breakers / Shading devices). • Photo Voltaic panels • Window Glazing: (Double/ Triple/ Colored/ Smart/ Nano) • Type, Size, and Orientation	• Thermal Insulation: (Coating or Foam Materials / PCM/ etc.) • Double Roof • Green Roof • Wind Turbines • Finishing Material: (Color/ U-value/etc.)
Carbon dioxide emission	• Green Wall • Eco-Material • Hybrid Ventilation	• Window Glazing: (Colored/ Smart/ Nano) • Type, Size, and Orientation	• Green Roof • Finishing Material

As for the roof design, it is extremely important to energy efficiency and sustainable development in general. However, new roof designs and construction on top of existing ones have not received sufficient attention up till now. Table 5 illustrates various re-roofing techniques that can be used in residential buildings. Thus, this study emphasizes the importance of the re-roofing concept as one of the strategic options to decrease energy consumption, improve overall building thermal performance, and enhance CO_2 levels, throughout using the green roof in its case study analysis[25, 26].

Table 5: Roof design different techniques[27,28,29,30].

Benefits	Green Roof	Roof Shading - Solar Panels	Double roof	Wind turbines
Example				
Benefits	• Reduce the high temperatures of the exterior surface. • Calms the low temperatures in the winter.	• Shading device causes a substantial decrease in cooling load • Giving low growth in heating load in comparison to the exposed roof.	• Effective method to decrease the conduction and convection heat.	• Reducing fossil-fuel-based electricity amount. • Removing ingress rates on wind turbine elements.

5.2. Indoor Environmental Quality

Designing for enhancing Indoor Environmental Quality and creating comfortable room conditions includes multiple elements that must be considered. These elements include human physiological aspects such as body metabolic rate, amount of activity, and occupant apparel, as well as microclimate conditions like humidity, radiant temperature, air temperatures, and air movement. A comfortable, healthy environment will be created mainly by good indoor thermal conditions to maintain occupants' quality of life that is free from heat stress or thermal strain. The human body temperature must be kept constant at 37°C, to maintain the highest levels of human performance and productivity. The research will only focus on the external parameters in its façade and roof design as illustrated in the above section, in relation to enhancing the Indoor Environmental Quality, in its case study[31].

6. Case Study; Egypt

Through the use of an actual case study, this part strives to analyze a real building form and its orientation, which is level one; the building footprint, in relation to thermal comfort, energy consumption, and CO_2 emissions. Furthermore, it will try to investigate the relationship between its results and the six basic shapes' results. Additionally, the residential buildings' design, Level Two, will be discussed in relation to applying two main techniques on the building: the PCM and green roofs. Then it will reach the detail level by monitoring one appartement consumption and analyzing its results in comparison to the design-builder results with its implication on costs. New Cairo city in Egypt was selected since it is one of Egypt's most famous city developments in the past 50 years, with its western neighbourhood development master. It is also the first city that established the compound concepts in Egypt, and its residential compounds, in general, are considered one of the most successful compound prototypes in Egypt, such as El-rehab Compound, Madinaty, Mountain View, etc. Additionally, at the junction of the Cairo/Suez Road and the Eastern Ring Road, it is situated 20 minutes from downtown Cairo and ten minutes from Heliopolis and Nasr City, as shown in Figure (7).

Fig. 7: a) on the right is the location the of New Cairo city masterplan, Cairo, Egypt[32], b) on the left is the case study building location[33].

6.1. Case Study Basic Information

Rawdat Al Azhar residential compound the first stage, with its sunrise compound as stage two, was selected as the research case study. It includes apartment buildings that consist of four stories and are designed in clusters, where each one encloses green open spaces, interconnecting together by a pedestrian network, vehicle roads, and parking lots as shown in Figure (8). Each building consists of four floors with a total height of 13.5 m, and each floor has four residential flats with an approximate area of 150 m2 each. The average number of occupants per inhabitant of flats varies. The compound provides a strict building design, that is repetitive in a way that resembles a universal plan within the individual 'community'. The case study building location and design and the selected apartment are illustrated in figures (7), (8), and (9).

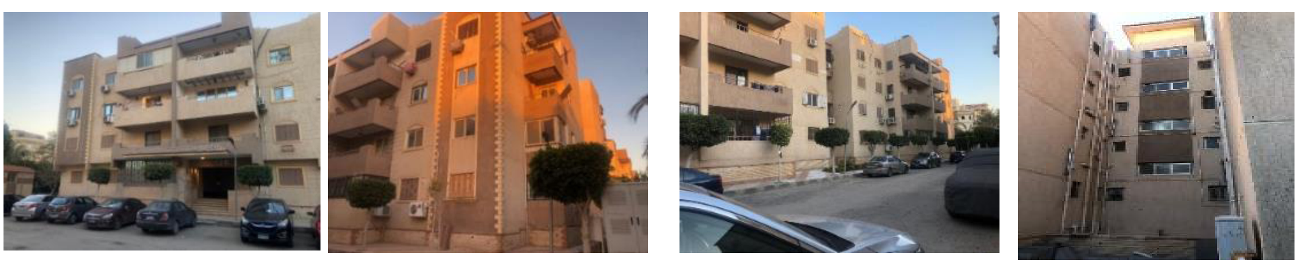


Fig. 8: a), b), c), and d) are various views of the case study building, illustrating its design and elevations in the layout[34].

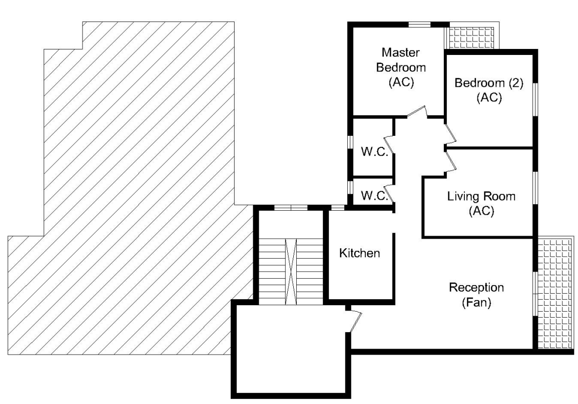


Fig. 9: Internal plan for the case study unit.

6.2. Building Analysis

A building group was analyzed by using the design-builder as shown in Figure (10). The case study consists of two identical buildings attached together. The data of the case study which included information related to building material and construction characteristics, schedules of occupancy, house appliances, and specifications of the HVAC and the lighting systems used in this building was added to the design-builder, as summarised in Table 6. The result of the building analysis was provided in Table 7 in relation to thermal comfort, internal gain, CO_2 emissions, and finally Fabric and Ventilation. And the charts demonstrating the monthly results are demonstrated in Appendix D.

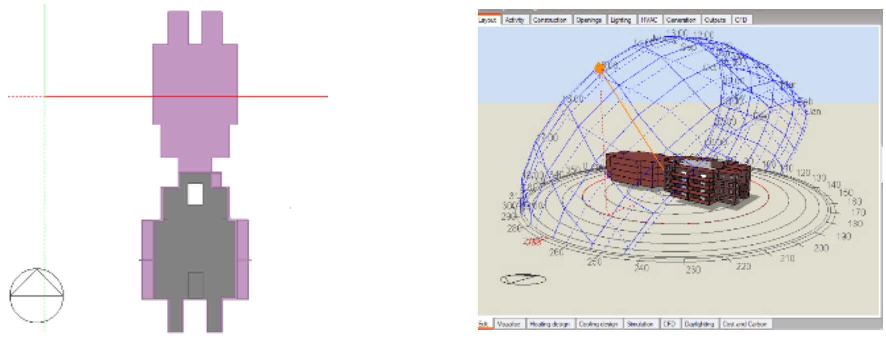


Fig. 10: a) and b) illustrates the Building Group design used in the design-builder.

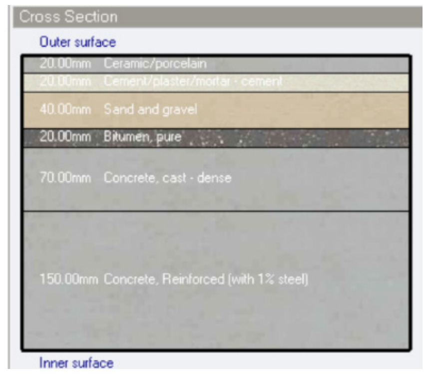
Table 6: Building Characteristics for Simulation Scenario

Function	Rate
Walls Construction	12 and 25 brickwork – outer leaf
Occupancy Rate	0.0196 (people/m2) - residential
Lighting Energy	1.00 w/m2 - 100 lux
Openings	30% Window-to-Wall Ratio – double glazing clear 6mm/6mm
HVAC	1.00 w/m2 - 100 lux
Infiltration	30% Window-to-Wall Ratio – double glazing clear 6mm/6mm

6.3. Level One; Building Footprint

The case study building form design is mainly like a rectangle with plus and minus parts of around a total area of 790 m^2. Its orientation is shown in Figure (10). The building was analyzed as demonstrated in Table 7, in regard to thermal comfort, internal gain, CO_2 emissions, and fabric and ventilation. It achieved an average annual Fanger PMV of +0.313, a total annual fuel for electricity of 24749.2 kWh, and CO_2 emissions of an average annual of 13302.29 kg. These are acceptable results, however, to understand these numbers in relation to the six basic forms results, first a calibration and correction to the results will be conducted mainly in relation to the number of floors, total area, and the number of apartments. Since the case study building has 4 floors with a total area of around 790 m2 each and the basic shapes have 6 floors with a total of 400 m^2. This means the case study has a total area of 3160 m^2 with around 16 units and the basic shapes are 2400 m^2 each with around 12 units. Hence, the results of the case study must be divided by almost 1.33 to reach the required calibration in the case of annual fuel consumption and CO_2 emissions. The Fanger PMV cannot be calibrated accordingly thus the current case study result which is considered to achieve better results than the rectangle with a courtyard with an annual average PMV of +0.70 being the best shape in-between the six studied shapes cannot be related to and will be exempted. As for the internal gain, it will now achieve a total annual fuel for electricity of 18608.4211 kWh, which is greater than the first five forms and only lesser that the highest consuming shape; the U-shape of 24862.21 kWh. As for the CO_2 emissions, the average annual will be 10001.7218 kg, which is again higher than the first five shapes and only lowest than the higher shape which is again the U-shaped by 15066.49 kg. Although other variables affect the calibration process and might lead to over or under-estimations for energy consumption and CO_2 emissions, however, still these results are affected by not only the changes in the building form and design, and the grouping in a cluster shape, but also reflect the effect of the different orientation as well. This requires further future investigation. Finally, when designing a building form and selecting its orientation a balanced level of success between the three main factors should be targeted for the best building footprint on its environment, with the help of the design-builder software.

Table 7: Results of the case study building in its current state (Traditional)

Traditional External Walls and Roof	
Walls Layers	Roof Layers
	
• Brickwork Outer (25 cm) • Plaster (0.13 cm)	• Ceramic tile (2 cm) • Cement/Plaster/Mortar (2 cm) • Sand and gravel (4 cm) • Bitumen (2 cm) • Concrete, cast-dense (7 cm) • Concrete, Reinforced (15 cm)
Thermal Comfort	Internal Gain
Analysis (1): Highest values achieved • Operative air temperature: 35.05 ^{o}C (August) • Relative Humidity: 53.49% (January) • Fanger PMV: +2.60 (August) Analysis (2): Average Annual Fanger PMV: +0.313	Analysis (1): Highest / Annual Average values achieved • Lighting: 10227.25 kWh (December) / 8133.10 kWh • Cooling: 33496.73 kWh (August) / 12972.55 kWh • Heating: 7844.16 kWh (January) / 1306.63 kWh Analysis (2): Total Annual Fuel (Electricity: 24749.2 kWh)
CO_2 Emissions	Fabric and Ventilation
Analysis for CO_2 Emissions: • Lowest value achieved: 7285.32 kg • Highest value achieved: 21331.79 kg • Average Annual achieved: 13302.29 kg	Analysis for Fabric and Ventilation Annual Average: • Glazing: 2895.54 (kWh) • Walls: 63036 (kWh) • Ceilings: 1047.78 (kWh) • Internal Floors: 1045.12 (kWh) • Roof: 3168.48 (kWh) • External Infiltrations: 6847.84 (kWh)

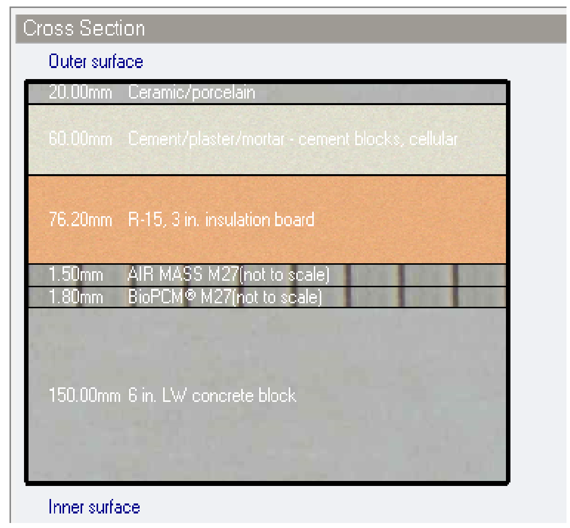
6.4. Level Two; Building Design

For the building design, the study preferred to investigate the effect of applying only two techniques from the previously mentioned techniques and solutions. The PCM and Green roofs were selected. That is because the PCM is considered one of the latest techniques that are offered and can be used in the building envelope as a whole; Façade and roof. As for the green roofs, they were selected in support of the notion that calls for greening the building roofs to compensate for the lack of enough green spaces in the city's design, where greening a city will be done vertically if not possible to be horizontal. These two techniques' results will be compared with the actual results of the traditional base case in the absence of the Energy Conserving Measures (ECM).

6.4.1. The Effect of Phase-Changing Material (PCM)

A phase change material (PCM) is a material that can release or absorb energy at the phase transition, in order to provide useful heating or cooling as needed. Employing PCMs into the building envelope efficiently, such as materials depending on Thermal energy Storage (TES) systems reduce the energy consumption of the buildingand enhances thermal comfort[35]. There are different techniques to implement PCM into the building'senvelope,facade,and roof.This is an easy and economical technique.Thus, a comparative analysis to the results was conducted between the traditional external walls and roof of the case study as demonstrated in Table 7, and the treated PCM external walls and roof, as illustrated in Table8. Just the south wall of the building has the longest sun exposure in the simulation, hence a layer of PCM was added to the wall's structure in addition to the roof. The analysis parameters and results included internal gain, thermal comfort, CO_2 emissions, and fabric and ventilation. And the charts demonstrating the monthly results are demonstrated in Appendix E.

Table 8: Results of the case study building after applying the PCM technique.

PCM-External Walls and Roof	
Walls Layers	Roof Layers
	
• Brickwork Outer (25 cm) • Bio-PCM (2.0 cm) / Plaster (0.13 cm)	• Ceramic tile (2 cm) • Cement/Plaster/Mortar (6 cm) • PCM insulation board (7.6 cm) • Air Mass (0.15 cm) • Bio-PCM (0.18 cm) • Concrete block (15 cm)
Thermal Comfort	Internal Gain
Analysis (1): Highest values achieved. • Operative air temperature: 27.8 ^{0}C (August) • Relative Humidity: 56.12% (August) • Fanger PMV: +0.75 (October) Analysis (2): Average Annual Fanger PMV: +0.035	Analysis (1): Highest / Annual Average values achieved. • Lighting: 9571.6 kWh (December) / 7663.15 kWh • Cooling: 17161.54 kWh (August) / 8119.98 kWh • Heating: 40.76 kWh (January) / 3.41 kWh Analysis (2): Total Annual Fuel (Electricity: 21345.83 kWh)
CO_2 Emissions	Fabric and Ventilation
Analysis for CO_2 Emissions: • Lowest value achieved: 8252.59 kg • Highest value achieved: 17048.35 kg • Average Annual achieved: 12935.56 kg	Analysis for Fabric and Ventilation Annual Average: • Glazing: 711.09 (kWh) • Walls: 271.89 (kWh) • Ceilings: 103.49 (kWh) • Internal Floors: 90.79 (kWh) • Roof: 67.94 (kWh) • External Infiltrations: 28767.56 (kWh)

When analyzing the thermal comfort after using PCM in the building envelope, it was found that great results were achieved. August was the highest month with thermal comfort issues. The simulation showed that a total reduction of 7.23^{o}C in the operative air temperature was achieved, which is accompanied by a 2.63% increase in the relative humidity, thus, transferring August from an uncomfortable month (35.05^{o}C, 53.49%) to a relatively comfortable month (27.82^{o}C, 56.12%). As for the Fanger PMV, it succeeded in entering the comfort range with +0.75 after being +2.6. As for the annual Fanger PMV, it went much closer to being optimum from +0.313 to +0.035.

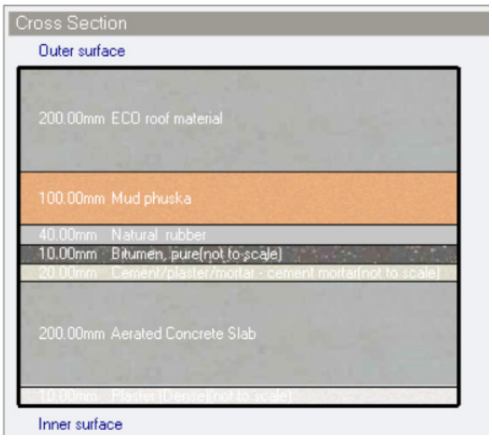
As for the internal gain, again the total annual fuel chart given by the design-builder was used for the comparative analyses of electricity consumption. It was found that there is a reduction of 13.75% (3403.37 kWh) in the total electrical consumption between the traditional envelope and the PCM envelope. Some might see this reduction as low, compared to the huge improvement conducted to the thermal comfort in August. However, when relating this number with the annual average Fanger PMV total reduction, which was in the comfort zone in the first place and just came closer to 0, this electricity reduction percentage becomes much more comprehensible. Additionally, the CO_2 emissions levels were reduced by an annual average of 2.76% (366.73 kg) after using PCM. This shows that PCM could not be considered a very effective strategy for CO_2 emissions reduction.

An additional parameter was analyzed here, which is the fabric and ventilation elements. It included the glazing, walls, ceilings, floors, roof, and external infiltrations. By analyzing these data, it is fair to say that the vertical envelope, especially the walls, gives better results when applying PCM treatment due to the obvious substantial reductions in all numbers it achieved. Furthermore, the figures shown in Table 8 indicate that the heat losses due to glazing, walls, roofs, ceiling, and external infiltration are related to the air movement and ventilation in the building.

6.4.2. The Effect of Green Roof

Green roofs have various environmental benefits, such as decreasing thermal radiation and simultaneously improving CO_2 levels and thermal comfort, while decreasing energy consumption levels. Thus, it was applied to the case study as the passive design concept it represents as illustrated in Table 9. And the charts demonstrating the monthly results are demonstrated in Appendix F. It was also compared to the traditional roof of the case study. The impact of the green roof on thermal behaviour and minimizing heat transfer was not affected by its orientation.

Table 9: Results of the case study building after applying the Green Roof technique.

Green Roof	
Roof Layers	
	• ECO Roof (2.0 cm) • Mud Phuska (1.0 cm) • Natural Rubber (0.4 cm) • Bitumen (0.1 cm) • Cement/Plaster/mortar (0.2 cm) • Concrete Slab (2.0 cm) • Plaster Dense (0.1 cm)
Thermal Comfort	Internal Gain
Analysis (1): Highest values achieved. • Operative air temperature: 28.27 ^{o}C (August) • Relative Humidity: 55.1% (August) • Fanger PMV: -1.49 (January) Analysis (2): Average Annual Fanger PMV: -0.299	Analysis (1): Highest / Annual Average values achieved. • Lighting: 4785.8 kWh (December) /4695.8 kWh • Cooling: 17550.46 kWh (August) / 7063.25 kWh • Heating: 1190.78 kWh (January) / 151.07 kWh Analysis (2): Total Annual Fuel (Electricity: 17648.68 kWh)
CO_2 Emissions	Fabric and Ventilation
Analysis for CO_2 Emissions: • Lowest value achieved: 5945.42 kg • Highest value achieved: 17089.47 kg • Average Annual achieved: 10695.09 kg	Analysis for Fabric and Ventilation Annual Average: • Glazing: 471.12 (kWh) • Walls: 648.91 (kWh) • Ceilings: 630.37 (kWh) • Internal Floors: 630.49 (kWh) • Roof: 1216.83 (kWh) • External Infiltrations: 1626.43 (kWh)

When analyzing the thermal comfort after using Green Roof in the building, it was found that again great results were achieved. August was the highest month with thermal comfort issues. The simulation showed that a total reduction of 6.78^{o}C in the operative air temperature was achieved, which is accompanied by a 1.61% increase in the relative humidity, thus, transferring August from an uncomfortable month (35.05^{o}C, 53.49%) to a relatively comfortable month (28.27^{o}C, 55.1%). As for the Fanger PMV, it succeeded in coming nearer to the comfort range with -1.49 after being +2.6. As for the annual Fanger PMV, it went closer to being optimum from +0.313 to -0.299.

As for the internal gain, again the total annual fuel chart given by the design-builder was used for the comparative analyses of electricity consumption. It was found that there is a reduction of 28.69% (7100.52 kWh) in the total electrical consumption between the traditional roof and the green roof. This is considered a substantial reduction, more than double the reduction achieved by using the PCM. When relating this number firstly with the annual average Fanger PMV which was in the comfort zone in the first place by a +ve number and came closer to the 0 by a -ve number, and secondly with Cairo's hot arid climate for most of the year, this electricity reduction percentage becomes muchly comprehendible from this scope. Additionally, the CO_2 emissions levels were reduced by an annual average of 19.6% (2607.2 kg) after using a green roof. This shows that green roofs are a great strategy for CO_2 emissions reduction. The fabric and ventilation elements were also analyzed here. By analyzing their data, it is fair to say that there is an obvious substantial reduction in all numbers achieved after using the green roof. Furthermore, the figures shown in Table 9 indicate that the heat losses due to glazing, walls, roofs, ceiling, and external infiltration are related to the air movement and ventilation in the building.

6.5. Unit Analysis: Actual Energy Consumption Vs Design Builder Estimation

This part was for going into the detail level of analysis which is a single apartment analysis by using calibration, which is the process of comparing the results of a model with data standards to determine any deviation. The model calibration aim in this part was to compare simulation predictions with actual numbers from usage for only the total energy consumption rate and its implication on actual costs. It must be acknowledged that cost outputs were not tested in the design-builder. In general, estimating energy use for calibration demands data analysis about various factors affecting energy use. Weather and occupancy are two main factors that can affect energy use. Thus, a set of model parameters were identified and used, in order to unbiases and neutralize the effect of these two factors on energy consumption comparing. Firstly, the data file supported by

Climate.OneBuilding.org for 2007-2021 was again used[36]. And in compliance with the ASHRAE Guideline 14, where the selected period for the study should cover an uninterrupted period of at least 12 months in energy use, the units' actual energy consumption was recorded over the period of 17 months starting from January 2021 until May 2022. This period was selected in order to work in harmony with the selected weather file, especially regarding air temperature and humidity. Secondly, the actual consumption rate represents the average electricity consumption, for a middle-class family with 2 to 3 Adults and 2 Children less than 5 years, as illustrated in Table 10. The unit has the standard electrical appliances for a residential apartment, with 2 air conditions in two rooms: the living room and the master bedroom. The design-builder was fed the same data and parameters for the activity, construction (internal partitions, and typical floor slap materials), openings, lighting, HVAC system, and the number of residents, and its results were compared with the actual consumption. This also helped in neutralizing the effect of another unchangeable parameter which is the building design and dimensions, however, it has a significant impact on energy use.

Table 10: The unit's monthly energy consumption over a period of 17 months, in relation to the estimated consumption by the design-builder

Month	Consumption Rate (kWh)	Costs (L.E.)	Design builder outputs-Consumption Rate (kWh)	Changed Rate	Changed Percentage
Jan 2021	269	212	225	44	16.36%
Feb 2021	0	9	200	-200	Invalid
Mar 2021	439	309	245	194	44.19%
Apr 2021	240	179	250	-10	-4.17%
May 2021	398	346	310	88	22.11%
Jun 2021	0	9	335	-335	Invalid
Jul 2021	670	816	455	215	32.09%
Aug 2021	579	621	540	39	6.74%
Sept 2021	592	638	425	167	28.21%
Oct 2021	604	653	355	249	41.23%
Nov 2021	19	10	325	-306	Invalid

Dec 2021	489	506	250	239	48.88%
Jan 2022	286	261	230	56	19.58%
Feb 2022	280	250	250	30	10.71%
Mar 2022	380	366	240	140	36.84%
Apr 2022	280	250	290	-10	-3.57%
May 2022	281	251	270	11	3.91%
Total	5806	5686	5195	-	10.52%
Average	342	335	306	36	10.52%

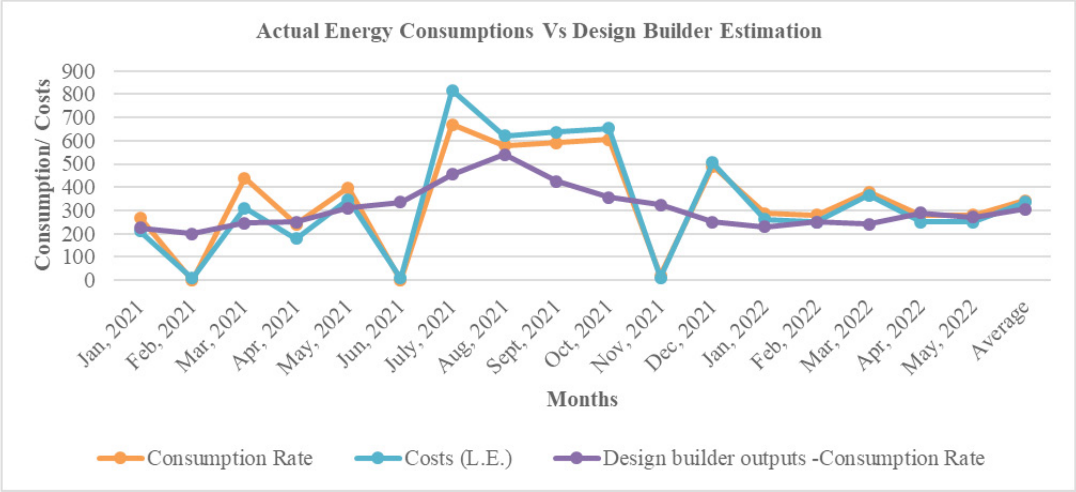


Fig. 11: Actual Energy Consumptions Vs Design Builder Estimation and Calibration Reflection on Monthly Electricity Bills.

It was realized that actual consumption rates are higher than the estimated average consumption rates with a total of 10.52% increased rates, which is deemed acceptable especially when knowing that the apartment unit analyzed is on the last floor of the building. Although it may still be viewed as high by some when related to ASHRAE Guideline 14, where the computer model shall have a Normalized Mean Bias Error (NMBE) of 5% and a Coefficient of Variation of the Root Mean Square Error CV(RMSE) of 15% in relation to monthly calibration. The monthly results vary from the lowest of -4.17% in April 2022 to the highest of 48.88% in December 2021. Three months has a clear drop in their actual consumptions which reached zero in some. This drop is estimated to be due to not taking the actual readings in those months or the earlier months. Therefore, their effect on the analyses of changed rates was exempted and considered invalid. However, this drop was reflected in the months before and after them as shown in Figure (11). For example, the drop in November 2021 with 19 kWh was followed by an increase in December 2021 with 489 kWh, which is almost double the consumption in January and February of 2022. Additionally, there was an unexpected increase from what was expected in September and October of 2021. These variations do not affect the total consumption or its change rate but will be reflected in the increased costs of the bills, especially if it entered another level of counting. Additionally, the design-builder is giving a steady flow, where there is a fluctuation relative to the variation between the heating and cooling required in each month. Furthermore, the effect of the global increase in temperature with the summers being hotter and the winters being colder is demonstrated in the same months' results but in different years, as shown in Figure (11).

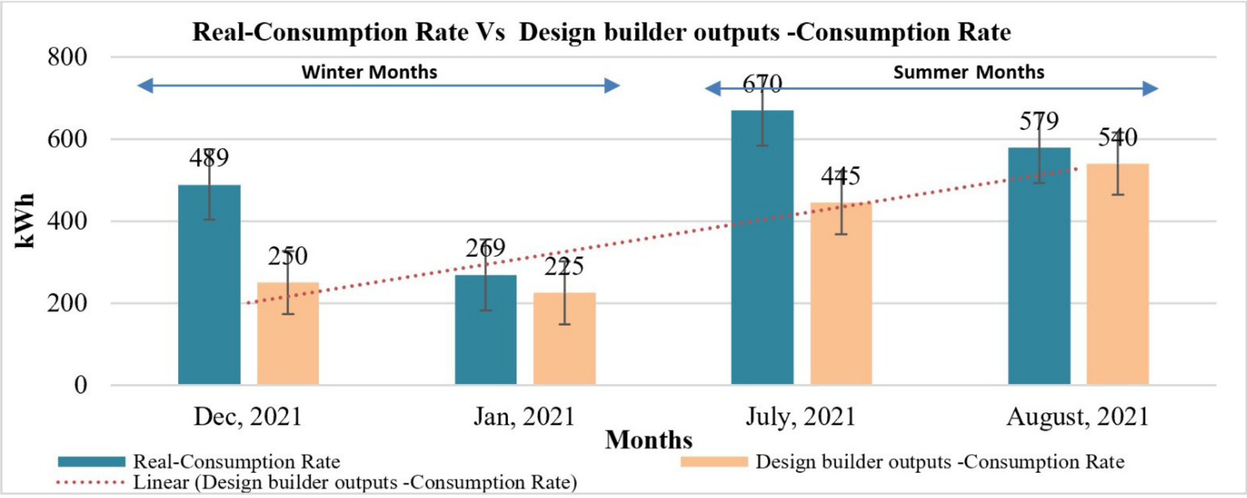


Fig. 12: Real Consumption Rate Vs Design Builder Estimation

As expected, the highest consumption in the simulation was in August 2021, while in reality it was found to be that July 2021 had the highest consumption rates as illustrated in Figure (12). This could be explained due to the drop in June 2021 as explained before and the annual vacation that is usually taken in August in many families. As for the winter months, it was clear that December 2021 has higher consumption than January 2021 and 2022, in both reality and the simulation as shown in Figure (12). Finally, as mentioned before if PCM was used an average annual reduction of 13.75% will be achieved which means around 798.33 kWh with almost 815 L.E. And if the green roof was used an average annual reduction of 28.69% will be achieved which means around 1665.74 kWh with almost around 1699 L.E. However, these figures will increase since this apartment is on the last floor. As for the whole building being a four-story building with four apartments on every floor means a total annual reduction of around 12,773.28 kWh with almost 13,040 L.E could be achieved when using PCM and a total annual reduction of around 26,651.84 kWh with almost 27,184 L.E could be achieved when using green roofs. When analyzing the initial costs in 2023, PCM costs around 379,050 L.E. for an elevation of 21 m width and 13.5 m height and a roof of 800 m^2. While the green roof will cost around 360,000 L.E. for a roof of 800 m^2 [33]. Again, the total initial costs of the green roof used in the study are slightly lower than the PCM Costs. However, residents might consider the annual reduction to be a low reduction, especially when related to the initial costs, time, and maintenance required in the case of a green roof. However, with the gradual increase in the costs of electricity due to the change in energy tariff rate, the potential inflation rate, and the crucial need to conserve energy (environmental costs), these numbers are considered a good start, especially for the green roof and if used for producing food to cover its initial costs sooner.

7. Conclusion

This paper was dedicated to discussing three parameters that the world is most concerned with in recent years to achieve sustainability; and they are thermal comfort, energy consumption, and CO_2 emissions. They were discussed on two levels in the residential sector. The first level is the building's footprint which includes the building form and orientation. With the help of the design-builder software, it was found that the best building form in achieving the best results, in almost all three above-mentioned parameters and in accordance with the research givens, is considered the rectangle with a courtyard. On the other hand, the U-shaped form could be considered the worst building form. Although the rectangle with a courtyard was expected to have good results, it was surprising to discover that the U-shaped form had the worst results in relation to the selected orientation. Additionally, all six building shapes' results variations could be related to the internal shading and closed environment due to using internal courtyards and the length of the elevation facing the north direction. Thus, further simulations could be conducted while changing some of the givens such as orientation for example and re-evaluating the six forms. As for level two, which is the building design that included the building façade and roof design and Indoor Environmental Quality various techniques and solutions were demonstrated such as various re-roofing techniques that include a green roof, roof shading, solar panels, double roof, and wind turbines. In addition to various envelope solutions and techniques such as thermal insulation coating materials, PCM, double skin, green walls, eco-material, and hybrid ventilation.

In the case study part, again with the use of the design-builder software, a real building's current footprint was analyzed in relation to its form and orientation. The building is in New Cairo, Egypt. Then its results were compared to the six basic shapes. It was found that the case study building had better results than only the worst shape results, the U-shaped, which means that form in relation to orientation greatly affects thermal comfort, energy consumption, and CO_2 emissions. Additionally, two different treatments were applied to the building envelope; walls and roof. The first treatment was using PCM on the walls and roof, which achieved an annual average total reduction of 13.75% in electricity consumption. This was achieved while maintaining an acceptable thermal comfort range with an annual average Fanger PMV of +0.035. Additionally, the CO_2 emissions levels were reduced by an annual average of 2.76%. The second treatment was using a green roof system; which achieved an annual average total reduction of 28.69% in electricity consumption. This substantial reduction will be achieved while maintaining an acceptable thermal comfort range with an annual average Fanger PMV of -0.299 Additionally, the CO_2 emissions levels were reduced by an annual average of 19.6%. Thus, it is fair to say that green roofs are a much better strategy for enhanced sustainable results in a hot arid climate such as Cairo, Egypt than PCM on all three levels; thermal comfort, energy consumption, and CO_2 emissions.

Finally, the paper further analyzed a single apartment on the last floor of the case study. The actual consumption rates were compared in relation to the proposed consumption rates by the design-builder and it was found that the actual rates were reduced by almost 10.52% than the software rates. Although this is an acceptable rate compared with other software results, however, it must be put into consideration that the software numbers are lower than the real numbers in all future work, which might be solved in newer versions of the program to better comply with the ASHRAE Guideline 14.

Additionally, for future work, it is advised for all researchers when working with the energy plus programs to use the most recent weather data that currently can be used from the Ladybug weather files, because the results could vary sustainably. These files are meteoblue climate diagrams which work based on 30 years of hourly weather model simulations and can be found for all places on Earth. They can give good indications of the location's climate patterns and estimated temperature, sunshine, precipitation, and wind[37]. It is also recommended in further research to adapt different climatic zones by using Alexandria and Aswan for example, as the case studies, especially for the applied treatments; the PCM and the green roof. Furthermore, simulations are recommended in relation to the six different forms and the varied orientations, while other treatments are recommended to use in more simulations and compare the results. Finally, it is recommended to study, in detail, the economical factor in relation to PCM and green roofs application to existing buildings.

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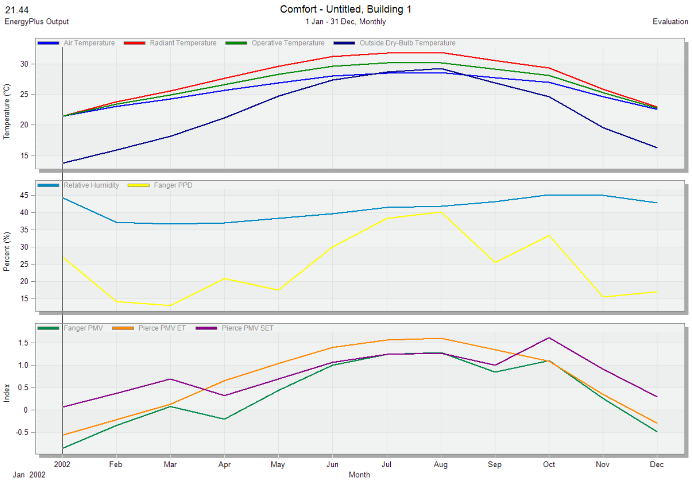
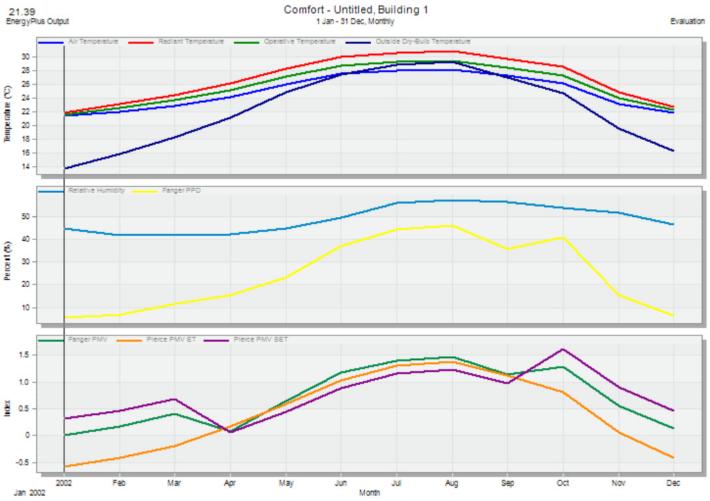
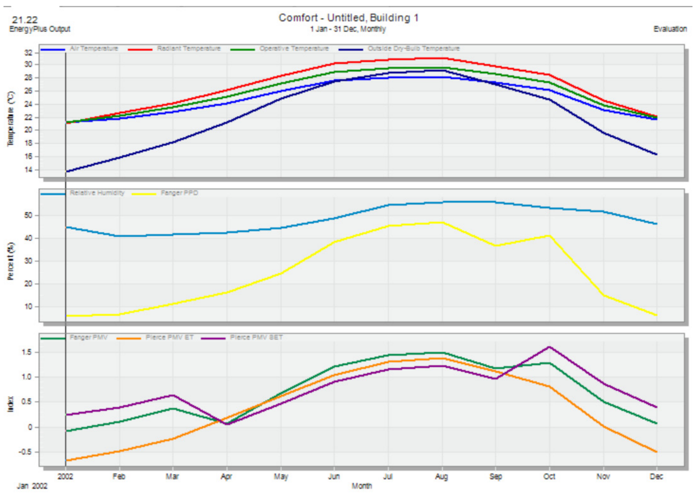
This section includes all the charts generated from the design-builder tool for all simulations conducted in the study, demonstrating the monthly values over a period of one year for the thermal comfort (Appendix A), internal gain (Appendix B), and CO_2 emissions (Appendix C) of the six tested forms. And also, the results concerning thermal comfort, internal gain, CO_2 emissions, and Fabric and Ventilation concerning the case study building Traditional base-case (Appendix D) and when applying the PCM (Appendix E) and green roof (Appendix F) techniques.

Appendix (A)

Table 11: Thermal Comfort design variables charts monthly results for the optimization analysis of the six forms

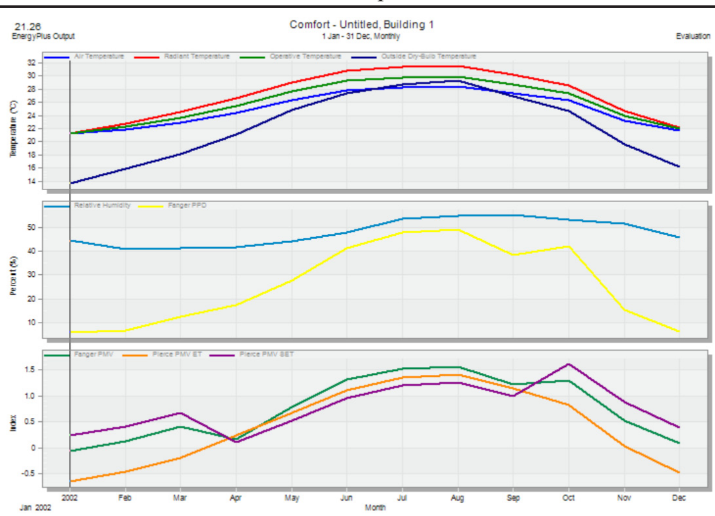
Thermal Comfort (Monthly result - Summer and Winter)
X-Axis: Months / Y-Axis: Temperature / Percentage / Index Comfort Range factors & Charts Colour Key: Air Temperature °C (First Temperature chart), Operative Temperature °C (First Temperature chart), Relative Humidity% (Second Percentage chart), Fanger PMV (Third Index chart)
U- Shape
 Y-Axis Grading Numbers: Temperature 15 – 30°C / Percent 15 – 45% / Index -0.5 – 1.5
Square Shape
 Y-Axis Grading Numbers: Temperature 14 – 30°C / Percent 10 – 50% / Index -0.5 – 1.5

Square with Courtyard Shape



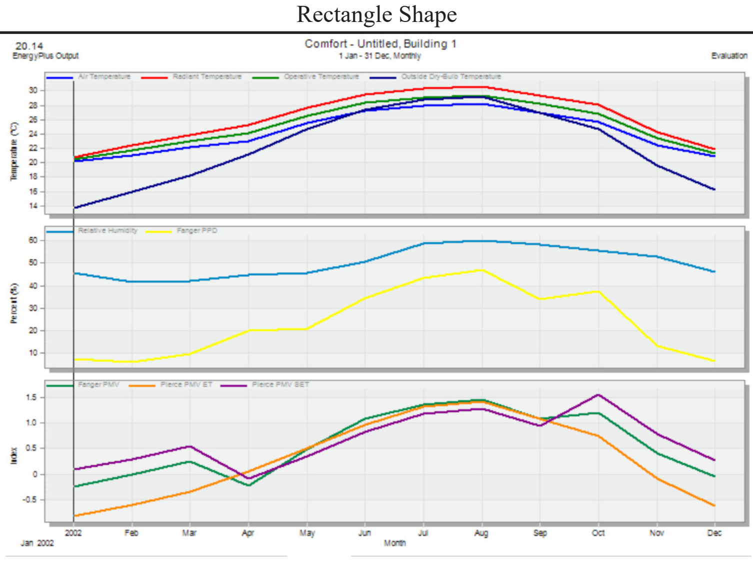
Y-Axis Grading Numbers: Temperature 14 – 32°C / Percent 10 – 50% / Index -0.5 – 1.5

L-Shape

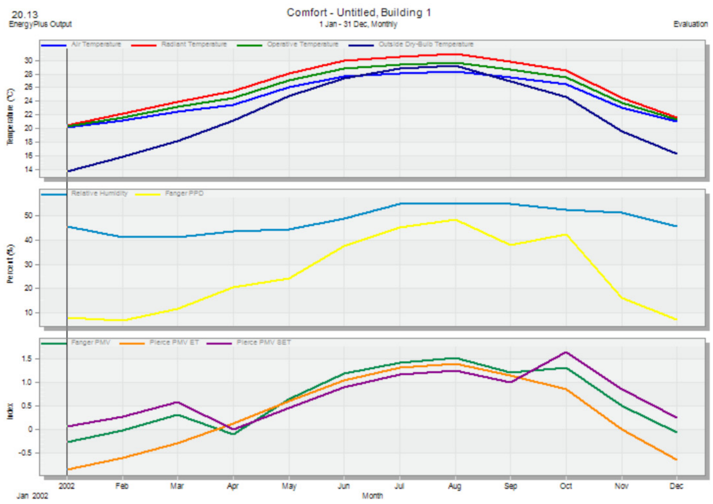


Y-Axis Grading Numbers: Temperature 14 – 32°C / Percent 10 – 50% / Index -0.5 – 1.5

Rectangle Shape

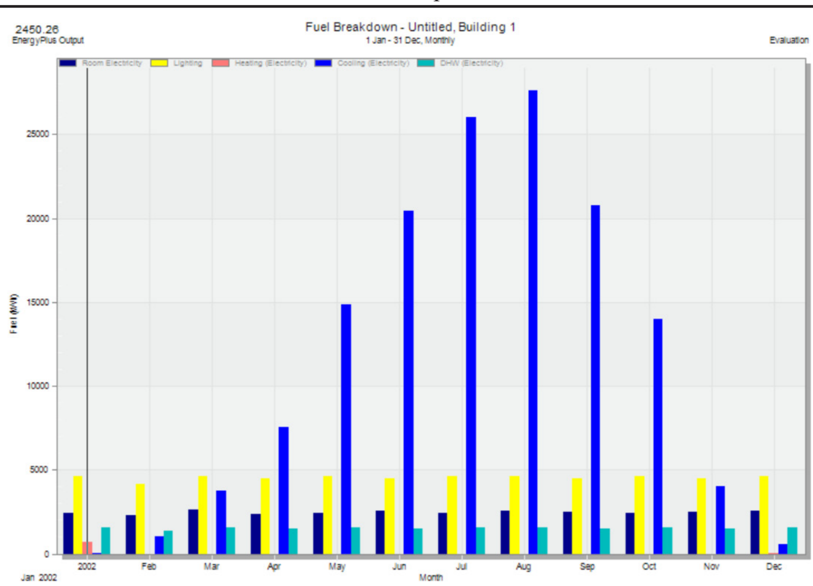


Y-Axis Grading Numbers: Temperature 14 – 30°C / Percent 10 – 60% / Index -0.5 – 1.5

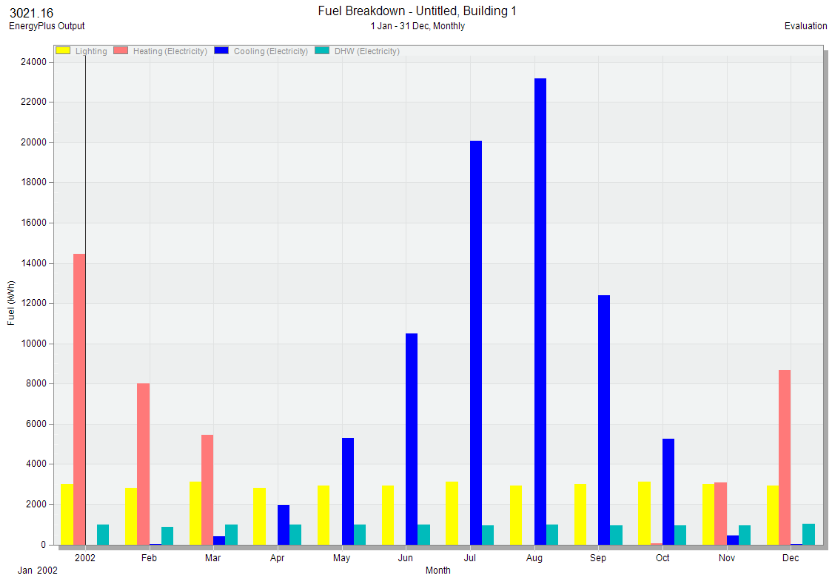
Rectangle With Courtyard Shape

Y-Axis Grading Numbers: Temperature 14 – 30°C / Percent 10 – 50% / Index -0.5 – 1.5

Appendix (B)

Table 12: Internal Gain design variables charts monthly results for the optimization analysis of the six forms

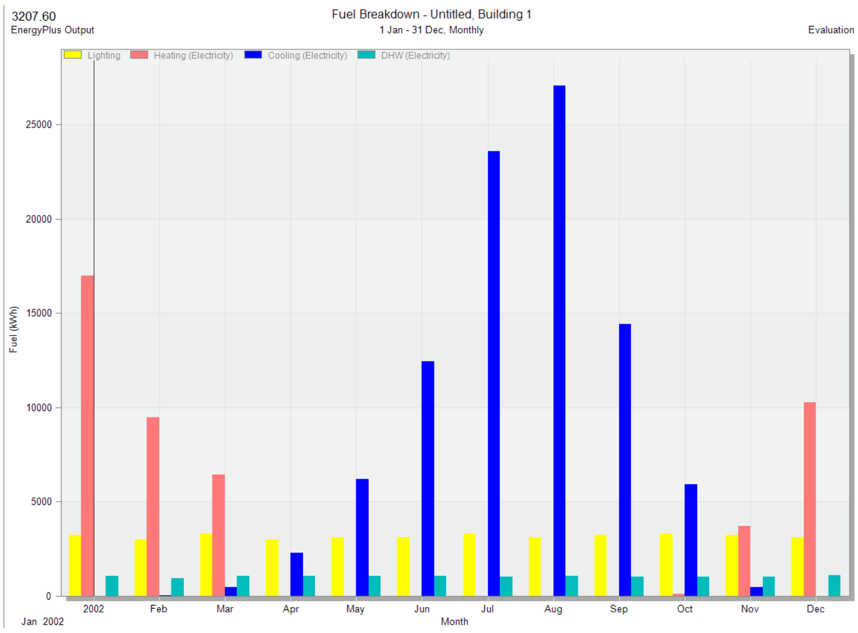
Internal Gain (Monthly result - Summer and Winter)
X-Axis: Months / Y-Axis: Fuel (kWh) Internal Gain Range factors and Charts Colour Key: Room Electricity, Lighting, Heating (Electricity), Cooling (Electricity), DHW (Electricity)
U- Shape

Y-Axis Grading Numbers: from 0 kWh to 25000 kWh

Square Shape



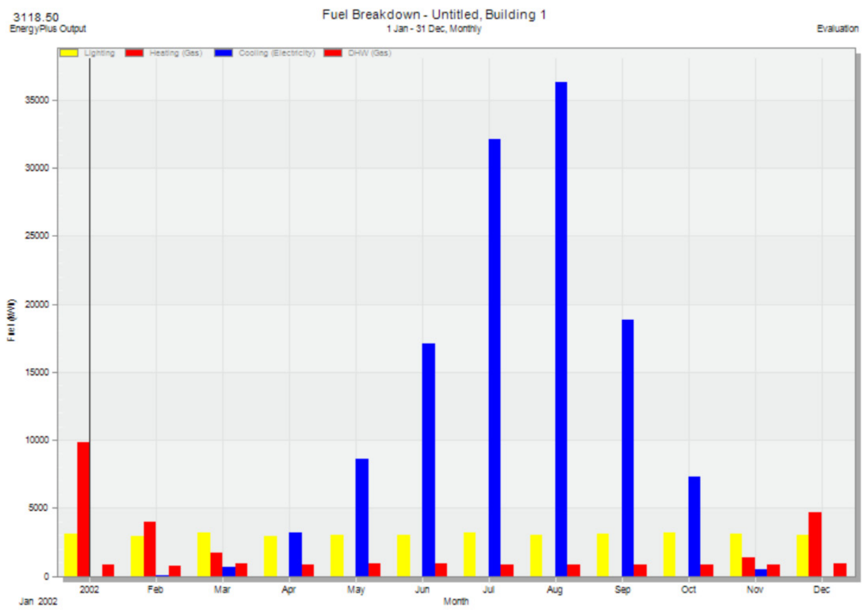
Y-Axis Grading Numbers: from 0 kWh to 24000 kWh

Square with Courtyard Shape



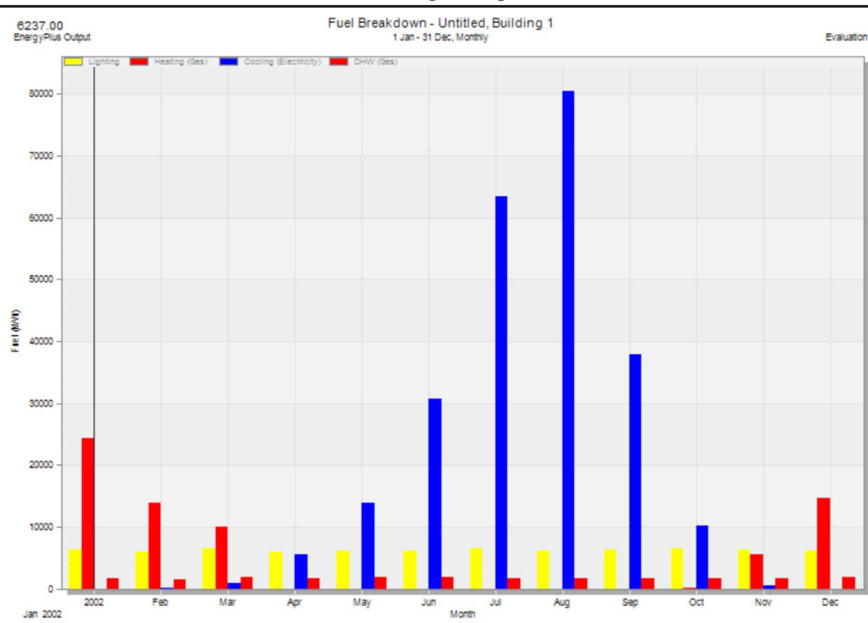
Y-Axis Grading Numbers: from 0 kWh to 25000 kWh

L-Shape

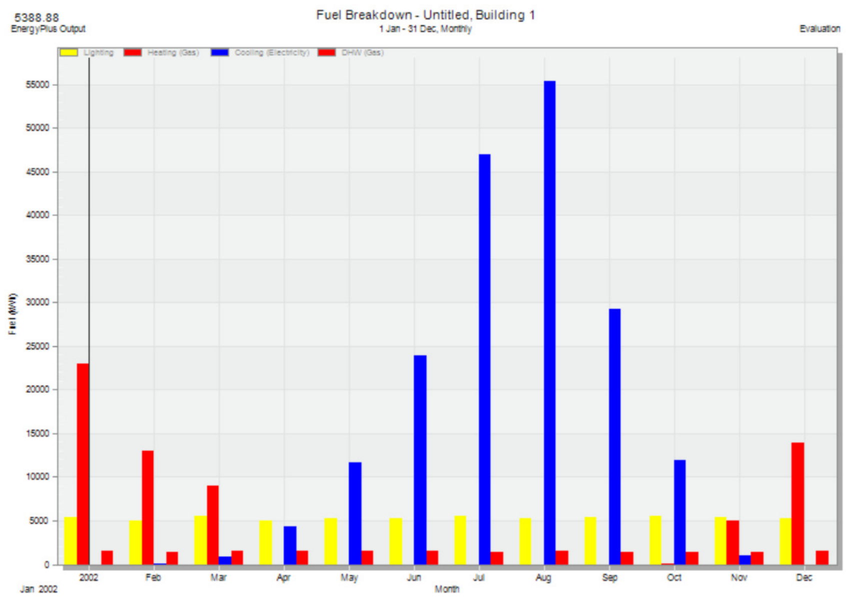


Y-Axis Grading Numbers: from 0 kWh to 35000 kWh

Rectangle Shape

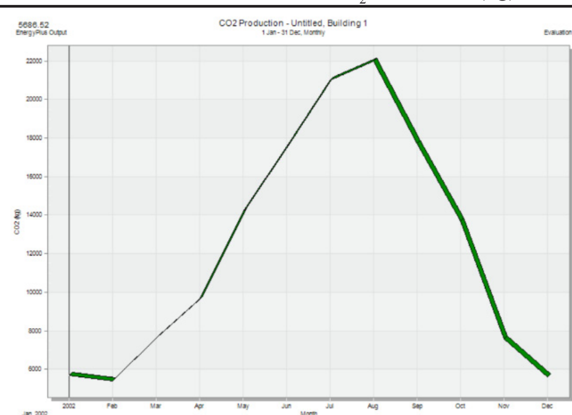
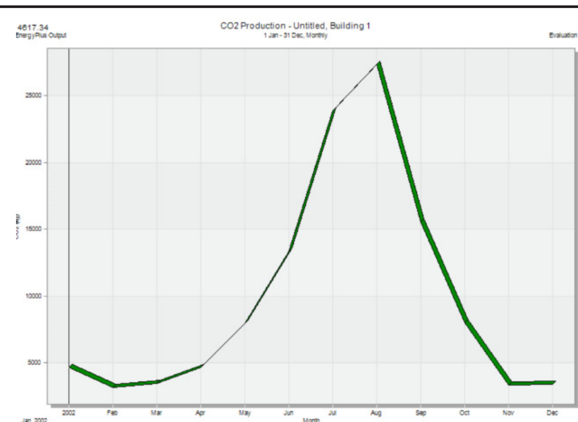


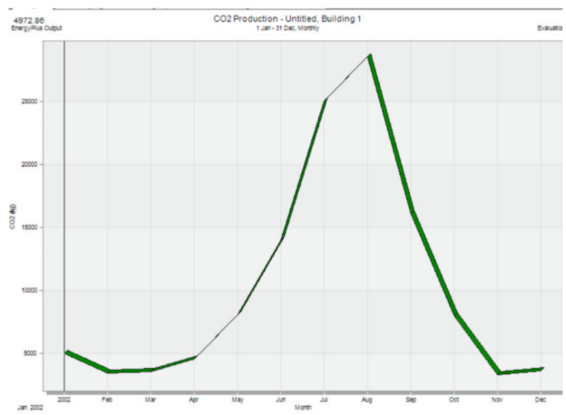
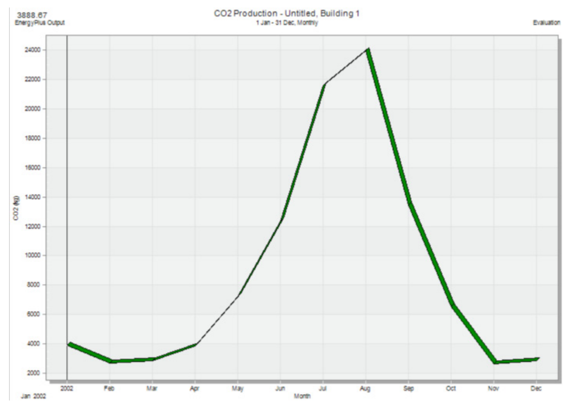
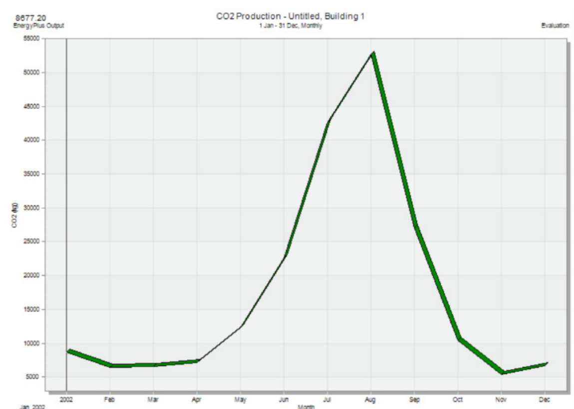
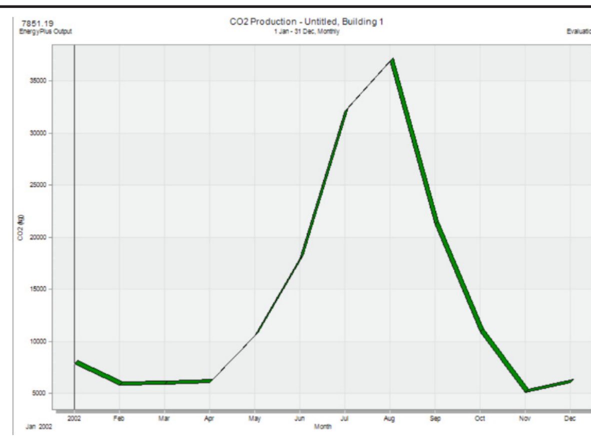
Y-Axis Grading Numbers: from 0 kWh to 80000 kWh

Rectangle With Courtyard Shape

Y-Axis Grading Numbers: from 0 kWh to 55000 kWh

Appendix (C)

Table 13: CO_2 Monthly emissions for the optimization analysis of the six forms

Basic Forms	CO_2 Emissions (Monthly result - Summer and Winter)
	X-Axis: Months / Y-Axis: CO_2 Emissions (kg)
U- Shape Y-Axis Grading Numbers From 6000 kg to 22000 kg	
Square-Shape Y-Axis Grading Numbers From 5000 kg to 25000 kg	

Square with Courtyard Y-Axis Grading Numbers From 5000 kg to 25000 kg	
L-Shape Y-Axis Grading Numbers From 2000 kg to 24000 kg	
Rectangle Y-Axis Grading Numbers From 5000 kg to 55000 kg	
Rectangle With Courtyard Y-Axis Grading Numbers From 5000 kg to 35000 kg	

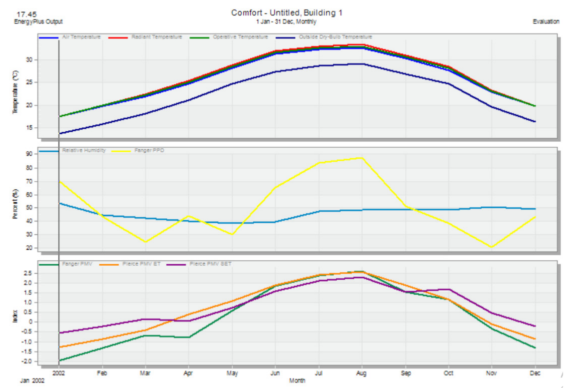
Appendix (D)

Table 14: Monthly Results of the case study building in its current state (Traditional)

Traditional Building

Thermal Comfort Monthly Results

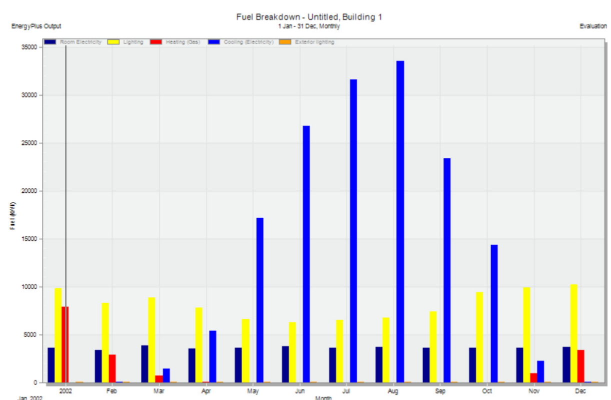
X-Axis: Months / Y-Axis: Temperature / Percentage / Index
Comfort Range factors and Colour Key: Operative Air Temperature / Relative Humidity / Fanger PMV



Y-Axis Grading Numbers: Temperature 15 – 30^{o}C / Percent 20 – 90% / Index -2.0 – 2.5

Internal Gain Monthly Results (kWh)

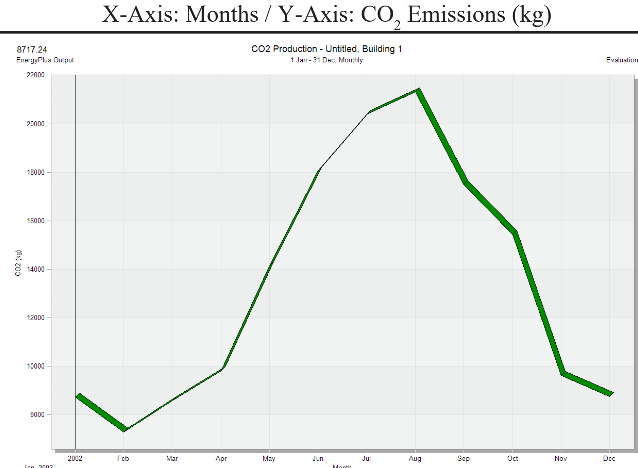
X-Axis: Months / Y-Axis: Fuel (kWh)
Internal Gain Factors and Charts Colour Key: Lighting / Cooling / Heating



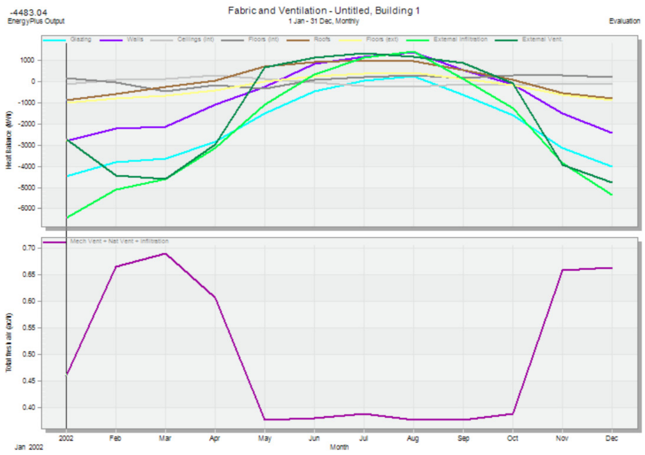
Y-Axis Grading Numbers: from 0 kWh to 35000 kWh

CO_2 Emissions Monthly Results (kg)

X-Axis: Months / Y-Axis: CO_2 Emissions (kg)

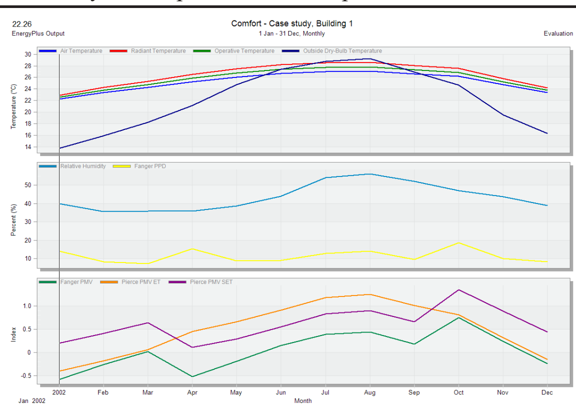


Y-Axis Grading Numbers: from 8000 kg to 22000 kg

Fabric and Ventilation
X-Axis: Months / Y-Axis: Heat Balance (kWh)/ Total Fresh Air (Air Changes/Hour (ac/h)) Fabric & Ventilation Colour Key: Glazing / Walls / Ceilings / Internal Floors / Roof / External Infiltrations
 Heat Balance Y-Axis Grading Numbers: from - 6000 kWh to 1000 kWh Total Fresh Air Y-Axis Grading Numbers: from 0.40 ac/h to 0.70 ac/h

Appendix (E)

Table 15: Monthly Results of the case study building after applying the PCM technique

PCM in External Walls & Roof
Thermal Comfort Monthly Results
X-Axis: Months / Y-Axis: Temperature / Percentage / Index Comfort Range factors and Colour Key: Operative Air Temperature / Relative Humidity / Fanger PMV
 Y-Axis Grading Numbers: Temperature 14 – 30°C / Percent 10 – 50% / Index -0.5 – 1.0
Internal Gain Monthly Results (kWh)
X-Axis: Months / Y-Axis: Fuel (kWh) Internal Gain Factors and Charts Colour Key: Lighting / Cooling / Heating

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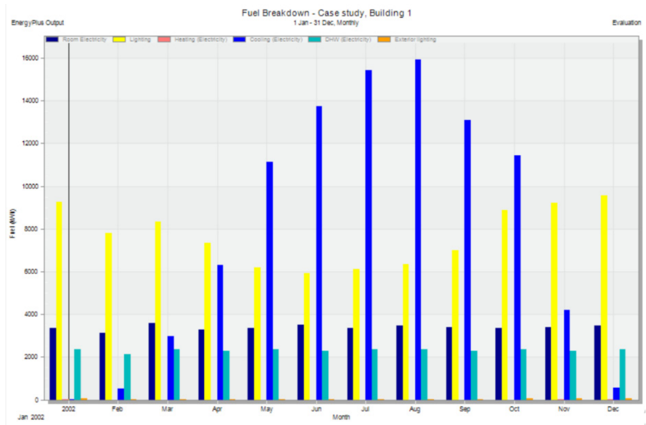
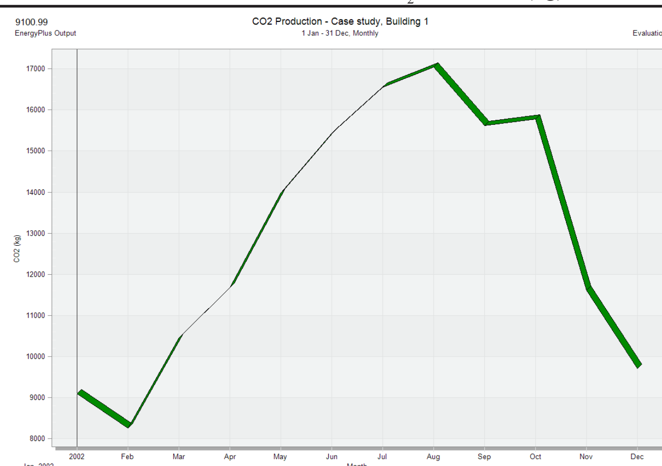


Y-Axis Grading Numbers: from 0 kWh to 16000 kWh

CO_2 Emissions Monthly Results (kg)

X-Axis: Months / Y-Axis: CO_2 Emissions (kg)

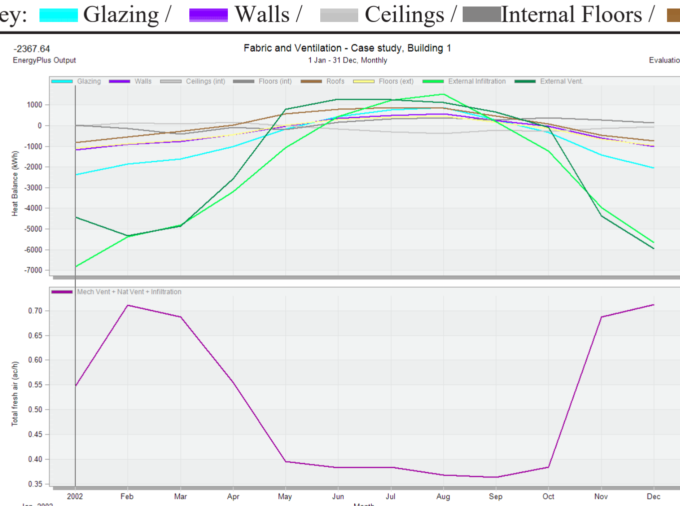


Y-Axis Grading Numbers: from 8000 kg to 17000 kg

Fabric and Ventilation

X-Axis: Months / Y-Axis: Heat Balance (kWh)/ Total Fresh Air (Air Changes/Hour (ac/h))

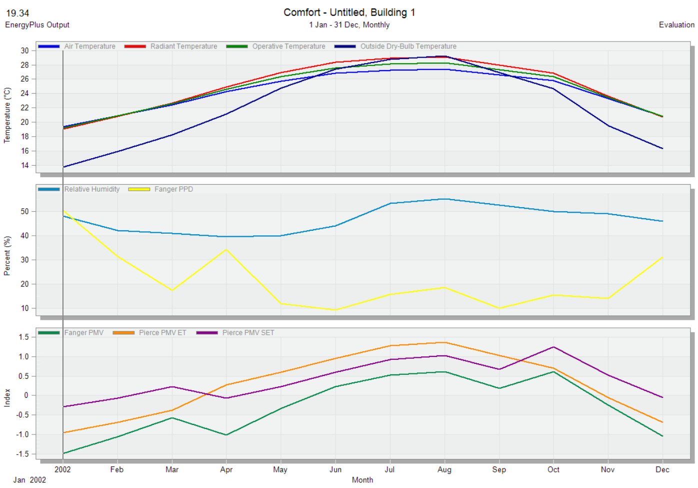
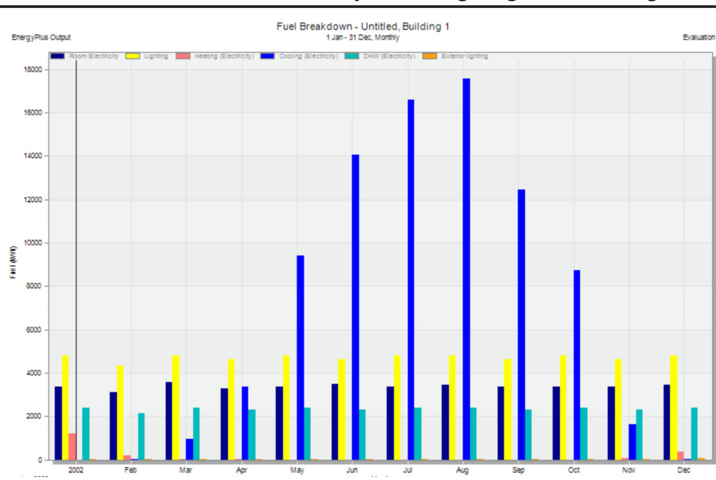
Fabric and Ventilation Colour Key: Glazing / Walls / Ceilings / Internal Floors / Roof / External Infiltrations



Heat Balance Y-Axis Grading Numbers: from -7000 kWh to 1000 kWh
Total Fresh Air Y-Axis Grading Numbers: from 0.35 ac/h to 0.70 ac/h

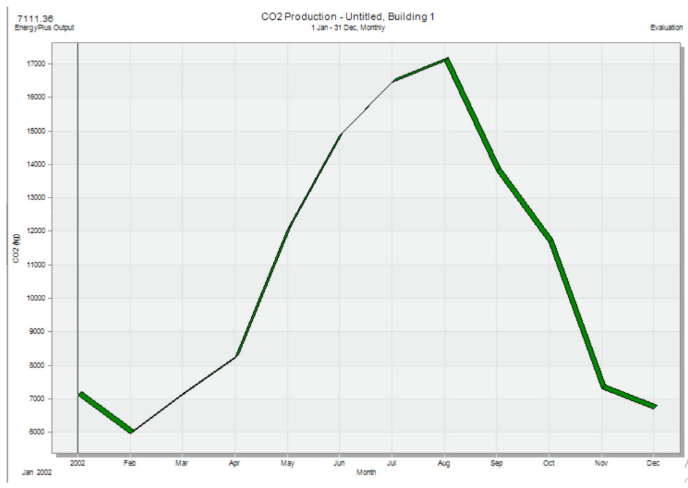
Appendix (F)

Table 16: Monthly Results of the case study building after applying the Green Roof technique

Green Roof
Thermal Comfort Monthly Results
X-Axis: Months / Y-Axis: Temperature / Percentage / Index Comfort Range factors and Colour Key: Operative Air Temperature / Relative Humidity / Fanger PMV
 Y-Axis Grading Numbers: Temperature 14 – 30°C / Percent 10 – 50% / Index -1.5 – 1.5
Internal Gain Monthly Results (kWh) X-Axis: Months / Y-Axis: Fuel (kWh) Internal Gain Factors and Charts Colour Key: Lighting / Cooling / Heating
 Y-Axis Grading Numbers: from 0 kWh to 18000 kWh

CO_2 Emissions Monthly Results (kg)

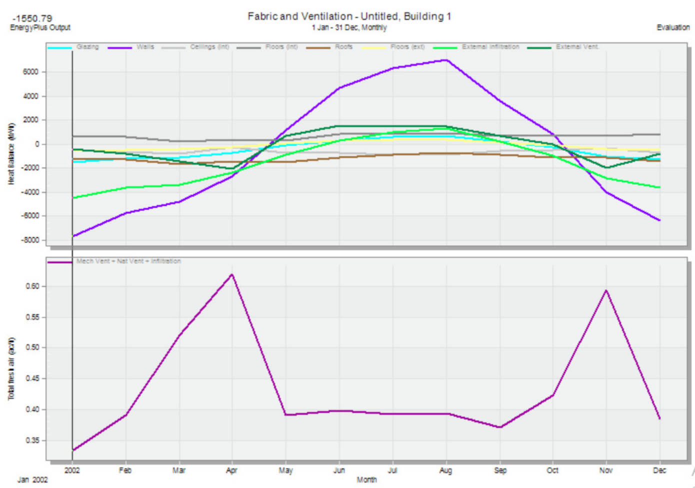
X-Axis: Months / Y-Axis: CO_2 Emissions (kg)



Y-Axis Grading Numbers: from 6000 kg to 17000 kg

Fabric and Ventilation

X-Axis: Months / Y-Axis: Heat Balance (kWh)/ Total Fresh Air (Air Changes/Hour (ac/h))
Fabric and Ventilation Colour Key: Glazing / Walls / Ceilings / Internal Floors / Roof / External Infiltrations



Heat Balance Y-Axis Grading Numbers: from - 8000 kWh to 6000 kWh
Total Fresh Air Y-Axis Grading Numbers: from 0.35 ac/h to 0.60 ac/h