# Life Cycle Optimisation Study for Retrofitting an Archetype Building in New Cities in Egypt

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## Abstract

This study aims to assess the potential environmental and economic benefits of retrofitting a residential archetype building under different scenarios. The study uses life cycle performance approaches to carry on a retrofitting scenario for an attached villa archetype in new cities in Egypt. After identifying three levels of energy retrofit measures (ERMs), a multi-objective optimisation framework was developed and carried out upon the case study model to optimise the Life Cycle Cost (LCC) and the Life Cycle Carbon Footprint (LCCF). The results of the study presented 4 different retrofitting scenarios with various investment costs and significantly improved operational costs and emissions.

## Highlights

- Develop retrofitting optimisation framework to minimise residential buildings LCC and LCCF.
- Layout guidelines for retrofitting the residential building stock in new cities in Egypt under different scenarios.

## Introduction

Egypt has unveiled its “National Strategy for Climate Change 2050”, intending to increase the share of renewables in its power generation to 42% to mitigate carbon emissions levels by 2035. However, given the robust growth of the building stock, not enough research addressed the economic and environmental benefits of retrofitting the residential building stock, especially in the new cities stock which is relatively new construction and has a longer life cycle than the rest of the stock.

More than 50% of the residential building stock in Egypt has been built in the last 20 years. In comparison, this percentage is much lower in developed European countries where the average percentage is around 10% **(Figure 1)**. This robust growth shows significant potential for assessing the energy performance of the new cities’ building stock, which provides several advantages to be selected as a research focus for the development of this study:

- Represents the largest segment of the national building stock, and consequently has a significant impact on national energy consumption and emissions.
- Have higher applicability for retrofitting interventions (Relatively new materials and no conservation areas).
- Relatively new construction and have a longer life cycle than the rest of the stock, hence, will impact long-term savings potential.

*Figure 1- Percentage of the dwellings built post-2000 in Egypt and European countries. (Source: CAPMAS, 2017 and EUROSTAT, EU-SILC 2015)*

Developing a retrofitting framework for this newly built stock can help mitigate the overall energy consumption and emissions in Egypt. It will also act as a key tool for decision-makers and stakeholders in Egypt, informing them about the energy-saving and cost-saving potential of the building stock. The framework can also help policy developers and building scientists to identify suitable energy-efficient and low-carbon scenarios for the various categories of Egypt’s housing archetypes. It can also provide guidelines for the Egyptian building codes and help in formulating new legislation for retrofitting existing building stock.

## Background

### The potential of retrofitting strategies for the building stock

The retrofit of existing buildings through the application of energy efficiency measures has gained increasing interest in the last few years, showing the high potential of reducing energy consumption and greenhouse gas emissions. Wilson et al. (2018) stated that implementing energy-efficient retrofits can save up to 50% of the households' energy, with the consideration of the policies that support decision-making. As part of this, many countries and international organizations have put significant effort to improve the energy efficiency of existing residential building stock. For example, the UK government planned in 2010 to upgrade 7 million homes by 2020 to improve energy efficiency and reduce carbon emissions by 29%.

However, in Egypt, no studies have addressed retrofitting the building stock in a holistic approach. Only a few theoretical studies addressing the retrofit of single buildings in Egypt have been found in the literature as in (Albadry, et al. 2017) and (Edeisy & Cecere, 2017).

### Building retrofit technologies

Assessing building energy performance via retrofitting can be addressed through several approaches and technologies. Ma, et al. (2012) categorised the major retrofit technology types into three main groups: demand-side management, supply-side management, and change of energy consumption patterns. These retrofit measures can also be found in the literature in an alternative classification, Chen et al., (2020) identified the technologies that reduce demand for heating and cooling as passive measures, while the low energy technologies as active measures, and the supply side as renewable energy measures.

Several studies utilised the method of using passive measures of retrofitting the building envelope in the literature to reduce the heating and cooling demand and improve indoor comfort in residential buildings. Saikia et al. (2020) proposed a methodology to minimise the heat gain in hot Indian climate with multi-retrofit building envelopes. The study concluded that optimizing the building envelope can reduce the heat gain to up to 33.5% as well as reducing the electricity consumption. Casquero-Modrego & Goñi-Modrego (2019) applied several envelope retrofit measures on an existing affordable house in Spain to minimise energy consumption and adjust indoor comfort. The study showed that adding horizontal and vertical insulation to the envelope can improve the indoor temperature during the winter season. Wu et al. (2017) applied a multi-objective optimisation method to a selection of residential buildings in Zernez, Switzerland to retrofit the building envelope. The study showed that with sufficient insulation, heating energy standards could be reached for most buildings in the study. However, the study also showed that high retrofit cost plays an important role in decision-making to retrofit the whole measures or partially some of the measures.

Using energy-efficient equipment and technologies also shows promising retrofitting potential for residential buildings, especially for the cooling loads in hot-arid zones. Krarti et al. (2020) proposed several passive and active retrofit measures to evaluate energy retrofit programs for the residential building stock in Saudi Arabia, the study suggested that upgrading the lighting system, using efficient equipment, increasing the cooling setpoints, and upgrading the HVAC systems could potentially save more than 60 TWh/year for the annual electricity consumption of the Saudi building stock. Also, Chen et al. (2020) used several energy-efficient measures in retrofitting a building in Norway. The study showed that adding a heat recovery system, adding a setpoint temperature sensor, and using an efficient lighting device can potentially save between 24% and 39% of the total electricity consumption of the building.

### Multi-objective optimisation for building retrofitting

The utilisation of computational optimisation in building retrofitting involves a search process through a wide range of options to determine an optional solution or set of solutions (Tian, et al. 2015). The optimisation problem can be defined by the objectives that require minimisation or maximisation, resulting in two main types of optimisation: mono-objective optimisation, which targets one objective, and multi-objective optimisation (MOO) which optimises two or more objectives. Over the years, many optimisation algorithms with different approaches have been developed to target the optimisation process. By reviewing more than 200 building optimisation studies, Nguyen et al., (2014) showed that the Genetic Algorithm (GA) is the most widely used optimisation algorithm. The review also showed that the Non-Sorting Genetic Algorithm (NSGA-II) can achieve more accurate results, faster, and more efficiently than other GAs.

## Methods

### Development of the Retrofitting Computational Framework

This study aims to formulate a modelling framework that tests the use of optimisation methods to find the optimal scenarios for retrofitting the existing residential building stock in new cities. The implementation of this part is illustrated in **Figure 2** and shall be carried on through the following steps.

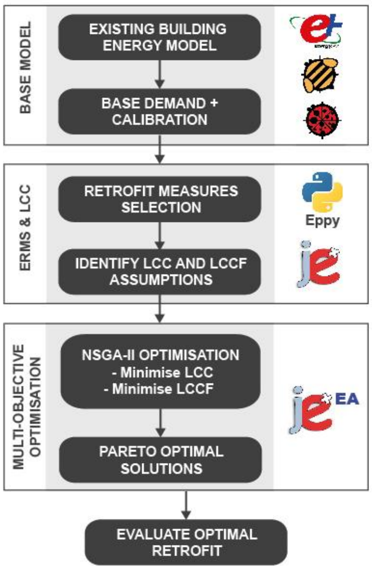

*Figure 2- Retrofit Framework*

### Selection of case study building

Abdelaziz (2021) developed a building stock model for the new cities in Egypt and classified it into three main categories: Private apartment housing, social apartment housing, and private villa housing, with three main attachments: Detached, Semi-attached, and Terraced (attached). This study is part of an ongoing research, so to confine the research area, the attached villa archetype was selected to carry on this study.

To validate the retrofitting framework, an existing reference building that represents this archetype was selected. Building characteristics were identified, and then a detailed energy model was developed and calibrated using electricity bills to identify the energy consumption profile for the baseline model.

### Energy retrofit measures (ERMs)

Responding to the energy consumption profile of the dwellings and the percentage of consumption for each element (e.g. Cooling, Hot water, etc.), several ERMs were selected to formulate the combinations of retrofit scenarios. These ERMs were selected in alignment with the current building regulations and energy codes in Egypt (HBRC, 2006). Three levels of ERMs were identified to be utilised in the optimisation framework: Passive, Active, and Renewable ERMs.

- Passive ERMs include retrofit measures for the existing building envelope, such as insulating external walls and roofs, upgrading existing windows, etc.
- Active ERMs include upgrading the building systems and utilising energy-efficient equipment and control systems to reduce energy consumption, such as the installation of an efficient lighting system, upgrading HVAC systems, etc.
- Renewable ERMs include the utilisation of renewable energy systems, such as solar PV cells to supply energy for the building.

### Optimisation Scope

In this step, the parameters and objectives of the optimisation were defined. A Multi-objective optimisation framework was applied using Genetic Algorithms (NSGA-II) upon the case study model to optimise its Life Cycle Cost (LCC) and Life Cycle Carbon Footprint (LCCF). The evaluation of the LCC and LCCF was carried out following the standard BS EN 15459-1:2017 (ISO, 2017) and EN 15978:2011 (BSI, 2011) respectively. Once the energy consumption and LCC of the optimal designs were found, a comparative analysis was carried out between the Pareto optimal models of the optimisation to validate the results of the retrofitting scenarios applied, and to identify the impact of the ERMs on the LCC and LCCF. Finally, the overall best solutions were identified and assessed to lay out a set of recommendations for retrofitting residential buildings in Egypt.

## Retrofitting model for villa archetype

This study aims to examine the potential of using optimisation methods to find the optimum retrofitting scenario. This was carried on by optimising one of the developed archetype models, the attached villa.

This process involved four main steps. Firstly, a baseline demand model for the existing archetype was simulated to estimate the building energy performance and identify the energy demand by element. then the energy model was calibrated using measured electricity bills. Thirdly, several retrofit measures were identified. Finally, a multi-objective optimisation was utilised using NSGA-II simulations to minimise the LCC and LCCF under 4 main different scenarios.

### Baseline demand model

An existing attached Villa in Sheikh Zayed City, Giza was selected as a case study for this research. A thorough field survey, monitoring, and an occupant's questionnaire were conducted for the building to define the building characteristic and energy model inputs. Then a baseline energy model was developed and simulated for the existing building using EnergyPlus to estimate the monthly electricity demand, operational $CO_2$ emissions, and monthly electricity bills. **Figure 3** shows the floor plans for the archetype and **Table 1** shows the building characteristics utilised for the model.

The total floor area of the dwelling is 258 m$^2$, and around 142 m$^2$ (55%) of the area is conditioned with split AC cooling units (Reception area on the ground floor and 3 bedrooms and living room on the first floor).

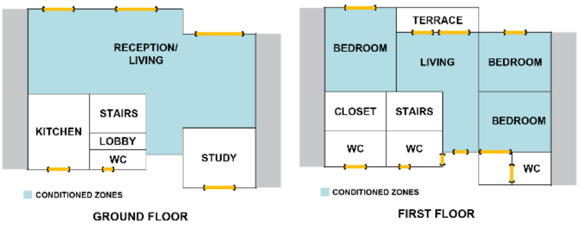

*Figure 3- Existing Mid-Terraced Villa Layouts. Conditioned zones are marked in blue.*

*Table 1- Baseline energy model characterization.*

| | |
|---|---|
| **Orientation** | Azimuth = 4° |
| **Wall Construction** | U-Value = 2.04 W/m$^2$ K |
| **Roof Construction** | U-Value = 3.55 W/m$^2$ K |
| **Floor Construction** | U-Value = 5.45 W/m$^2$ K |
| **Glazing** | U-Value = 5.78 W/m$^2$ K, SHGC = 0.9 |
| | Single Clear + Aluminium frames |
| **Window-to-Wall Ratio** | 15 - 20% |
| **Air Infiltration** | 0.7 ACH |
| **Lighting Power** | 5.0 W/m$^2$ |
| **Equipment** | 4.0 W/m$^2$ |
| **Cooling System** | Split DX HVAC - Cooling only |
| **Cooling CoP/EER** | CoP = 3.0/ EER = 10.23 |
| **Cooling Setpoint** | 23 °C |
| **Heating System** | Electric Coil Heater |
| **Domestic Hot Water** | Electric Heater |

**Figure 4** shows the monthly electricity demand by element in comparison to the measured monthly bills. The results showed that the electricity demand and bills peak in the summer season due to cooling loads, reaching the highest result in August with 1600 kWh. The annual simulated electricity demand for each element was as follows: Cooling 28.5%, Water Heating, 30.8%, Equipment 20.3%, Lighting 16.9%, and Heating 3.5%. The annual electricity intensity resulted in 53.7 kWh/m$^2$, while the annual $CO_2$ emissions intensity resulted in 33.6 kg$CO_2$/m$^2$.

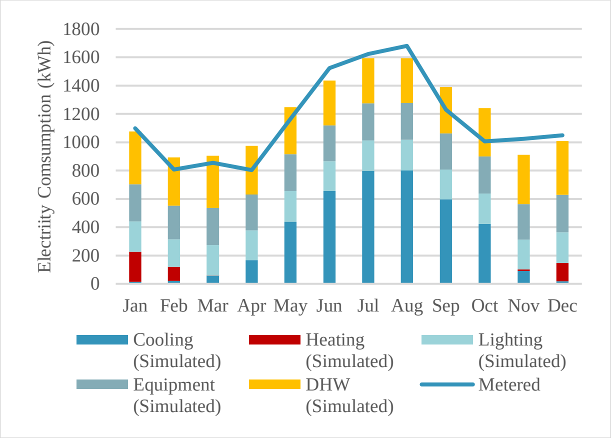

*Figure 4- Monthly simulated and measured electricity consumption. (Readings are an average of 2 years of bills)*

### Energy model calibration

To increase the accuracy of the building's performance, the energy model of the building underwent a calibration process based on measured monthly electricity bills for 2 years (March 2021 – February 2023). The calibration was performed following the (ASHRAE 14, 2014) guideline for energy model calibration. This guideline employs two main criteria, Coefficient of Variation of the Root Mean Square Error CV (RMSE) and Mean Bias Error (MBE).

$$CV(RMSE) = \frac{1}{m}\frac{\sum_{i=1}^{Np}(m_i - s_i)^2}{Np}\ \% \qquad \textbf{(1)}$$

$$MBE = \frac{\sum_{i=1}^{Np}(m_i - s_i)}{\sum_{i=1}^{Np}(m_i)}\ \% \qquad \textbf{(2)}$$

$m_i, s_i$ = The measured and simulated data, respectively.

$i$ = Time interval

$Np$ = Total number of data values (24 months)

$m$ = Average of the measured data

The (ASHRAE 14, 2014) guideline states that for a simulation model to be deemed calibrated, its CV (RMSE) should not exceed 15% and its MBE should not exceed 5%, when monthly data is utilised for calibration.

The two indices were calculated with a result value of 9.9% for the CV (RMSE) and 0.46% for the MBE, where both values are less than the required ASHRAE benchmarks.

### Identification of retrofit measures

After simulating the base demand model for the building, three levels of ERMs were identified to be utilised in the optimisation framework: passive, active, and renewable energy measures. Based on the building energy consumption condition, 6 passive ERMs, 3 active ERMs, and 1 renewable ERM have been defined. **Table 2** shows the technical specifications along with costs and carbon emissions for the selected ERMs. Passive ERMs were selected according to the recommended technical specifications of the Egyptian energy code for residential buildings in the Cairo and Delta Regions (HBRC, 2006), while active and renewable ERMs were selected according to the available efficient products in the Egyptian market. Product costs were obtained from the Egyptian construction prices report which is published monthly by the Ministry of Housing (MHUC, 2023).

Glazing (SGR – DGR – TGR): The existing windows in the building are single clear glazing with an average U-value of 5.78 W/m$^2$·K. According to the Egyptian standard code of energy (HBRC, 2006), the U-value of the glazing for all orientations should not exceed 2.5 W/m$^2$·K. The study suggests five glazing replacements: Single tinted and reflected glazing, Double glazing with U-value 2.89 W/m$^2$·K, and Triple glazing with U-value 0.99 W/m$^2$·K.

Shading system (OH): The study suggests adding overhangs over southern windows to mitigate direct solar radiations on fenestrations with depths varying from 0.4 to 1.2 meters.

Roof insulation (R-EPS – R-XPS – R-RW): The existing roof construction in the building has an average U-value of 3.55 W/m$^2$·K with no insulation. However, (HBRC, 2006) recommends that the average U-value for the roof should not exceed 0.37 W/m$^2$·K. The study suggests three different insulation materials upgrade for the roof: adding 10mm to 150mm of EPS, XPS, or Rockwool insulation.

Wall insulation (W-EPS – W-XPS – W-RW): The existing wall construction consists of 250mm medium-weight red brick blocks with an average U-value of 2.04 W/m$^2$.K with no insulation. (HBRC, 2006) recommends that the average U-value for the walls should be 1.25, 0.71, 0.71, and 1.11 W/m$^2$.K for North, East, West, and South orientations respectively. The study suggests three insulation upgrades for the exterior walls: adding 10mm to 150mm of EPS, XPS, or Rockwool insulation.

Airtightness (AT): The study suggests adding an EPDM rubber membrane on window cracks and thermal bridges to reduce the air infiltration rate from 0.7 ACH to 0.35 ACH.

HVAC system (AC): the existing air conditioning system used is split units for cooling 2 living spaces and 3 bedrooms. The current cooling coefficient of performance (CoP) and energy efficiency ratio (EER) are 3.0 and 10.23 respectively. The study suggests replacing the current units with efficient inverter AC split units with CoP of 5.3 and EER of 18.

Setpoint control (STP): Adding a smart indoor thermostat with a constant indoor temperature of 24 °C to 26 °C during the summer cooling season.

Efficient lighting (EL): replace current CFL light bulbs with efficient LED dimming lights with an intensity of 2.5 W/m$^2$ which can achieve energy saving by around 50%.

Photovoltaic Cells (PV): Benefiting from the high solar radiation in Egypt, the roof of the building can be equipped with a PV system. The total area available for installation is 24m$^2$.

This area can provide a system with 5kW power distributed to 3 rows of panels with 3 series panels in each row. The power of each panel is 580 W with 22% efficiency. With a tilt angle of 23° and an azimuth of 180° from the north.

*Table 2- ERMs associated with technical specifications, costs, and emissions.*

| **ERMs** | | | **Technical Specification** | **Unit** | **Cost/Unit (USD)** (1) | **kgCO2/kg** (2) |
|---|---|---|---|---|---|---|
| **Passive** | Glazing Retrofit | SGR - Single Glazing | Tinted, Reflective Glass | Sqm. | 10 | 25 |
| | | DGR - Double Glazing | U = 2.89 W/m²·K | Sqm. | 65 | 110 |
| | | TGR - Triple Glazing | U = 0.99 W/m²·K | Sqm. | 82 | 130 |
| | Shading | OH - Adding Overhangs | Depth = 0.2, 0.3,.., 1.2m | Sqm. | 33 | 45.9 |
| | Roof Insulation | R-EPS - EPS Insulation | 10mm -150mm | $m^3$ | 69 | 2.5 |
| | | R-XPS - XPS Insulation | 10mm -150mm | $m^3$ | 79 | 2.88 |
| | | R-RW - Rockwool Insulation | 50mm -150mm | $m^3$ | 59 | 1.05 |
| | Wall Insulation | W-EPS - EPS Insulation | 10mm -150mm | $m^3$ | 69 | 2.5 |
| | | W-XPS - XPS Insulation | 10mm -150mm | $m^3$ | 79 | 2.88 |
| | | W-RW - Rockwool Insulation | 50mm -150mm | $m^3$ | 59 | 1.05 |
| | Air Tightness | AT – Seal with EPDM membrane | 0.35 ac/h | m | 6.5 | -- |
| **Active** | HVAC | AC - Replace the Cooling System | CoP = 5.3, EER = 18 | All Units | 3,950 | 500 / Unit |
| | | STP - Cooling Setpoints | Setpoint = 24 -26 °C | Unit / AC | 100 | - |
| | Lighting | EL - Efficient Lighting | LED lighting 2.5 W/m² | Total System | 329 | -- |
| **Renew.** | PV Cells | PV - Integrated Photovoltaics | A = 24 m², Tilt angle = 23, Efficiency= 22% | Watt | 0.5 | 2450 / kWp |

* Rate of exchange USD to EGP = 30.40

(1) Egyptian construction prices (MHUC, 2023) (2) Inventory of Carbon and Emissions (Geoff Hammond, 2008)

### LCC and LCCF: calculation and assumptions

Life cycle cost (LCC) was conducted as an objective in the optimisation process to analyse which scenario offers the most profit. LCC(τ) refers to the life cycle cost with a study period $T_c$ **(Equation 3)**, this was calculated by taking the sum of the initial replacement cost of the ERMs $C_{init}$ and the annual operational, maintenance, and replacement costs $C_o$ and $C_m$ , $C_r$ respectively for different ERMs combinations $j$ . The calculation period set for this study is 30 years.

Because the LCC includes cash flows and costs taking place at various periods of the life cycle of the dwelling, all those costs must be converted to their present values. This allows for the comparison of the calculated LCC based on the current value of money (Salem, et al. 2019).

Net present value (NPV) is split into costs (operational costs) and savings that result from the initial investment. The NPV for the operational costs was used to calculate the LCC of each scenario, this is the sum of all annual operating, maintenance, and replacement costs affected by an annual discount rate $(\alpha)$ and annual energy price increase rate $(I_e)$ **(Equation 3)**.

NPV for savings was utilised in this study as an index for the return on investment as it considers the change in prices caused by inflation. NPV for the savings is the sum of the annual bills' savings $S_i$, caused by the initial investment cost in each retrofit combination, affected by the annual discount rate $\alpha$. Then the initial investment cost is subtracted from this value. A positive result indicates a worthy return on investment **(Equation 4)**.

Several studies use the payback period as an indicator of a worthy investment. However, the payback period does not consider the change in prices and thus does not present a realistic assessment.

The LCCF conducted in this study includes the emissions resulting from the Cradle to Gate only. Thus, estimating emissions due to overall building materials production, manufacturing, and transport to the site, emissions due to construction works on site, in addition to emissions through the operational stage of the building (lighting, space cooling, etc.) **(Equation 5)** Inventory of Carbon and Emissions (Geoff Hammond, 2008) was used as main source for carbon emission values for each ERM.

$$LCC = C_{init} + \sum_{i=1}^{T_c} \frac{C_{o,i} \times (1+I_e)^i}{(1+\alpha)^i} + \frac{C_{m,i} + C_{r,i}}{(1+\alpha)^i}(j) \qquad \textbf{(3)}$$

$LCC$ = Life cycle cost (USD/m²/y)

$i$ = Year

$j$ = Combination model number

$C_{init}$= Initial investment (replacement cost)

$C_o$= Annual operational cost (Electricity bills)

$C_m, C_r$= Maintenance and replacement costs

$I_e$ = Annual increase in electricity prices

$$NPV_{T_c} = \sum_{i=1}^{T_c} \frac{S_i}{(1+\alpha)^i}(j) - \mathrm{C}_{init} \qquad \textbf{(4)}$$

$NPV_{T_c}$= Net present value of the analysis period savings

$S_i$ = Annual savings (Difference in operational costs current baseline model combination model $j$)

$\alpha$ = Discount rate

$$LCCF_i = E_p + E_t + E_c + \sum_{i=0}^{T_c} E_o \qquad \textbf{(5)}$$

LCCF = Life Cycle Carbon Footprint (kgCO$_2$/m$^2$/y)

$j$ = Combination model number

$E_p + E_t$ = Materials production, manufacturing, and transport to the site

$E_c$ = Emissions due to construction works on site

$E_o$ = Operational Emissions

*Table 3- LCC and LCCF Stage Data Source and References*

| | |
|---|---|
| Life cycle study period | 30 years |
| Annual energy cost increase | 10% (1) |
| Discount rate (for NPV calculation) | 3% (2) |
| Electricity emission rates | 0.628 kgCO$_2$/kWh (3) |
| Electricity cost (Based on the average of Egyptian tariff tiers) | \$0.06/kWh (1) |
| Assumed HVAC lifespan | 15 years |
| Assumed PV lifespan | 25 years |
| Annual reduction in PV efficiency | 1% |
| Weather file | Cairo Intl.Ap .epw |
| (1) Egyptian Ministry of Electricity reports<br>(2) (Churcher D and Tse P., 2016)<br>(3) (Abdallah & El-Shennawy, 2020) | |

### Multi-objective retrofit optimisation

After selecting the ERMs for the different retrofitting scenarios, an IDF file was exported from Rhino and Ladybug tools to EnergyPlus simulation software. Envelope ERM constructions and U-values were added to the IDF file using Python with Eppy module. Following that, JE+ was used to add the required parameters and the objectives for the optimisation. And the optimisation was conducted using JE+EA 2.1 with the NSGA-II algorithm. Nine parameters were defined with all possible values, and the total number of possible combinations is 4,181,760. Two main objectives were defined for the optimisation, minimising LCC and LCCF.

To investigate different retrofitting scenarios, the optimisation was executed in 4 separate runs with different combinations; the First run: Passive ERMs, the Second run: Passive and Active ERMs, the Third run: Passive and renewable ERMs, and the Fourth run: All ERMs. The optimisation execution was conducted on a 16-core / 32-thread CPU computer for 20 generations each consisting of 32 individuals. The simulation took around 2.5 hours for each run to complete the optimisation and reach a convergence.

## Results and discussion

After conducting the optimisation, LCC and LCCF calculations for 30 years were also conducted on the existing building model to compare the results with the Pareto optimal results to assess the savings and evaluate the ERMs. The LCC and LCCF values for the existing building were 178 USD/m$^2$ and 1008kgCO2/m$^2$ respectively.

The results of the optimisation presented four main clusters of combinations, all with positive NPV savings (Error! Reference source not found.**)**. The first cluster included the combinations of passive ERMs only. The Pareto front of this cluster reached an LCC value of 150 USD/m$^2$ and an LCCF value of 795 kgCO2/m$^2$ with savings of 16.7% and 20% respectively **(Figure 5)**. The second cluster included the combinations of passive and active ERMs together. The optimum Pareto front values for this cluster reached an LCC value of 128 USD/m$^2$ and an LCCF value of 650 kgCO2/m$^2$ with savings of 28.9% and 35% respectively **(Figure 6)**. The third cluster, which included the combination of passive ERMs with PV cells reached an LCC value of 55 USD/m$^2$ and an LCCF value of 215 kgCO2/m$^2$ with savings of 69% and 78% respectively **(Figure 6)**. While the last cluster which included all ERMs had a significant impact on decreasing the LCC to 39 USD/m$^2$ and the LCCF to 100 kgCO2/m$^2$ with savings of 79% and 90% respectively **(Figure 6)**.

Cooling loads were found to be the main energy type impacted by applying the passive and active retrofitting measures. Error! Reference source not found. shows the savings in annual net electricity and cooling consumption for different ERMs combinations. The Pareto of the passive measures reduced the annual cooling loads by 70%. While combining passive and active measures can save up to 83% of the cooling loads.

The Pareto optimal results for the ‘All ERMs’ scenario showed that 95% of annual electricity consumption (Nearly Zero Energy Building) and 93% of the annual cooling loads could be achieved by applying all measures with an investment cost of 16,200 USD/m$^2$.

All the 23 Pareto front solutions for the ‘All ERMs’ scenario provided positive NPV for savings of around 1130 USD/ year. Moreover, the payback period for the results varied between 14 and 23 years.

By comparing the ratio of the investment cost and the total LCC of the optimal Pareto solutions, **Figure 8** shows that applying the ‘Passive’ scenario or the ‘Passive and active’ scenario, the operational costs contribute most of the LCC of the building, around 129 USD/m$^2$ (84%) and 105 USD/m$^2$ (79%) for both scenarios respectively. However, investing 12.5 USD/m$^2$ more to add PV panels to the building, could significantly reduce the operational costs to 20.7 USD/m$^2$ for the ‘Passive and renewable’ scenario, and 7.6 USD/ m$^2$ for the ‘All ERMs’ scenario, around 36% and 16% of the total LCC respectively.

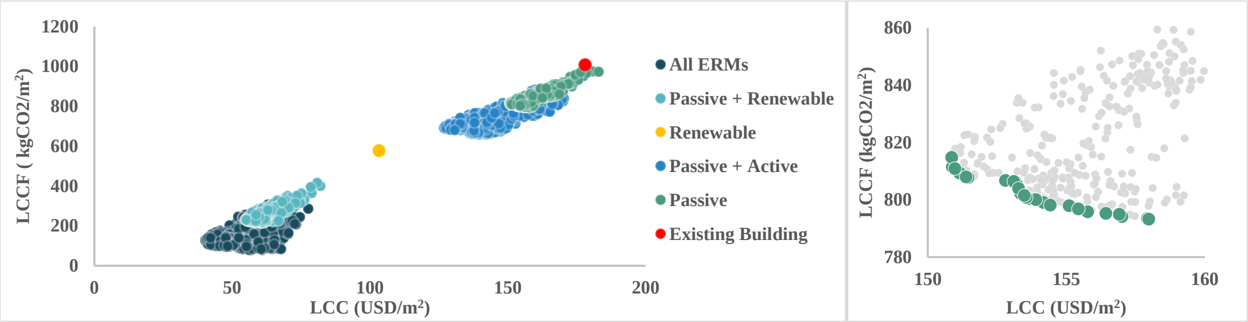

*Figure 5- (a) Optimisation for different combinations of ERMs, (b) Passive ERMs Pareto Front.*

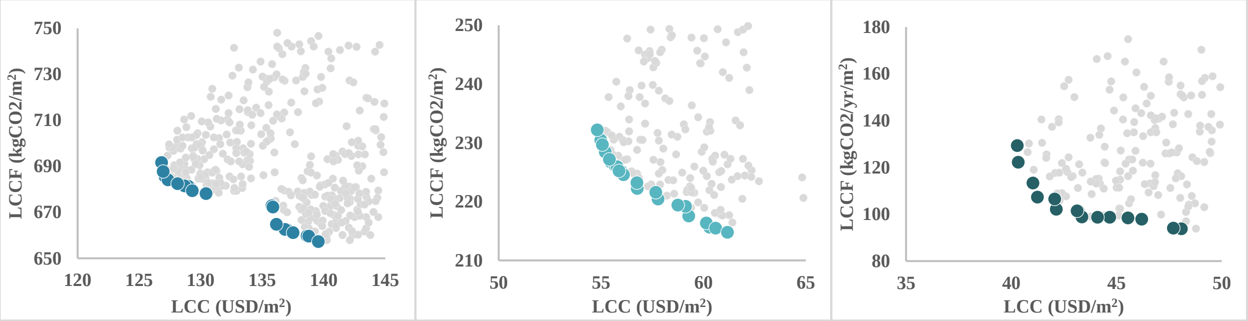

*Figure 6- (a) Passive + Active ERMs Pareto Front, (b) Passive + Renewable ERMs Pareto Front, (c) All ERMs Pareto Front*

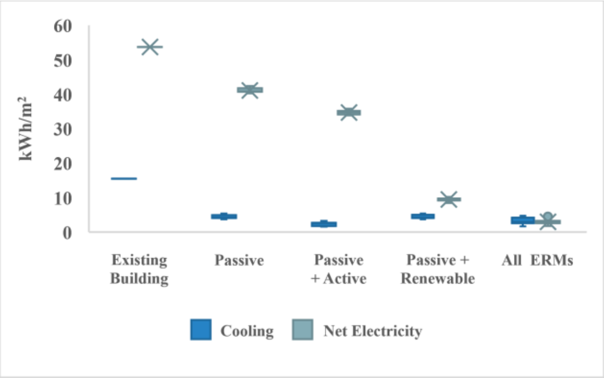

*Figure 7- Annual cooling and annual net electricity consumption for the Pareto of different ERMs combinations.*

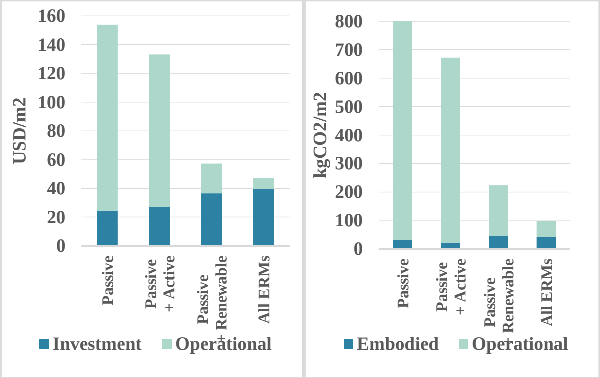

*Figure 8- (a) Investment and operational costs, (b) Embodied and operational emissions. (Average of the Pareto front)*

## Conclusion

This study aimed to develop a retrofitting framework for assessing the life cycle potential of existing residential buildings. By applying passive, active, and renewable energy measures, a multi-objective optimization framework was conducted on one of the new cities' villa archetypes. The results showed significant reductions in both LCC and LCCF, revealing 20 to 30 optimal retrofit models for each retrofitting scenario.

The study provided insight into different retrofitting scenarios either by retrofitting the building envelope only, setting guidelines for the occupants for recommended setpoints and equipment efficiency levels, or setting plans for implementing PV panels with incentives as a robust retrofitting measure.

The results of the study showed that applying the (Passive and Active ERMs (Low budget scenario), with an average investment of 27 USD/m$^2$, can save around 35% of annual energy loads and 83% of annual cooling loads. Moreover, applying all proposed ERMs with an average investment of 39 USD/m$^2$ (around 3% to 5% of the total villa unit price) can reach 95% savings in annual energy demand and 93% of annual cooling loads.

Overall, several ERMs showed a significant impact on both the life cycle and energy savings of the Pareto models such as efficient lighting, envelope insulation and air tightness, cooling setpoints, and adding PV systems. Although adding an efficient HVAC system can have a high energy saving potential, it had a low return on investment due to high cost, thus lower LCC impact.

In summary, both Passive ERMs and Passive and Active ERMs scenarios prove to be highly suitable for dwellings characterized by higher cooling loads with lower capital for investment. On the other hand, adding PV panels to any have a much higher potential for saving energy for all energy-demand aspects of the dwelling on equal terms.

The development of this model could serve as a valuable resource for Egyptian policymakers and stakeholders, providing insights into the energy-saving opportunities of the country's building stock. Additionally, the model could assist policymakers in determining appropriate energy efficiency measures for different types of housing in Egypt and offering recommendations for the implementation of building codes and regulations in new constructions.

## Limitations and Future Work

This study examined the life cycle performance of an existing building with certain settings (Construction materials, orientation, etc.). However, the study is part of an ongoing project to assess different archetypes that represent the residential building stock in new cities in Egypt. It is important to mention that the outcomes of the study may vary depending on the specific characteristics of the selected archetype.

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