Journal of Engineering, Project, and Production Management
2021, 11(3), 196-206

Energy Performance Analysis of Building Envelopes

Ibrahim Motawa[1], Asser Elsheikh[2], and Esraa Diab[3]

[1]Professor, Structural Engineering Department, Mansoura University, Elgomhouria St., Mansoura, 35516, Egypt, E-mail: i_a_motawa@mans.edu.eg

[2]Assistant Professor, Department of Civil Engineering, Peoples' Friendship University of Russia (RUDN), Russia. E-mail: elsheykh-am@pfur.ru; Structural Engineering Department, Mansoura University, Egypt. E-mail: assermfee@mans.edu.eg

[3]Graduate Student, Building and Construction Engineering Department, Tanta Higher Institute for Engineering and Technology, Tanta, El-Gharbia, Egypt, E-mail: esraadiab807@yahoo.com (corresponding author).

Engineering Management
Received November 15, 2020; revised December 30, 2020; accepted January 1, 2021
Available online February 2, 2021

Abstract: The building sector has a high level of energy consumption caused mainly by the buildings heating and cooling energy demands to satisfy indoor comfort requirements. Reducing both the amount of energy consumed and the life cycle cost is a main challenge for the construction of buildings. It is evident that sustainable materials have low environmental impacts and need low consumption of energetic resources in addition to their durability and recyclability. Therefore, this research aims to test different sustainable materials available in Egypt for the construction of building envelopes that include local stones "Marble and Limestone" and insulation materials "Polyurethane- expanded and Extruded polystyrene (XPS) foam" in order to achieve savings in energy and total life cycle cost. The simulation tests were conducted through Design Builder software. The results aim to provide solutions for building designers to achieve energy-efficiency and cost-effective design. The proposed alternatives showed a significant reduction in energy consumption by up to 62% and the total life cycle costs significantly reduced by up to 45.8%.

Keywords: Building energy performance, thermal comfort, initial cost, payback period, life cycle cost.

DOI 10.2478/jeppm-2021-0019

1. Introduction

The energy sector across the globe is facing huge challenges. For example, Egypt has the largest consumption of oil and natural gas in Africa: about 20% of Africa's oil consumption and 40% of dry natural gas consumption (Energy Information Administration, 2015). Additionally, the population inflated issue increases the demands for new buildings, which will rapidly increase the energy consumption rate of the operation stage for these buildings. In this way, the electricity demand is expected to increase by 6.8% annually over the next years (Hanna, 2015). For this reason, building designers and stakeholders are searching for more effective solutions to restrict building energy consumption. During the building life cycle, the operation stage is responsible for a large amount of energy consumption, through the HVAC loads: heating, cooling, ventilation, lighting, and equipment loads. During this stage, there are a large amount of energy losses through the building envelope elements: external wall, roof, doors, windows, which raise the demand for energy to recover the indoor temperature to the thermal comfort region. In order to improve the efficacy of the envelope elements, the heat transmittance value (U-value) must be reduced. As sustainable materials have low environmental impacts and need low consumption of energetic resources in addition to their durability and recyclability, many research has been conducted to use such materials for various building elements. This research aims to test different sustainable materials for the construction of building envelopes. As the study is conducted in Egypt, local stones and insulation materials "Polyurethane- expanded and Extruded polystyrene (XPS) foam" are used to modify external walls and roof systems. The study evaluates the impact of using these materials on energy consumption and the building life cycle cost. The research uses simulation tests as experimental works are not part of the methodology at this stage. This paper firstly reviews the related literature on building envelopes, then the proposed sustainable materials for cladding and roofing will be described, and then the simulation tests and results will be discussed.

2. Literature Review

The design of high thermal performance envelope systems has attracted increasing attention in both academic and professional fields (Lin et al., 2016). The exterior surfaces of a building envelope system are exposed to several environmental factors specific to the local climate, such as:

dirt, wind, sunlight, snow, and rain. All these environmental factors contribute to variations in thermal and moisture performance. When the incident solar radiation hits the envelope surface, part of the solar radiation is reflected back and the other part is absorbed by the envelope system. The absorbed part of solar radiation results in increasing the surface temperature, thereby increasing the cooling energy loads in summer and decreasing/ increasing the heating energy loads in winter. Therefore, the studies to improve the thermal performance of the building envelope try to minimize the thermal transmittance (U-value) of the envelope elements in order to reduce the heat gains or losses. For this research, the focus will be on improving the thermal performance of the external walls and roof elements. The following sections will review previous works on testing external wall and roof systems using simulation (numerical analysis) methods as well as those systems tested in experimental work.

2.1. Testing External Wall Systems using Numerical Analysis

Mayhoub et al. (2019) compared the thermal performance of the sustainable material "Autoclaved Aerated Concrete Blocks" instead of brickworks in a modified wall system that consisted of gypsum plaster, concrete block, extruded polystyrene, and brickwork as shown in Fig. 1-A. The effect of this replacement led to a slight reduction of energy consumption by 0.18% in addition to the great increase of the environmental impacts by 54%. However, it enhanced thermal comfort conditions by 18.9%. According to these results, the proposed sustainable material did not achieve the enhancement of all objective functions as targeted, and it was not enough to convince the costumers toward that choice.

Ingrao et al. (2016) created a wall system that consisted of plaster, thermal block, thermal insulation, air gab, and cement plaster, as shown in Fig. 1-B. The proposed system achieved energy reduction by 13% with usage of recycled materials "polyester fiber" which is characterized by low energy demand during the life cycle and is also eco-friendly. Although the proposed system reduced the energy consumption and the environmental impacts, the total thickness of this system is great "47.5 cm". To help the wide adoption of green buildings, the total wall thickness must be reasonable that could be acceptable by designers and homeowners.

The effect of different insulation thicknesses on the energy-saving percentage has been tested by Aktemur and Atikol (2017) in order to find an optimum insulation thickness. The study used a wall system as shown in Fig. 1-C that consisted of plaster, brickworks, insulation, brickworks, and plaster. The maximum energy saving achieved was at 45.1 cm, while the total wall thickness greatly increased to 96.1 cm.

Salandin and Soler (2018) analyzed different scenarios for material types as well as the thickness of each layer in wall system that consisted of plaster, brickworks, insulation, air gab, brickworks, and plaster, as shown in Fig. 1-D. Although the study tested the wall system thermal performance, the energy-saving percentage was not entirely clear for the suggested solution. This makes homeowners not aware of how the suggested solution could save more energy than the existing system.

2.2. Testing External Wall Systems using Experimental Works

Tejedor et al. (2017) measured the U-value for a modified wall system that consisted of plaster, insulation, brickworks, and plaster as shown in Fig. 2-A. The results showed low U-value with a reasonable thickness, the construction costs and the life cycle costs were unknown in order to evaluate the suitability of the suggested solution to implement.

An advanced wall system that consisted of plaster, brickworks, insulation material, air gab, and brickworks as shown in Fig. 2-B was tested by Guillen et al. (2014). The indoor thermal comfort was enhanced by 30%. The annual energy consumption for the wall system could not be evaluated by the experimental work, which makes it difficult for homeowners to understand the advantages of such an energy-efficient system.

Asdrubali et al. (2014) tested another advanced wall system that consisted of plaster, thermal block, insulation, and thermal block as shown in Fig. 2-C. The study recommended that there should be a trade-off between the increase of total thickness and the U-value reduction to meet other social and economic measures. The thermal performance of a green wall system was tested by Nadia et al. (2013) which consisted of cement plaster, brickworks, cement plaster, and plant cover layer "Jasmine and Aristolochia" as shown in Fig. 2-D. The test was conducted in the semi-arid regions during the summer period. The results showed that the plant cover layer minimized the indoor temperature; however, it increased the relative humidity.

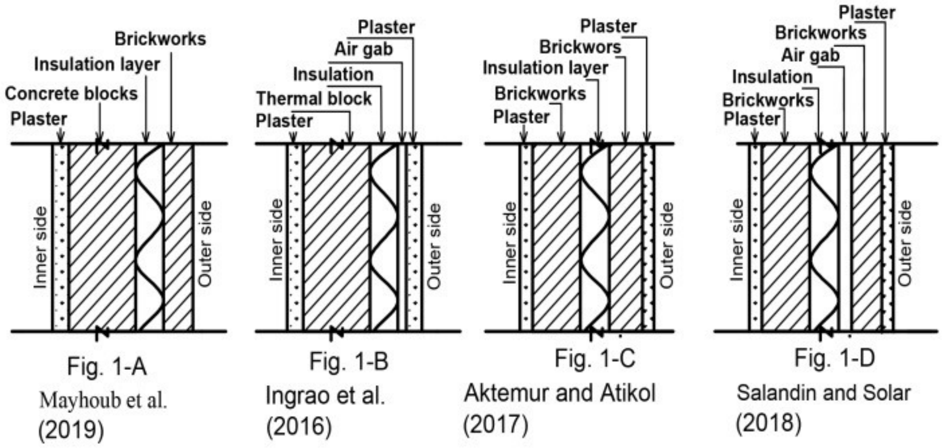
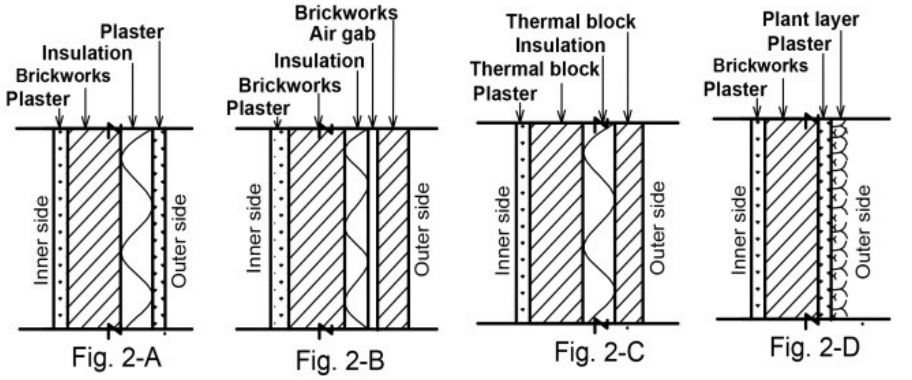


Fig.1. External wall systems tested using numerical analysis



Tejedor et al. (2017) | **Guillen et al. (2014)** | **Asdrubali et al. (2014)** | Nadi et al. **(2013)**

Fig.2. External wall systems tested using experimental works

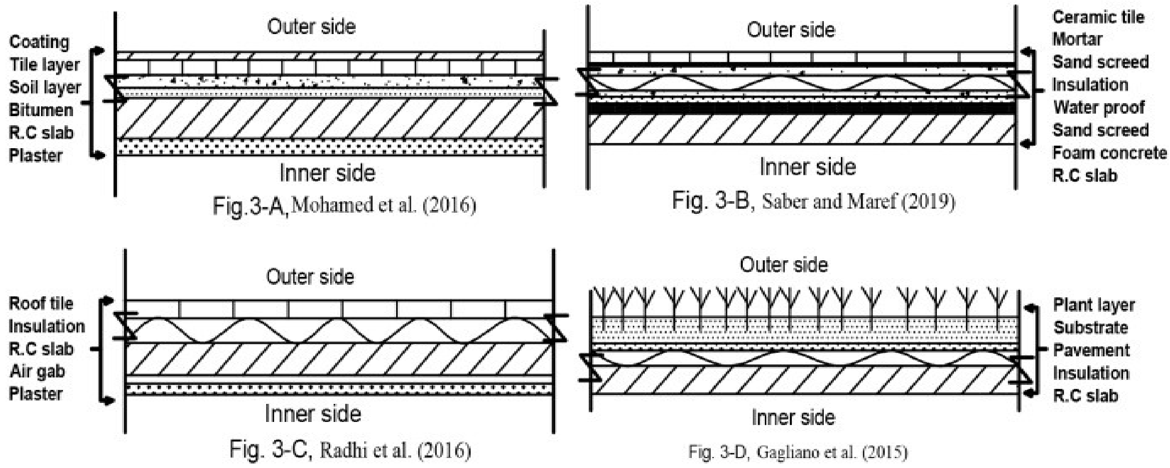


Fig. 3. Flat roof systems using numerical analysis

2.3. Testing Flat Roof Systems using Numerical Analysis

The effect of adding a reflective coating to a roof system on the building energy consumption was tested by Mohamed et al. (2016). The proposed system consisted of cement sealant "reflective coating," concrete blocks tiles, soil, bitumen, reinforced concrete R.C slab, and gypsum plaster, as shown in Fig. 3-A. The reflective coating has a great effect on saving energy consumption by 17.4%. The proposed roof system included some unsustainable materials that worsen the environmental impacts during the building life cycle.

Saber and Maref (2019) analyzed a roof system which consisted of ceramic tile "light color," mortar, sand screed, insulation layer, waterproofing, sand screed, foam concrete, and reinforced concrete slab as shown in Fig. 3-B. The study focused on maximizing the energy-saving only without specifying the proposed other sustainability goals: the environmental impacts and the life cycle costs.

The effect of different tile materials on energy saving was tested by Radhi et al. (2017). The tile materials tested were concrete screed, bituminous felt, light tile ceramic, and dark tile ceramic. The roof system consisted of tile, insulation layer, reinforced concrete slab, air gab, and gypsum plaster, as shown in Fig. 3-C. It is concluded that changing the material type has a small effect on energy saving by 7%, so the study did not provide a convincing solution to homeowners.

Gagliano et al. (2015) tested the thermal performance of a green roof system that consisted of plant layer, soil, pavement layer, insulation layer "8 cm", and reinforced concrete slab as shown in Fig. 3-D. This system reduced the annual energy needs by 85.2% and the thermal discomfort intensity has been reduced by 96%. This system used a massive thickness of "54 cm". The study did not investigate the life cycle cost to evaluate the profitability of such a system.

2.4. Testing Flat Roof Systems using Experimental Works

The effect of the total evaporation in different plant growth stages on energy consumption was tested by Bevilacqua et al. (2015). The study performed an experimental test in Catalonia-Spain,and determined the required depth of the substrate layer to enhance energy savings. The green roof system consisted of plant layer, substrate layer, insulation layer, porous concrete, geotextile felt, air/water layer, waterproofing, and geotextile felt, as shown in Fig. 4-A. The results highlighted that the maximum plant grows that occurred at the beginning of spring and summer seasons has a negative impact on energy-saving caused by the lack of moisture in the substrate layer. Therefore, the substrate layer depth must set at 8 cm.

Zhao et al. (2013) tested the effect of variable green roof materials which included: seven types of plants and five types of substrates on green roof thermal performance based on evaluating the roof U-value for a commercial building in Chicago. The roof system consisted of a plant layer, substrate layer, filter layer, waterproof layer, and reinforced concrete slab “R.C” as shown in Fig. 4-B. The results show that both plant and substrate types could affect the green roof thermal performance as high as 15%.

The thermal performance of four roof tile types was tested by Ascione et al. (2018) which included: dark bituminous membrane, commercial high reflectivity paint, polished aluminum paint, and acrylic white paint. The roof system consisted of a mineral fiber panel, steel sheet, insulation material, and steel sheet as shown in Fig. 4-C. The results show that the white roof paints reduced the variation of the inside and outside temperature and also reduced the cooling loads. However, the heating loads have been increased significantly during the winter season.

Tang and Zheng (2019) tested the thermal performance of a green roof during sunny summer days. The green roof system consisted of a canopy layer, substrate layer, planting plate, waterproofing, cement mortar, hollow core slab, and plaster as shown in Fig. 4-D. The results showed that the green system reduced energy consumption by 14.7%.

2.5. Testing Building Envelope Systems in Egyptian Climates

Khalil et al. (2018) suggested two types of envelope systems: a low and a high envelope technology using a reflective slats shading system. The low type uses the insulation material “straw bale” with 10 cm thickness for walls and roofs. The high type uses polyurethane foam with 5cm thickness for the walls and roofs. The two systems consist of the same wall and roof layers as shown in Fig. 5-A and 5-B. The results showed a reduction in the annual energy consumption by 46% and 50% for the low and high technologies, respectively. While the low type is 5 cm thicker than the high type, the high type has higher initial construction costs.

Mahmoud et al. (2019) tested a modified building envelope located in Cairo, where the system consisted of a traditional roof system, modified wall system, and 6 mm single reflective glass with reinforced concrete sunshades over each window. The traditional roof system consisted of concrete tile, mortar, sand, insulation board, bituminous damp insulation, and reinforced concrete slab. The modified wall system consisted of a double brickworks layer with an air gap in between, as shown in Fig. 5-C and 5-D. The results showed that this system slightly reduced energy consumption by 13%.

2.6. Aim and Objectives of This Research

From the reviewed literature on building envelope systems to minimize energy consumption, researchers have used different envelope component materials including the addition of insulation layers in order to maximize energy saving. Not all research has conducted an economic evaluation for these developments despite its importance to homeowners (Mayhoub et al., 2019; Ingrao et al., 2016; Aktemur and Atikol, 2017; Salandin and Soler, 2018; Tejedor et al., 2017; Guillen et al., 2014; Asdrubali et al., 2014) and also the use of sustainable materials are not widely adopted. Many works were also conducted to improve building thermal performance by adding reflective coating and insulation layers but also without economic evaluation of these developments (Mohamed et al., 2016; Saber and Maref, 2019; Radhi et al., 2017; Ascione et al., 2018). On the other hand, adding a plant layer to building envelope systems has been tested which significantly improved building thermal performance during the summer season; however, the side effect of these solutions was recorded in the increase of the relative humidity (Nadia et al., 2013; Gagliano et al., 2015; Bevilacqua et al., 2015; Zhao et al., 2013; Tang and Zheng, 2019). In the Egyptian context, the improvement of thermal performance by using insulation layers and by adding air gab layers to building envelope systems have been studied. The use of air gap layers has slightly reduced energy consumption compared to the use of insulation layers, but the initial costs were approved to be significantly higher in case of using insulation layers that suggested this solution is not appropriate to the economic situation in Egypt (Khalil et al., 2018; Mahmoud et al., 2019). Furthermore, the use of sustainable materials for building envelope systems in Egypt still needs further research. In this regard, the research analyzes the performance of different stone cladding “Marble and Limestone” and different insulation materials “Polyurethane-expanded and Extruded polystyrene (XPS) foam” to modify external walls and roof systems. The following sections will illustrate the methodology adopted to achieve these objectives.

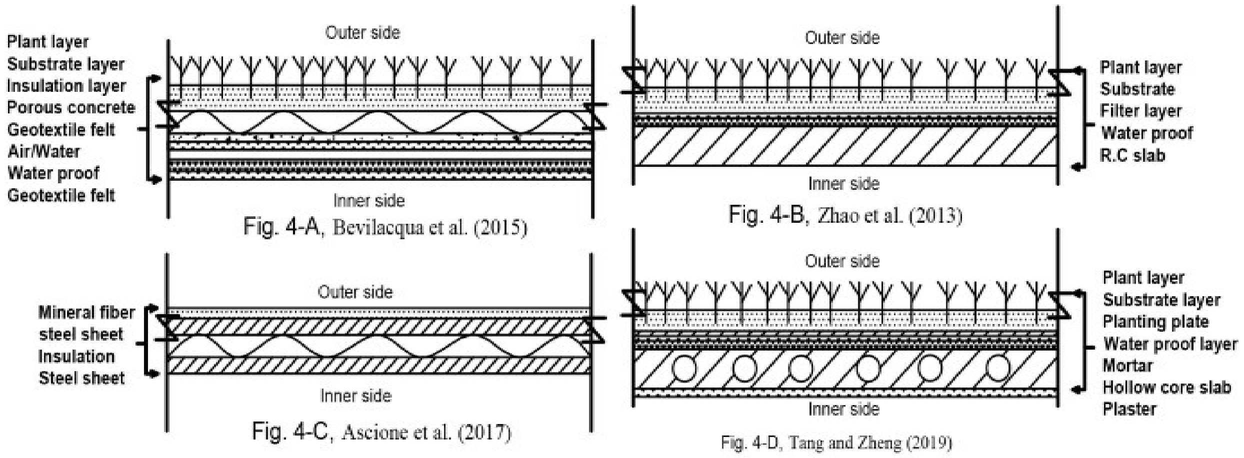


Fig. 4. Flat roof systems tested using experimental works

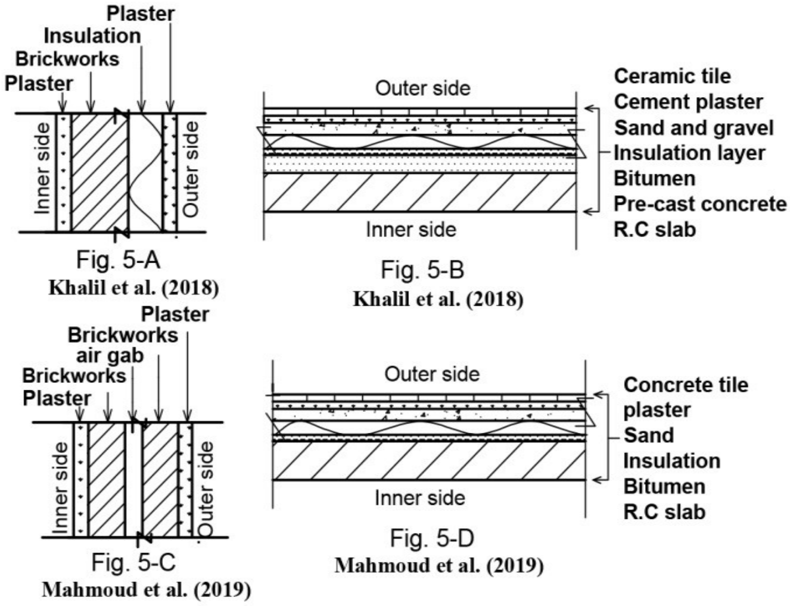


Fig. 5. Building envelope systems tested in Egyptian climates

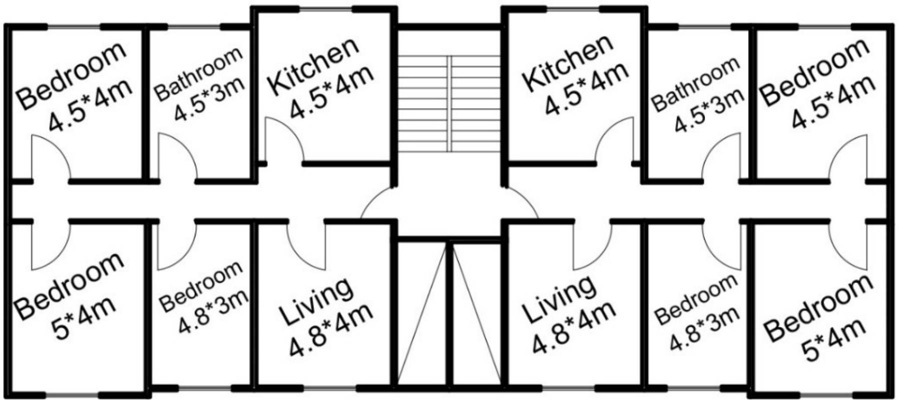


Fig. 6. A residential building unit layout (Khalil et al., 2018)

3. Material and Methods

This research aims to test different sustainable materials for the construction of building envelopes. To achieve the study aim, three objectives have been defined:

- To select a reference case
- To design the proposed wall and roof cross-sections
- To test the designed cross-sections against energy consumption, thermal discomfort, life cycle cost (LCC), and payback period

3.1. Selection of a Reference Case

A local existing building model has been chosen to test the proposed new wall and roof cross-sections and to compare the performance results with its current known results. The current building energy performance has been measured by Khalil et al. (2018). The building is a residential apartment block located in Alexandria, Egypt. Fig. 6 shows the plan layout of the building. Table 1 shows the building properties and typology components characteristics. The year calendar is divided as follows: season 1 (1th October : 31st May), season 2 (1st June : 30th August), and season 3 (31st August : 30th September). Table 2 summarized occupancy, artificial lighting, and HVAC system schedules.

Khalil et al. (2018) have developed the design of building model shown in Fig. 6 where he added an insulation layer of 5cm to the wall and roof systems, and changed the glazing system to double-glazing with blinds shading system, as detailed in Table 3. The modified model showed a significant reduction of 48% for the energy consumption and a reduction of 18.7% for the discomfort hours compared with the base model.

3.2. Description of the Proposed Stone Cladding Materials for the Wall and Roof Systems

This research proposes different alternatives by adding an insulation layer and a stone cladding layer to the external wall system and the roof system in order to improve energy efficacy. The proposed cross-sections for the external wall and roof alternatives are shown in Fig. 7.

Table 1. Case study building and its typology components (Khalil et al., 2018)

Building Description (Base model)	
Shape	Rectangular (25 m × 11 m)
Floor height	2.8 m
Occupancy density	5 person
Building features	Description of the housing in initial case
External wall components	2 cm cement plaster + 12.5 cm burned brick + 2 cm cement plaster, U-value = 2.5 $W/m^2.K$
Flat roof components	2 cm ceramic/porcelain + 2 cm cement plaster + 4 cm sand and gravel + 2 cm bitumen pure + 7 cm pre-cast concrete + 16 cm reinforced concrete slab, U-value = 1.39 $W/m^2.K$, roof surface absorbance = 0.6
Ground floor slab	2 cm ceramic/clay tile + 2 cm cement plaster + 6 cm sand and gravel + 5 cm pre-cast concrete + 2 cm bitumen + 20 cm pre-cast concrete , U-value = 1.58 $W/m^2.K$
Typical Floor slab components	2 cm ceramic tile + 2 cm mortar + 4 cm sand and gravel + 15 cm reinforced concrete slab, U-value = 1.8 $W/m^2.K$
Partition wall	Wall U-value = 1.732 W/m^2 K Wall surface absorbance = 0.7
Glazing type	6 mm single clear pane glass, U-value = 6.25 $W/m^2.K$ Solar heat gain coefficient = 0.5 Shading coefficient for glass = 0.70
WWR	0.45 north, 0.35 south facades
Window frame type	Wooden frame type
Temperature set point	24 °C - adaptive
Lighting installation power density	Living rooms 17 W/m^2 Bedrooms 13 W/m^2 Others 9 W/m^2
Plug loads average installation power density	6 W/m^2

Table 2. Occupancy, artificial lighting, and HVAC system schedules (Khalil et al., 2018)

Season		**1**	**2**	**3**
Occupancy schedules	Living room	6 a.m. to 11 p.m.	10 a.m. to 11 p.m.	11 a.m. to 11 p.m.
	Bed rooms	11 p.m. to 6 a.m.	11 p.m. to 10 a.m.	11 p.m. to 11 a.m.
Artificial lighting schedules	Living room	6 to 10 p.m.	7 to 11 p.m.	8 to 11 p.m.
	Bed rooms	9 p.m. to 11 p.m.	11 p.m. to midnight	11 p.m. to midnight
HVAC system schedules	Living room	-	5 to 11 p.m.	3 to 11 p.m.
	Bed rooms	-	11 p.m. to 5 a.m.	11 p.m. to 5 a.m.

Table 3. Modified typology components (Khalil et al., 2018)

Building features	**Description of the developed envelope system (Khalil's model)**
External wall components	2 cm cement plaster + 5 cm polyurethane, foam + 12.5 cm burned brick + 2 cm cement plaster, U-value = 0.4 $W/m^2.K$
Flat roof components	2 cm ceramic/porcelain + 2 cm cement plaster + 4 cm sand and gravel + 5 cm polyurethane, foam + 2 cm bitumen pure + 7 cm pre-cast concrete + 16 cm reinforced concrete slab, U-value = 0.4 W/m2.K
Glazing type	Double blue glass with 6 mm/13 mm argon, U-value = 2.5 $W/m^2.K$, solar heat gain coefficient = 0.494, direct solar transmission is 0.373, light transmission is 0.5
WWR	0.45 north, 0.50 south facades
Shading system	Blind with high reflectivity slats for the external glass layer of south facade, which worked dynamically from 8:00 to 18:00

The study uses two local stone cladding (Marble and Limestone) which are found in Egypt as follows:

- Marble stone found in the areas of Assiout, Kharga, Zafarana, and East of Sohag (Kandil and Selim, 2006)
- Limestone found in the areas of South of Luxor, Giseh plateau, and Holocene (Klemm and Klemm, 2001)

These stone cladding materials have been selected for the following reasons:

- Sustainable natural materials have low environmental impacts and need low consumption of energetic resources in addition to its durability and recyclability.
- The use of natural stones gives the opportunity to maintain the identity and peculiarity of the construction culture.
- Marble envelopes represent a relatively common architectural solution used in a variety of building facades (including historical buildings). It has the ability to reduce solar heat gains, while improving indoor thermal comfort and energy efficiency in the summer time. Limestone also has the ability to enhance the thermal comfort of a house and its sustainability.

Based on the base model described above, this research proposes different alternatives to the external wall construction and to the roof construction as detailed in Table 4. The window to wall ratio is reduced to 20% for all proposed alternatives. The HVAC system is allowed for the mixed mode, so that natural ventilation could be involved during the determination of HVAC working period in order to minimize energy consumption. The thermo-physical properties of the building construction materials are defined according to the materials databases provided by ASHRAE (ASHRAE Handbook, 2009). The unit cost of each wall type was determined by the researcher through a field study conducted in March 2019. It is subject to changes based on market prices. The following sections illustrate the adopted methodology to determine energy consumption, discomfort hours, and the LCC for case study building.

3.3. Testing the Proposed Design Alternatives

A BIM model was first developed to test the building performance using “Design Builder” that used to evaluate the annual energy consumption and initial cost in this study. All input data (such as zones types assignment, occupancy density, occupancy schedules, HVAC type, HVAC schedules, lighting systems, economic data, etc.) was then exported for energy simulation using “Energy Plus.”

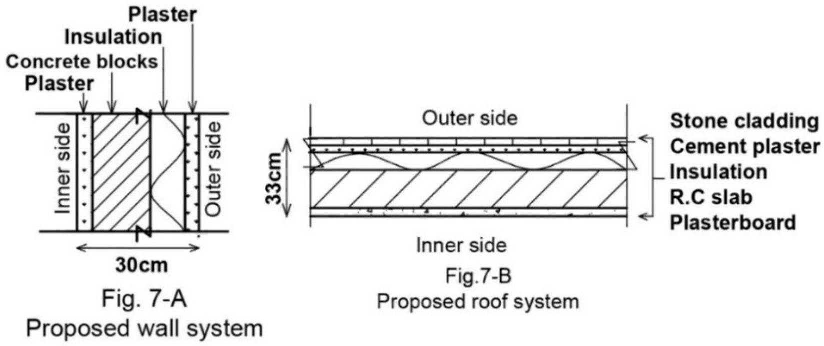


Fig. 7. Proposed stone cladding elements

Table 4. Modified building elements

Building element	Element layer	Thickness (cm)	U-value	Cost/m^2(LE)	Weight (Kg/m^2)
Wall 1	Lime stone cladding Cement plaster Polyurethane, expanded Concrete blocks Plaster board	2.5 2 8 15 2.5	0.216	600	205.4
Wall 2	Marble board Cement plaster XPS layer Concrete blocks Plaster board	2.5 2 8 15 2.5	0.285	735	221.75
Roof 1	Lime stone Cement plaster Polyurethane, expanded R.C slab Plasterboard	2.5 2 10 16 2.5	0.198	1730	499.85
Roof 2	Marble tile Cement plaster XPS R.C slab Plasterboard	2.5 2 10 16 2.5	0.274	1915	516.45

Then, the design variables alternatives were created and a test was conducted for each alternative to evaluate energy consumption, thermal discomfort, life cycle cost (LCC), and payback period. The prediction of the annual energy consumption is based on the heat balance method adopted by the "Energy Plus" mathematical model and used as a plug-in for the BIM software (Design Builder) to run energy simulation.

3.3.1. Discomfort hour calculation

The energy simulation tool (Energy Plus) generates the annual discomfort hours according to the American National Standard ASHRAE 55 (2004). ASHRAE establishes the ranges of indoor environmental conditions to achieve acceptable thermal comfort for occupants of buildings according to specific parameters that must be taken into account to examine the thermal comfort in any building. These parameters include environmental parameters, air temperature, mean radiant temperature, relative humidity, in addition to personal parameters: like activity levels and clothing insulation (ASHRAE Standard 55, 2004).

3.3.2. Life cycle cost and relative payback period calculation

The used simulation tool (Design Builder) provides a limited lifetime of up to 40 years to determine the LCC (Life Cycle Cost/ Parameters/Design Builder Website, 2019). Therefore, the life cycle cost will be calculated in this research using a mathematical model that formed by the Federal Energy Management Program (Fuller and Petersen, 1996) as shown in Eq. (1). For the purpose of comparison, the values of few variables were assumed according to Khalil et al. (2018).

$$LCC = IC + \frac{P(\frac{(1+L)^n}{(1+r)^n} - 1)}{L - r} \quad (1)$$

Where: *I.C.*: initial costs, *P*: annual operating cost which calculated based on Egyptian Electricity Holding Company Annual Report (Egyptian Electricity Holding Company Annual Report, 2018), *L*: annual increase rate in the price of electricity = 16% (Khalil et al., 2018), *r*: Bank interest rate = 12% (Khalil et al., 2018), *n*: lifetime = 90 years (Khalil et al., 2018).

The relative payback period between alternatives is calculated by drawing their cash flow lines as shown in Fig. 8. The intersection of these lines means that the difference between the initial cost value of the two alternatives "base model and Khalil's modified model" has been achieved, where the relative payback period will be determined from the line initiation to the intersection point.

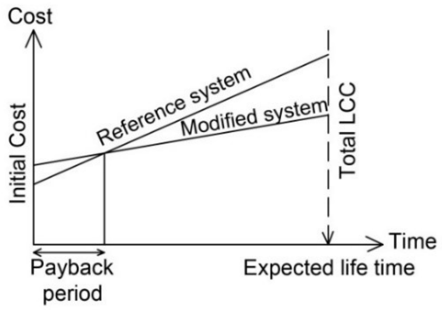


Fig. 8. Comparison between different systems to determine the payback period (Khalil et al., 2018)

4. Results and Discussion

This section discusses the energy simulation results for the suggested alternatives in comparison with the reference cases. Table 5 shows the results obtained by the simulation and calculation of the annual energy consumption (AEC) in Kwh/m^2, the percentage of reduction in the annual energy consumption (% AEC), discomfort hours per year (D.H.), the percentage of reduction in the annual discomfort hours (% D.H.), the initial cost in USD (I.C.), the percentage of reduction in the initial costs (% I.C.), the total life cycle cost (LCC) in USD, the percentage of reduction in the LCC (% LCC), and payback period (P.P.).

The base model represents the traditional building properties used in Egypt; therefore, its energy simulation results are set as a benchmark point "base case" for comparison. In addition, Khalil's model was also used for comparison as it was developed based on the same model. As shown in Table 5, Khalil's model reduced energy consumption by 48%, and thermal discomfort by 18.7%. However, the initial costs increased by 20.7%, and also the total life cycle costs were reduced by 32.1%.

Alternatives wall 1 and wall 2 proposed by this research significantly reduced the energy consumption by 62% with slight increase in the initial costs by 5.2% and 8%, respectively. Furthermore, the life cycle costs were reduced by 45.8% and 44.6%, respectively. However, the thermal discomfort hours have slightly reduced by 4.4% and 4.3%, respectively. Alternatives roof 1 and roof 2 have achieved a great reduction of the initial costs by 11.4% and 7.3%, respectively with a significant reduction of energy consumption by 56% and 55%. The total life cycle costs were reduced by 42.4% and 41.1%. However, the discomfort hours slightly reduced by 3.6% and 3.4%, respectively.

Table 5. Results of the simulation tests

Model name	AEC	%AEC	DH	% D.H.	I.C.	%IC	LCC	%LCC	PP
Base model	22.4	Base case	3271.85	Base case	37179.5	Base case	157228	Base case	Base case
Khalil's model	11.54	-48	2659.20	-18.7	44871.8	+20.7	106718	-32.1	12
Alternative wall 1	8.45	-62	3126.10	-4.4	39107.9	+5.2	85209	-45.8	3
Alternative wall 2	8.62	-62	3132.54	-4.3	40136.5	+8.0	87159	-44.6	5
Alternative roof 1	9.81	-56	3154.88	-3.6	32938.1	-11.4	90495	-42.4	0
Alternative roof 2	9.97	-55	3160.58	-3.4	34477.8	-7.3	92657	-41.1	0

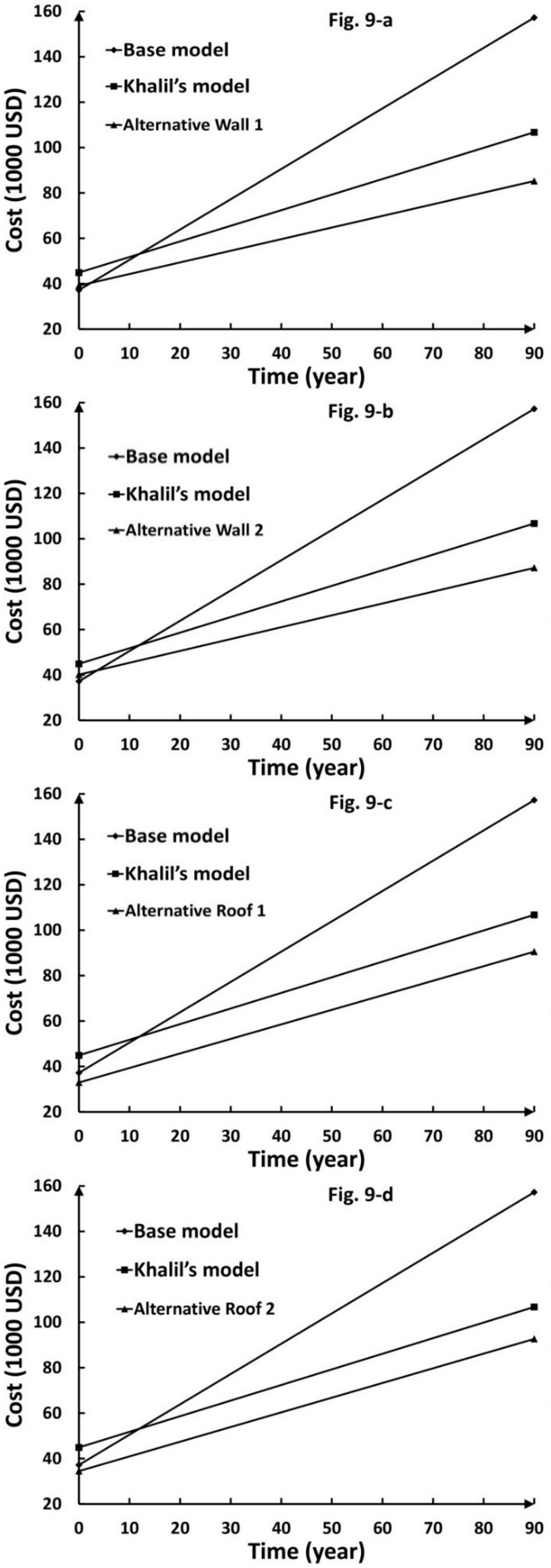


Fig. 9. Determination of the relative payback periods (adopted and modified from Khalil et al. (2018))

All proposed alternatives have higher energy saving percentage than Khalil's model. However, the discomfort reduction percentage is lower than Khalil's model. Also, the total LCC saving percentage of the proposed alternatives are higher than Khalil's model. Alternatives roof 1 and roof 2 have lower initial costs than the costs of the base model, but the initial costs of alternatives wall 1 and wall 2 are slightly higher than the initial costs of the base model. Both alternatives wall 1 and wall 2 have lower initial costs percentage than Khalil's model.

The relative payback periods of the proposed alternatives have shown much lower values than Khalil's model in comparison with the base model. While the relative payback period of Khalil's model is 12 years, the results show 3 and 5 years for alternatives wall 1 and wall 2, respectively, as shown in Fig. 9-a and 9-b. However, alternatives roof 1 and roof 2 have initial costs lower than the base and Khalil's models, so the relative payback periods are considered zero for the two alternatives as shown in Fig. 9-c and 9-d.

The base model used a wall thickness of 16.5 cm where the wall thickness of Khalil's model was 21.5 cm. The total thickness of alternatives wall 1 and 2 is 30 cm, which may explain the difference in the results of the AEC and the D.H. While the proposed wall alternatives are thicker but they still provide less I.C. and LCC. For the roof system, the base model used a roof thickness of 35 cm where the roof thickness in Khalil's model was 38 cm. The total thickness of alternatives roof 1 and 2 is 33 cm, which still gives lower values for all measures.

The wall and roof weights of the base model are 257.9 kg/m^2 and 718.2 kg/m^2 respectively where the wall and roof weight of Khalil's model were slightly higher 259.4 kg/m^2 and 719.7 kg/m^2 respectively. The proposed alternatives wall and roof have significantly reduced weight 205.4, 221.75, 499.85, and 516.45 kg/m^2 respectively, which is a quite important factor for design and construction purposes that gives an advantage to the proposed alternatives over the reference cases.

4.1. Discussion

From the above analysis, all proposed alternatives showed a significant reduction in energy consumption by up to 62%. However, for the discomfort hours the alternatives showed slight reduction by up to 4.4%. The total life cycle costs of all proposed alternatives were significantly reduced by up to 45.8%. While the initial costs increased by 5.2%, and 8% respectively for alternative wall 1 and wall 2, alternatives roof 1 and roof 2 have shown reduced initial costs by 11.4% and 7.3%, respectively. Alternative wall 2 has the maximum payback period of the proposed alternatives "5 years", followed by alternative wall 1 "3 years", and alternatives roof 1 and 2 have payback periods equals to zero. However, Khalil's model has the maximum payback periods "12 years", so all proposed alternatives significantly reduced the payback period compared to Khalil's model. One of the disadvantages of the proposed alternatives wall 1 and wall 2 is related to the wall thickness which is thicker than the reference cases. However, the total thickness of alternatives roof 1 and roof 2 is reasonable when compared with the reference cases. A key advantage of the proposed alternatives over the reference cases was approved as they are lighter in weight (reduction of 20.4%, 14%, 30.4%, and 28% respectively compared to the reference case). Although this study was implemented in Egypt, the study results could be achieved in different countries by adding such sustainable materials to the building envelope components.

5. Conclusion

Sustainability in buildings has been considered a key issue over the last decades in the construction industry. The need to use energy efficiently is increasing; thus, improving the thermal performance of buildings has acquired high importance. In this regard, through sustainable building envelopes, designers can achieve energy-efficiency, occupant satisfaction and cost-effective design. This study suggested four alternative building envelopes to minimize energy consumption, discomfort hours, initial costs, and life cycle costs for residential buildings. These alternatives are designed using local stone cladding materials "Marble and Limestone" and insulation material "Polyurethane-expanded and Extruded polystyrene (XPS) foam." The simulation tests were conducted through Design Builder software. The proposed alternatives showed a significant reduction in energy consumption by up to 62% and the total life cycle costs significantly reduced by up to 45.8%. A key conclusion from this study can then be drawn from the fact that sustainable materials can provide energy efficiency for building envelopes, and at the same time can provide lighter wall and roof elements and keep the initial cost, LCC and payback period down. There is a great deal of potential for future research in this research area as a selection of the best design combinations considering a wide range of the building envelope parameters (such as wall, roof, window to wall ratio, window type, etc.) by applying an optimization technique. In addition to evaluation of the embodied energy for building envelope materials during its raw material excavation, production, and its transportation.

References

Aktemur, C. and Atikol, U. (2017). Optimum insulation thickness for the exterior walls of buildings in Turkey based on different materials, energy sources and climate regions. *International Journal of Engineering Technologies*, 3(2), 72-82. https://doi.org/10.19072/ijet.307239.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), (2009). ASHRAE Handbook - Fundamentals (S.I. Edition).

Ascione, F., De-Masi, R. F., Santamouris, M., Ruggiero, S., and Vanoli, G. P. (2018). Experimental and numerical evaluations on the energy penalty of reflective roofs during the heating season for Mediterranean climate. *Energy*, 144, 178-199. DOI: 10.1016/j.energy.2017.12.018.

Asdrubali, F., D'Alessandro, F., Baldinelli, G., and Bianchi, F. (2014). Evaluating in situ thermal transmittance of green buildings masonries—A case study. *Case Studies in Construction Materials*, 1, 53-59. http://dx.doi.org/10.1016/j.cscm.2014.04.004.

ASHRAE Standard 55. (2004). Thermal Environmental Conditions for Human Occupancy. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, Atlanta.

Bevilacqua, P., Coma, J., Perez, G., Chocarro, C., Juarez, A., Sole, C., De-Simone, M., and Cabeza, L. F. (2015). Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. *Building and Environment*, 92, 305-316. http://dx.doi.org/10.1016/j.buildenv.2015.04.026.

Egyptian Electricity Holding Company Annual Report. (2018). *Ministry of electricity and energy Alexandria*. Retrieved 2020 from: http://www.moee.gov.eg/english_new/report.aspx/2018.pdf

Energy Information Administration. (2015). *International Energy Data and Analysis, Egypt Full Report*. Accessed on 20 March 2019 from: http://www.iberglobal.com/files/2016/egypt_eia.pdf June 2015.

Fuller, S. and Petersen, S. (1996). *Life-cycle costing manual for the federal energy management program*. Department of Commerce, USA.

Gagliano, A., De-Tommaso, M., Nocera, F., and Evola, G. (2015). A multi criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Building and Environment*, 90, 71-81. http://dx.doi.org/10.1016/j.buildenv.2015.02.043.

Guillen, I., Omez-Lozano, V. G., Fran, J. M., and Lopez-Jimenez, P. A. (2014). Thermal behavior analysis of different multilayer facade: numerical model versus experimental prototype. *Energy and Buildings*, 79, 184-190. http://dx.doi.org/10.1016/j.enbuild.2014.05.006.

Hanna, B. G. (2015). Energy analysis for new office buildings in Egypt. *International Journal of Science and Research (IJSR)*, 4(1), 554-560.

Ingrao, C., Scrucca, F., Tricase, C., and Asdrubali, F. (2016). A comparative life cycle assessment of external wall-compositions for cleaner construction solutions in buildings. *Journal of Cleaner Production*, 124, 283-298. DOI: 10.1016/j.jclepro.2016.02.112.

Kandil, A. I. and Selim, T. H. (2006). Characteristics of the marble industry in Egypt: structure, conduct, and performance. *International Business and Economics Research Journal (IBER)*, 5(3), 25-33. https://doi.org/10.19030/iber.v5i3.3466.

Khalil, A., Fikry, M., and Abdeaal, W. (2018). High technology or low technology for buildings envelopes in residential buildings in Egypt. *Alexandria Engineering Journal*, 57(4), 3779-3792. https://doi.org/10.1016/j.aej.2018.11.001.

Klemm, D. D. and Klemm, R. (2001). The building stones of ancient Egypt–a gift of its geology. *Journal of African Earth Sciences*, 33, 631-642. DOI: 10.1016/S0899-5362(01)00085-9.

Life Cycle Cost/ Parameters/Design Builder Website. Accessed on 10 March 2019 from https://www.DesignBuilder.co.uk/helpv4.7/Content/LCCParameters.htm.

Lin, Y. H., Tsai, K. T., Lin, M. D., and Yang, M. D. (2016). Design optimization of office building envelope configurations for energy conservation. *Applied Energy*, 171, 336–346. http://dx.doi.org/10.1016/j.apenergy.2016.03.018.

Mahmoud, S., Fahmy, M., Mahdy, M., Elwy, I., and Abdelalim, M. (2019). Comparative energy performance simulation for passive and conventional design: A case study in Cairo, Egypt. *Proceedings of 6th International Conference on Energy and Environmental Research (ICEER),* Aveiro University, Portugal. https://doi.org/10.1016/j.egyr.2019.09.052.

Mayhoub, M. G., Ibrahim, M. G., and El-Sayad, Z. T. (2019). Development of green building materials' evaluation criteria to achieve optimum building facade energy performance. *Proceedings of International Conference on Sustainable Energy Engineering and Application (ICSEEA)*.

Mohamed, H. I., Lee, J., and Chang, J. D. (2016). The effect of exterior and interior roof thermal radiation on buildings cooling energy. *Proceedings of International Conference on Sustainable Design, Engineering and*

Construction, Procedia Engineering, 145, 987–994. DOI: 10.1016/j.proeng.2016.04.128.

Nadia, S., Noureddine, S., Hichem, N., and Djamila, D. (2013). Experimental study of thermal performance and the contribution of plant-covered walls to the thermal behavior of building. *Energy Procedia*, 36, 995–1001. DOI:10.1016/j.egypro.2013.07.113.

Radhi, H., Sharples, S., Taleb, H., and Fahmy, M. (2017). Will cool roofs improve the thermal performance of our built environment? A study assessing roof systems in Bahrain. *Energy and Buildings*, 135, 324-337. http://dx.doi.org/10.1016/j.enbuild.2016.11.048.

Saber, H. H. and Maref, W. (2019). Energy performance of cool roofs followed by development of practical design tool. *Frontiers in Energy Research*, 7, Article No.122. DOI: 10.3389/fenrg.2019.00122.

Salandin, A. and Soler, D. (2018). Computing the minimum construction cost of a building's external wall taking into account its energy efficiency. *Journal of Computational and Applied Mathematics*, 338, 199-211. https://doi.org/10.1016/j.cam.2018.02.003.

Tang, M. and Zheng, X. (2019). Experimental study of the thermal performance of an extensive green roof on sunny summer days. *Applied Energy*, 242, 1010-1021. DOI:10.1016/j.apenergy.2019.03.153.

Tejedor, B., Casals, M., Gangolells, M., and Roca, X. (2017). Quantitative internal infrared thermography for determining in-situ thermal behaviour of façades. *Energy and Buildings*, 151, 187-197. DOI: 10.1016/j.enbuild.2017.06.040.

Zhao, M., Tabares-Velasco, P. C., Srebric, J., and Komameni, S. (2013). Comparison of green roof plants and substrates based on simulated green roof thermal performance with measured material properties. *Proceedings of 13th Conference of the International Building Performance Simulation Association, BS,* Chambery, France.

Prof. Ibrahim Motawa is a Professor of Construction Engineering and Management, Mansoura University, Egypt. Prof Motawa obtained his PhD from the School of Architecture, Building and Civil Engineering, Loughborough University, UK. He got his undergraduate degree in Civil Engineering and his Master degree in Structural Engineering. His research work covers the areas of: Building Information Modelling, Big data in construction, Construction Simulation and Optimisation, Modelling Complexity in the Built Environment, Energy Efficient Construction and Knowledge Management. Prof Motawa has been the principle investigator of research projects related to BIM development and energy efficiency in buildings, and has supervised many PhD students in related areas.

Asser Elsheikh is Assistant Professor, Department of Civil Engineering, Peoples' Friendship University of Russia (RUDN), Structural Engineering Department, Mansoura University. In 2015 he achieved his PhD degree in Moscow State University of Civil Engineering, Moscow, Russia. He received his BSc and MSc in Mansoura University (2000, 2005). He is author of 6 journal publications, and 6 papers in the proceedings of international conferences. He has research interests of: BIM, cost estimation, building materials, and construction project management.

Esraa Diab is Demonstrator at Building and Construction Engineering Department, Tanta Higher Institute for Engineering and Technology, El-Gharbia, Egypt. In 2016 she achieved BSc in Civil Engineering Department, Delta Higher Institute for Engineering and Technology, Mansoura, Egypt. She has research interests of BIM, energy efficiency in building, thermal comfort, life cycle cost, and building envelope elements design.