Thermal envelope retrofit: an assessment framework

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Abstract

Generally, energy consumption in buildings has increased in the last 10 years by almost 95%, and with existing stock that is expected to have a long life; sustainable improvements to buildings should extend to existing buildings as well as new builds; retrofit should be embraced by developing an integrated decision to assess existing buildings' conditions and to recommend an optimal set of sustainable retrofitting strategies.

Energy consumption in office buildings is one of the highest compared to other building types; with an annual consumption that ranges between 100 and 1000kWh/m^2 depending on geographic location, use, type of office equipment, type of envelope, use of HVAC systems and type of lighting. Several factors could reduce the energy consumption in offices; such as passive design, energy conservation plans, water management systems, controlled lighting systems, use of renewable energy, limited use of active air conditioning system and building envelope improvements. This paper aims at developing an assessment and retrofit strategy for improving the energy performance of offices with focus on the building's envelope which with careful design could reduce energy consumption and carbon footprint by up to 15%.

The paper starts by exploring the features of the building envelope, and how they impact energy consumption, in addition to suitable retrofit systems. Both envelope elements and retrofit systems formulate a framework; which is then applied to an office building in Alexandria, Egypt as a case-study.
Keywords: retrofit potential, energy consumption, existing office buildings, energy performance, building envelope.

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1 Introduction

Climate change has drawn the attention of many researchers to focus on the methods, framework and ideas of reducing the greenhouse gas emissions to achieve low carbon buildings. Necessity to reduce fossil fuel consumption and CO_2 emissions led to energy efficient improvements of existing buildings specially office buildings as they consume energy higher than other building types [1]. Retrofitting existing office buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions, which is considered as one of the main approaches to achieve sustainability on the built environment as well as achievement of low carbon buildings.

Recent research has covered different retrofit strategies for the whole office building such as "Passive retrofitting of office buildings to improve their performance and indoor environment: the OFFICE project" by Santamouris and Dascalaki [2] discussed 10 different office buildings in different climate zones and studied retrofit strategies for the whole office building to improve the energy performance and indoor working conditions. "Renovation of existing office buildings in regard to energy economy" by Çakmanus [3], also discussed the same topic but from a different point of view where 40% of energy consumption can be reduced and environment can be protected through reduction of CO_2 emissions when using energy efficiently in office buildings, an energy efficiency evaluation is done on the case study building and then a set of possible measures to increase the energy efficiency in the building are concluded. Also "A hybrid decision support system for sustainable office building renovation and energy performance improvement" by Juan *et al.* [4], develops an integrated decision support system to assess existing office building conditions and to recommend an optimal set of sustainable retrofit actions while considering the trade-offs between renovation cost, improved building quality and environmental impacts. Not many references discussed the retrofit strategies of the thermal envelope as an effective factor in office buildings. Only a few strategies are mentioned as a part of the whole building retrofit plan in the previous research. In this paper features of the building envelope are to be studied and how they impact energy consumption, and what are the suitable retrofit systems. Both envelope elements and retrofit systems formulate a framework; which is then applied to an office building in Alexandria-Egypt as a case-study using energy simulation software.

2 Building envelope features

The building envelope is the front line of the building's interface with the exterior environment and climate, it is important in maintaining desired interior comfort conditions for occupants; it consists of exterior walls, windows, roof, exterior doors and floors, and therefore it's a critical element in the energy performance of any building and vital to the performance of low to net zero energy buildings. Lighting, passive design and energy conservation affect the building envelope through several factors such as the daylighting and natural ventilation, Daylighting can impact heat gains, while the use of only artificial lighting and HVAC systems would lead to high energy consumption rates which in turn increases the carbon footprint of the building. The envelope separates the building from the surrounding environment, which highlights the importance of its thermal characteristics. The overall performance of the building envelope typically affects 15–30% of overall energy use [5].

The objective is to limit thermal losses during winter and thermal gains during summer; a building envelope designed considering light, heat and sound as a whole and carrying required performances can be called optimum building envelope which has visual, thermal and acoustical comfort for occupants.

The exterior environment can generate thermal energy loads within a building in all modes of heat transfer such as conduction, convection and radiation; thermal design is about controlling thermal loads at the perimeter, due to the exterior environment, and controlling the internal heat gain loads. The primary factors influencing thermal transmission are the temperature differences between the interior and exterior surfaces of the building envelope and the capability of the building envelope to resist thermal energy flow.

The overall thermal transfer value (OTTV) is an index for comparing the thermal performance of buildings. It measures the average heat gain into a building through the building envelope in order to reduce cooling loads for air conditioning systems used in buildings for energy conservation; it consists of three major components: conduction through opaque walls, conduction through window glass and solar radiation through window glass (Hui [6]).

The U-value for various assemblies in a building envelope is an important design factor in reducing the OTTV, thus the building envelope should be designed and constructed with low U-value for wall, roof, slab, glazing and door assemblies and other openings. It indicates the hourly rate of thermal energy transfer per unit square area of a thermal barrier per unit temperature difference.
The inverse of heat flow, or resistance to heat transfer, is expressed as an R-value, which measures thermal resistance; in addition to thermal transmittance properties of construction assemblies, the detailing of the building envelope and eliminating thermal bridging also plays a critical role in reducing heat flow through the envelope.

Any opening in a building's envelope including windows, doors and skylights can be called fenestration; it has always been regarded as the weak element in the building envelope due to its role in determining the energy balance of the building, at the same time cooling performance becomes a significant parameter for evaluating the energy performance of the buildings.

One of the major energy performance characteristics of fenestration products is the ability to control solar heat gain through glazing which is one of the most important factors in determining the air-conditioning load in commercial buildings; another important factor in glazing system design is the window-to-wall ratio (WWR) for the building, and its different orientations. The WWR needs to be no larger than necessary to provide the required level of daylight and natural ventilation. It should also be designed for quality views and connections to the outdoors, most of high energy performance buildings have WWR of 25%

to 35% (Hootman [7]). Building regulations in different countries and states also usually indicate ideal WWR for different orientations.

Solar radiation can cause excessive heating which reduces cooling requirements. When WWR reduction is not possible the use of shading devices might be a successful alternative in which it minimizes glare, where horizontal shading can be applied for south windows which can be also useful on the east and west windows; vertical louvers can be applied for east and west facing windows and can be used on north windows to block early morning and late afternoon low sun. Daylight is one of the most important strategies for net zero energy buildings because it can lead to substantial energy saving It is necessary to distribute the calculated area of glazing so that daylight can reach all parts of the room. Outside air enters the building through infiltration and ventilation, for mechanically ventilated commercial buildings reduction of infiltration and optimizing ventilation for fresh air requirements is an important strategy for low-energy and net zero energy buildings, as proper detailing can result in energy cost saving up to 36% for heating and cooling (Hootman [7]).

The integration of vegetation on buildings through vertical greening such as green facades and living walls allows obtaining a significant improvement of the building's efficiency and environmental benefits; measurements on a plant covered wall and a bare wall shows a temperature reduction at the green façade in a range of 2 to 6°C compared with the bare wall (Perini *et al*. [8]).

For the roofs; green roofs are important for the urban heat island effect, reduction used also to hold storm water and improve the insulation properties of a building, hence reducing annual energy consumption (Bell *et al*. [9]).

Also cool roofs or roof coatings that reflect the sun's energy instead of absorbing it is becoming a new energy standard, their effectiveness is determined by their high reflectance and high emittance.

3 Methodology

A literature review was conducted first to study the performance of existing office buildings and to set the factors affecting their energy consumption, international successful examples of retrofitting office buildings were studied in order to identify different retrofit strategies to be applied to the selected case study building where its energy-related behavior was studied through the information from the technical staff of the building. Energy simulation software was used for accurate calculation of energy consumption and in order to assess the effectiveness of proposed retrofitting scenarios aiming to improve their energy performance.

4 Case study

4.1 Building description

The office building (Petroleum Complex) is located in Alexandria, Egypt; it was designed in 1995 and construction in 2000 finished. The building consists of five floors; ground and 4 typical floors of a total construction area of 3370m^2, it's a free-standing building. Weather in Alexandria is Mediterranean, January and February are the coolest months with average daily maximum temperature ranging from 12ºC to 18ºC while July and August are the hottest months with average daily maximum temperature of 30ºC, average monthly relative humidity is 74%. The building uses central mechanical ventilation system, heating cooling and ventilation systems are used to acclimatize the indoor environment and to maintain indoor air quality. Cooling system is used mainly in summer according to the weather conditions, it's an air-cooled liquid chiller with heat recovery system and runs on electricity and heating systems are not used in winter. Comfort temperature range for offices is around 22ºC and for circulation spaces 20ºC. Number of occupants is 400 which operate on a twelve-hour basis during the weekdays, the building's typical working hours are from 5am till 5pm on the weekdays and is off on Friday and Saturday except for the control rooms which are on 24 hours all week. The main building structure is made of reinforced concrete. Elevations are mainly made up of curtain walls of blue double glazed 80% reflective glazing which consists of aluminum frames. Also there is a skylight above the main court in the building which is single glazed; the roof is 20cm flat insulated roof. The interior space layout is an open plan, consists of 4 wings connected through 4 main corridors, having a big court in the middle where the offices are located on the perimeter of the building with secondary double loaded corridors (Figure 1).

The monthly energy bills of the building indicate an average consumption of 157584 kWh with highest consumption of 169585 kWh is recorded in August and the lowest is 110623 kWh in January.

4.2 Building envelope energy audit and possible retrofits

Based on example analysis and literature review, Table 1 is derived to help in the audit of building envelopes and their retrofit strategies. The table is split into five sections; wall insulation, floor insulation, roof insulation, fenestration, and orientation showing different retrofit strategies possible. The building uses mechanical ventilation so natural ventilation is not used; the building is a tilted rectangle of dimensions 60m x 67m and height 20m, all elevations are unshaded externally with large area of fixed curtain walls which lead to heat gains increasing the use of mechanical ventilation. Tinted glazing leads to inefficient use of daylighting, where inner set of offices only get very poor daylight from the skylight as they overlook the court in the middle of the plan, internal shading devices (blinds) are installed in all offices, operable from inside of each office and are used frequently by occupants to avoid in sun subject façades.

Exterior walls are not insulated, they consist of a 20cm brick wall, 2cm interior and exterior paint which has a total u-value of 1.5 W/m^{2}K. DesignBuilder software was used to identify the u-value of different thermal elements of the building. WWR in all elevations is 80% except for the north and north west elevations are 90% of blue double glazed curtain walls with a u-value of 2.7 W/m^{2}K. For each façade; the area of unshaded windows exposed to direct sunlight in the north-east elevation is 880m^2, the north-west is 1098m^2, the

Table 1: Possible retrofit strategies.

Factor affecting Carbon Footprint of building				Possible Retrofit Strategies
	BUILDING ENVELOPE	Wall insulation	interior walls	Adding insulation to interior walls
			External walls	Adding insulation layers to the building exterior
				Spray-in-place foam insulation
				Wall colors and shading
		floor insulation	solid ground insulation	Insulation above slab with reinforced screed above
				Raised floor with rigid or non-rigid insulation
			intermediate floors	Replacing slab with rigid insulation beneath
				Applying insulation to the inderside of the floor
				Remove deck and apply semi-rigid insulation between joists.,
		Roof insulation	Roof	Addition of insulation
				Replacing existing roof
				Cool roof coating
				Addition of green roof
				Addition of roof ponds
				Addition of building integrated photovoltaics
		fenestration retrofit	Windows	Introducing new shading or light-shelves
				Using interpane shading (roller blinds within the glazing)
				Internal shading
				Building integrated photovoltaics for shading or glazing
				Replacing the window glazing
				Adding suspended film to existing window
				Replacing the window frames
			External doors	Replacing the exiting doors
			Daylight	more light integration to the building
			Natural Ventilation	Operable panes for ventilation

Table 1: Continued.

Factor affecting Carbon Footprint of building				Possible Retrofit Strategies
	BUILDING ENVELOPE	Orientation	North	Blocking the openings in the wrong orientation and wrong WWR
			South	
			East	
			West	
			N/E	
			N/W	
			S/E	
			S/W	

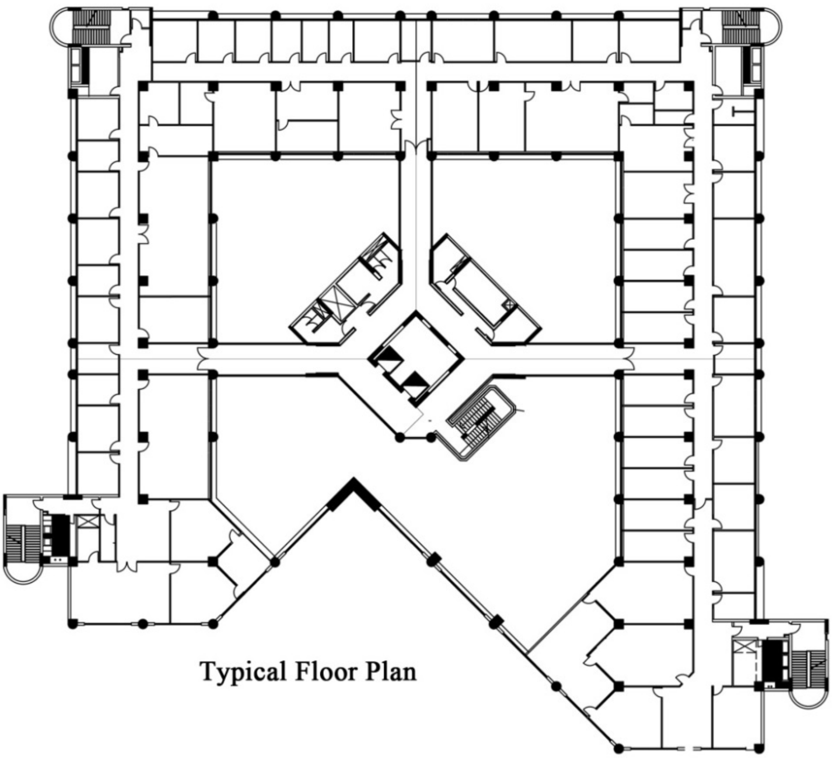

Figure 1: Typical floor plan of the case study building.

south-west is 1072m^2 and the south-east is 960m^2. The total area of exposed windows is 4010m^2. Conventional roofs are installed to the building, with single glazed skylight. 3130m^2 roof assembly consists of 20cm reinforced concrete roof, interior paint and insulation material having a u-value of 0.5 W/m^{2}K. Area of skylight is 240m^2 with a u-value of 3.7 W/m^{2}K located on top of the atrium on the four corners of the building. Throughout the building's envelope audit, critical energy factors are identified, accordingly improvements that could be carried out will be applied in the energy simulation program for assessment. For daylight enhancement, blue double glazing could be replaced with clear double or triple glazing, and insulated window frames could be used, external wall insulation can be applied as well to the building, spray-in-place foam can help reduce infiltration through the building cracks; according to the Egyptian code for improvement of energy efficiency usage in buildings, the WWR should be no more than 30% specially in the south-west and south-east elevations where the existing WWR is 80%; thus reducing some of the windows might help reduce heat gains, also external shading devices could be added to reduce glare, for south-west and south-east elevations horizontal louvers can be added and for the north-east elevation vertical louvers can be added. Green roofs can be added to the conventional roof already existing to improve the roof's u-value to 0.3 W/m^{2}K.

4.3 Building envelope simulation

The energy consumption is calculated through energy simulation program (DesignBuilder) and the readings of monthly energy consumption are used for verification. The model was run on a 64-bit laptop with an Intel Core i5 processor, simulation of a monthly energy consumption result took around 8 minutes; this allowed running the model repeatedly as required for error checking throughout the development process and the incremental development; after the initial model development, the model was thoroughly checked for errors until the simulations gave realistic results.

The simulation model is divided into several blocks representing each floor, which are then divided into four zones where each zone represents an elevation. Because HVAC is outside the scope of this research, mechanical cooling is not changed and set to 20ºC in summer and 22ºC in winter and circulation corridors are set to 20°C all year.

A whole year has been calculated for the base case model and the results were compared to energy bills (Figure 2).

Incremental improvements are applied to the building according to energy audit (Table 1), in which the most applicable strategies to reduce the energy consumption of the building in a retrofit are applied. The incremental improvements simulations are calculated in the summer month (August) as this month has the highest temperature and heat gains as well. Incremental improvements are applied to the building in which the most applicable strategies to reduce the energy consumption of the building in a retrofit are applied. Three upgrades were conducted; upgrade case A; WWR adjustments (to accommodate the requirements of the Egyptian code for improvement of energy efficiency

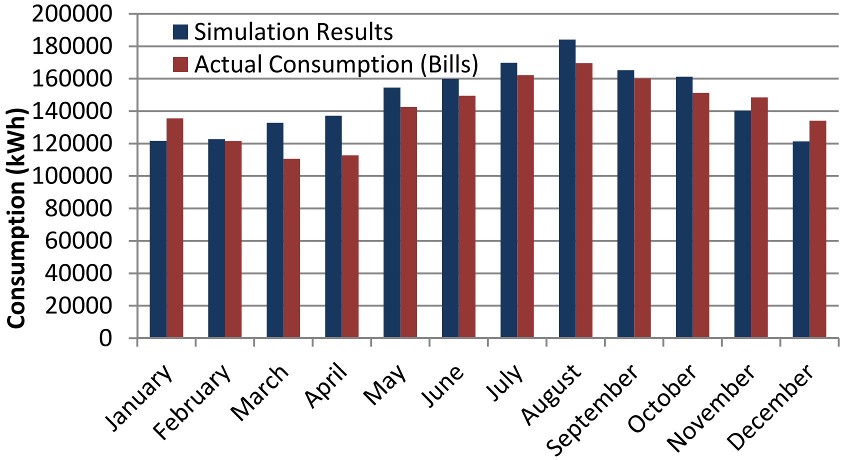

Figure 2: Simulation and actual consumption monthly results of case study building.

usage in buildings) in which the WWR of the building facades are changed to 30% for all elevations except for the north elevation which was kept as it is.

Upgrade case B; following the WWR improvements comes the improvement to the thermal characteristics of the building envelop improve its u-value through the addition of 20cm insulation to external walls, also glazing was changed to triple glazed clear with argon fill instead of blue double glazing with air fill as well as green roof.

Upgrade case C; addition of external fixed shading devices was applied; 0.3m horizontal louvers were applied to the building elevations.

All shading design was conducted to calculations by using the following equation, where sizing overhangs and fins can be determined, also calculating depth required for shading element or extent of shadow cast by shading element with a given depth (Eqn. (1).

$$\mathbf{h} = \frac{\mathbf{D}\times \mathbf{tan}\,(\mathbf{solar\ altitude})}{\mathbf{cos}\,(\mathbf{solarazimuth} - \mathbf{window\ azimuth})\pm} \tag{1}$$

4.4 Results

As a result of the analysis on the energy consumption reduction the lower the WWR, the less the exposure, heat gains and the less the chiller consumption as the cooling becomes more efficient which reduces the energy loads and consumption by 24662 kWh which is equivalent to 13%. This retrofit strategy was the most effective compared to the other strategies applied to the building and resulted in great reductions.

The improvement of the u-value of the skin (insulating walls, replacing window glazing and addition of green roof) was not as effective as the WWR improvement in case A yet reduction was 3838kWh which is a further reduction of 2.5% of the total consumption, 20cm insulation was added to the walls, window glazing replaced to triple glazed clear argon fill 3mm and the green roof was installed above the conventional roof; also the addition of external shading resulted in reduction of 4938kWh which is 3% reduction of the total consumption in addition to previous reductions in case B (Figure 3).

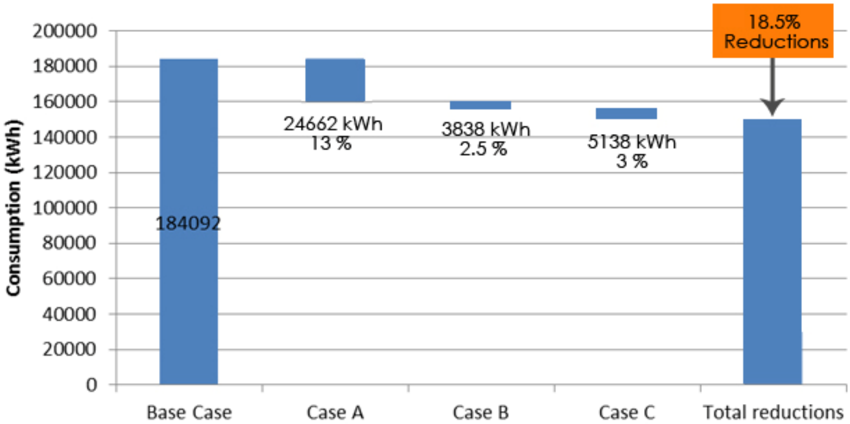

Figure 3: Detailed accumulative reductions.

5 Conclusion

The research investigated the auditing of the energy impact of different aspects of the building envelope, which was concluded from a literature review which studied several factors affecting the building envelope energy performance of the existing buildings. The factors affecting building envelope performance and possible retrofit strategies concluded in Table 1 were then conducted in the case study building energy simulation.

Three cases were studied; the base case which is the existing case, case A which is the window to wall ratio adjustment, case B is the improvement of the u-value of the building skin and case C is addition of shading devices to the building. As a result of the analysis on the energy consumption reduction; the lower the window to wall ratio, the less the exposure, heat gains and the less the chiller consumption as the cooling becomes more efficient which reduced the energy loads and consumption by 13%. This retrofit strategy was the most effective compared to the other strategies applied to the building and resulted in great reductions, this percentage is also variable depending on the building size where the size of this building could respond to several retrofit strategies and a larger building could just need one retrofit strategy.

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