Chapter 21
Multiple-Criteria Optimization of Residential Buildings Envelope Toward nZEBs: Simplified Approach for Damascus Post-war

Lina A. Khaddour and Siegfried K. Yeboah

Abstract Syria faces significant challenges in optimizing residential building energy consumption to subsequently reduce CO_2 emissions due to its conventional construction methods and systems, exacerbated by the recent conflict. Post-war re-construction provides new opportunities for improvement in building standards through the 2009 BIC insulation code towards nearly Zero Energy Buildings (nZEBs). However, the decline in economy growth poses significant challenges. In this study, we formulate a simplified building envelope selection approach using multi-criterion optimization methodology based on simulated thermal loads using IESVE and cost-energy trade-off. IESVE was used to evaluate the thermal performances of five cases representing 5 different building envelope structures on existing buildings in Damascus, Syria. Four out of the five cases were BIC compliant, and their thermal performances and cost energy trade-offs were evaluated against that of a conventional building representing the construction-as-usual case. Payback on the investment in insulation improvement of the envelope structures were also calculated. The results overall shows that the envelope structures incorporating insulation layer reduced annual heating, cooling, and combined energy loads of those buildings. Comparatively, these improvements were slightly better under winter conditions than in summer. Based on payback period analysis, none of the improvements provided acceptable economical payback within five years, as energy consumption tariffs were extremely low and insulation material costs were extremely high. A Multi-Criteria Decision Making (MCDM) framework was developed and applied to the cases investigated. Based on the limitations of the BIC, no optimal solution was obtained. However, the framework provides a good basis for stakeholders to make sound decisions in transitioning buildings especially under post war context towards nZEBs.

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Nomenclature

A	Total envelope area (m^2)
A_s	Annual savings in running energy consumption considered for 50 years lifetime
C_{enr}	Energy cost actual value over n = 50 years housing life-cycle
C_t	Total cost per wall surface square meter which includes C_{enr} (the running energy cost present value)
C_i	(The insulation purchase and installation costs)
d	Time value of money during n = 50 years housing life-cycle
d_i	Layer thickness (m) where i is the number of layers
i	Inflation rate effects on energy cost
PWF	Present Worth Factor
Ri	Thermal resistance (K.m)/W
R_T	Thermal resistance (K.m^2)/W
R_{Se}	Heat transfer resistance (externally) (K.m^2)/W (Table 21.1)
R_{Si}	Heat transfer resistance (internally) (K.m^2)/W (Table 21.1)
ΔT	Temperature difference [k]
U	Heat transmission W/(K.m^2)

Greek Letters

λ_i	Thermal conductivity W/(K.m)
Φ	Is measured in units of Power [W] (i.e. energy units per second)

21.1 Introduction

Between 1990 and 2019, global CO_2 emissions from buildings increased by 50%, while global final energy demand from buildings grew by 38%. Over the same period global final electricity demand increased by 161% out of which residential buildings accounted for 70% (90 EJ) [1]. By 2020, buildings accounted for 36% of global energy demand and 37% of energy-related CO_2 emissions [1]. To place the building sector on-track to net zero emissions by 2050, IEA [2] proposes a move towards nearly Zero Energy Buildings (nZEBs) improvement pathway, increasing the share of building stock that is zero carbon ready, increasing the stock of solar thermal systems, growing solar PV generation and ensuring all new buildings are zero-carbon-ready by 2030. Decarbonizing the building sector requires cutting down on energy consumption and increasing nZEBs investments [1]. However, significant challenges exist for developing countries in terms of investment R&D in nZEBs, viable building techniques, building standards and regulations [3].

Post war Syria faces significant challenges including a slow economy, difficulties in accessing affordable and reliable energy supplies, decline in construction sector activities amongst many others 0. The war created chaos in the country's energy sector dramatically diminishing oil and natural gas production [3]. This severely affected economic activities between 2011 and 2020 as the state electricity supply reduced to 15% of 2010 capacity [3]. Current available energy hardly supports half the housing energy demand resulting in long hours of power cuts, decreased families heating fuel allocations and increasing energy prices [1]. The country's post-war reconstruction has experienced significant growth in demand for energy efficient affordable housing, mainly due to the wartime disruption, infrastructural damage, scarcity, and sanctions [4]. This move potentially can help reduce energy consumption and CO_2 emissions as Syria's residential buildings contribute to 49% of the country's energy consumption and up to 40% of the energy-related carbon emissions [3].

Successful, orderly, and broad-based transitions to nZEBs where Syria benefits from global investment will depend on adapting new energy efficient codes and building regulations. Syria's post-war energy sector involves varied and often complex interactions between electricity, fuels, and storage markets, creating fresh challenges for regulation and buildings design [3]. Its construction sector traditionally has challenges in its methods and systems that negatively impacts the environment and consume significant natural resources [4]. Customarily, there is the widespread use of unsustainable construction materials that does not fit with the climate, occupants' wellbeing, and environmental requirements [4].

Increasing the heat transfer resistance of the building envelope is one of the key approaches towards reducing building energy consumption towards achieving nZEBs ([5, 6]). Many countries around the globe have developed building insulation codes to enhance housing energy-saving towards minimizing negative environmental impacts. Syria has initiated similar steps through the Building Insulation Code (BIC), Energy Efficiency for Homes Labels in addition to the Energy Conservation Law enacted in 2009 by the National Centre for Energy Research (NCER). The BIC sets an objective of 20% reduction of energy demand, 20% reduction of CO_2 emission, and 20% increase of renewable energy introduction by 2020. It contains five Chapters and seven Appendices covering the general requirements, building envelope scope and thermal compliance, building insulation material selection and implementation, humidity in buildings and operational energy efficiency. It also sets standards for envelop components compliance parameters such as the ratio of openable window to floor area, windows thermal transmittance (U-window), roof thermal performance (U-roof) and external walls thermal transmittance (U-wall), based on the climate zone [6]. There are many barriers for implementing BIC towards nZEBs. For instance, Khaddour [7] identified the main barriers including economic (e.g. low financial horizons, investment risk, sanction, and limited income), institutional (e.g. insufficient regulatory processes, lack of essential enforced regulations, poor knowledge and professional expertise) and behavioural customs (e.g. routines, and important behavioural characteristics, lack of knowledge about potential for conserving, undervaluing and lacking interest in Energy Efficiency) that threatens the implementation of such measures towards nZEBs [7].

Reviewing the BIC insulation code, it is apparent that selecting building envelope construction technique that complies with thermal comfort, energy efficiency, low building thermal loads and cost-saving towards nZEBs will be a new challenge for Syria's post-war re-construction. Hence, the aim of this study is to develop a simplified building envelope selection approach using multi-criterion optimization methodology, simulated thermal loads (IESVE heating and cooling) and cost-energy trade-off, to assist engineers in the early-design phases of new residential projects to achieve expense-efficient energy performance solutions. The selection criteria were used to examine efficient envelop structures suitable for the climate in Damascus.

21.2 Methodology

The research was on a case study of building performance in Damascus, Syria. Five cases representing 5 different building envelope structures on existing buildings in Damascus were investigated. The research focused on the analysis of data from a conventional building and an energy-efficient pilot building project in Damascus. The thermal performances of the 5 cases representing the different building envelope structures were evaluated via simulation using IESVE. After the thermal performance analysis, cost-energy efficiency trade-off and payback period were calculated for the five cases. A simplified multiple-criteria decision approach was then developed to assess the appropriate building envelop technique suitable for the climate in Damascus.

21.2.1 The Case Study

The case study area is Damascus (36° 13′ N, 33° 29′ E). It is in the southern part of Syria, about 80km from the western side of the Mediterranean Sea and separated by mountains bordering Lebanon. In summer, cooling is typically required for approximately 120 days from 1st June to 31st September. In winter, heating is typically required for roughly 150 days from 15th November to 15th April. At the peak of summer, Damascus records maximum temperatures of around 40°C whereas in winter the lowest temperature is about − 2 °C. All the five cases have same building design and total external wall surface area of 398 m^2 each. Figure 21.1 shows the case study building with external insulation layer.

Fig. 21.1 Case 1 the pilot project compliant building

The building envelope structures and components U-values for the 5 cases calculated based on Eq. (21.1) from the BIC document- Appendix 4 [6] are presented in Table 21.1.

The envelope material specifications including thermal resistance properties and thickness obtained from the building contract specifications were used to calculate the U-values in Table 21.1 by applying Eq. (21.1).

$$U = \frac{1}{R_T} = \frac{1}{R_{Se} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \ldots + R_{si}} \tag{21.1}$$

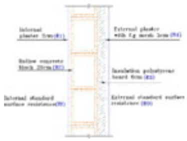
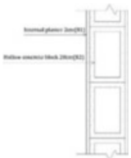
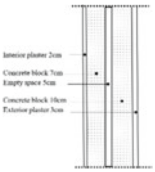
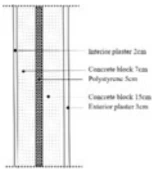
The building envelope structures and components surface resistances for upward and horizontal flow directions are presented in Table 21.2.

21.2.2 Simulation Methodology

The thermal loads for the 5 cases were simulated in IESVE to evaluate the BIC compliance of the buildings' envelope structures. The key requirements here were the building models with the respective 5 envelope structures, thermal properties data for the materials and weather data for Damascus. The cases were modelled following typical Syrian residential design parameters of 7.8 W/m^2 lighting power density, 8.0 W/m^2 equipment power density and 25.5 m^2/person average occupancy density. For this reason, there were variations in annual heating and cooling load estimations due to the variation in parameters and envelope construction materials.

It was assumed that envelope inside and outside surfaces had the same surrounding air temperature, thermal conductivity coefficients, convection, and radiation properties. Yearly thermal loads were calculated for each day of the summer cooling season (June to September) and for winter heating season (November to April). The fixed indoor comfort design temperature was 22 °C in summer and 19 °C in winter. The

Table 21.1 Building envelope structures and components U-values

Cases	Wall cross section	External wall construction technique	Overall wall thickness (cm)	Wall U-value (W/m^2/k)	Glazing U-value (W/m^2/k) (material specification)	Roof U-value (W/m^2/k)
Case-1		20 cm Concrete block, 5 cm polystyrene & 2 cm internal mortar, and 3 cm external cement mortar	30	0.44	1.9	0.4
Case-2		20 cm concrete block & 2 cm internal mortar and 3 cm external cement mortar (Base line)	25	2.045		2.69
Case-3		(7 cm and 10 cm) Double Concrete block, 5 cm empty space, 2 cm internal mortar and 3 cm external cement morta	27	1.4	1.9	2.69
Case-4		(7 cm and 15 cm) Double Concrete block, 5 cm polystyrene and 2 cm internal mortar and 3 cm external cement mortar	32	0.15	1.9	2.69

(continued)

Table 21.1 (continued)

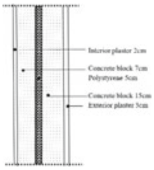
Cases	Wall cross section	External wall construction technique	Overall wall thickness (cm)	Wall U-value (W/m^2/k)	Glazing U-value (W/m^2/k) (material specification)	Roof U-value (W/m^2/k)
Case-5		(7 cm and 10 cm) Double Concrete block, 5 cm styropor, 2 cm internal mortar and 3 cm external cement mortar	27	0.2	1.9	2.69

Table 21.2 BIC Building Envelope and Surface resistance

Surface resistance (K·m^2/W)	Heat flow direction	
	Upward	Horizontal
$R_{s.i}$	0.1	0.13
$R_{s.e}$	0.04	0.04

selected design Window to Floor Ratio (WFR) was determined to be 16.66% for all cases. Daily thermal loads were then added up for each season to obtain annual cooling and heating loads. The estimated wind speed was assumed to be 5.5m/s. The heat loss through the building was calculated using Eq. (21.2).

$$\Phi = (\sigma A_i \times U_i) \times \Delta T \tag{21.2}$$

(σ $Ai \times Ui$) is the sum of all heat transfer areas (walls, roof, windows, etc.)

The BIC [6] specifies the maximum (allowable) U-values hence those values were considered in the simulation. Each building wall had (n) layers of different materials and thicknesses. The building envelope design temperature T_i was specified as fixed on the inside surface, whereas the outside surface was exposed to the periodic temperature variation per the weather data. The cooling load and heating load were evaluated for each case. The five cases used the same building design as shown in Fig. 21.1 but with different envelope structures as specified for the cases in Table 21.1. The percentage improvement for annual total, annual heating or annual cooling load was determined using Eq. (21.3).

$$\%\ Improvement = \frac{\left[\Phi_{Baseline(Total\ or\ Heating\ or\ Cooling)} - \Phi_{Total\ or\ Heating\ or\ Cooling}\right]}{\Phi_{Baseline(Total\ or\ Heating\ or\ Cooling)}} \tag{21.3}$$

21.3 Results and Discussion

The simulation results cover the annual cooling and heating transmission loads per square meter for both cooling and heating seasons for the different envelope structures. The results presented in Table 21.3 show significant impact of envelope structure on building thermal performance. Case-2, the baseline building with no insulation (conventional building), had the highest heating and cooling loads with a total of 345.1 MWh. Out of the four BIC compliant cases (1, 3, 4 and 5), the best improvement was achieved with case-4 with total heating and cooling annual load of (72.5153 MWh). The polystyrene insulation in case-4 achieved slightly better results than the styropor insulation layer in case-5. The worst envelope performance among the selected BIC compliant cases was case-3 with higher values of annual transmission loads of 185.5054 MWh due to the empty cavity space in the walls resulting in a high u-value of 1.4 W/m^2/k. The results overall shows that having the envelope structure incorporating insulation layer reduced the annual heating, cooling, and combined energy loads. For cases 1, 3, 4 and 5 respectively, the % improvement in annual cooling loads achieved from the simulation ranged between 62 and 79% depending on the envelope structure improvement type. For heating, the % improvement ranged between 61 and 89%, also depending on the envelope structure utilized. The combined % improvement for the annual total energy utilized for cases 1, 3, 4 and 5 respectively were 78.89%, 61.53%, 84.96% and 84.23%. It is evident from the results that the envelope structure improvement resulted in a slightly better winter building thermal performance than summer.

21.4 Payback Period Analysis

Equations (21.4, 21.5 and 21.6), payback calculation method developed by Sullivan et al. [8] were used to calculate the payback on investment in the envelope structure. This approach was used to calculate the payback in years for all cases to allow comparison between the BIC compliant cases (1, 3, 4, 5) and case 2, the baseline. Here considerations were made in terms of the initial cost of materials and construction and the running costs once the envelope structure was installed and functioning.

$$PWF = \sum_{u=1}^{n}\left(\frac{1+i}{1+d}\right)^{u} = \begin{cases} \frac{1+i}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^{n}\right] & i \neq d \\ \frac{n}{1+i} & i = d \end{cases} \tag{21.4}$$

$$C_{enr} = PWF\left(\frac{Q_c}{COP}\frac{C_{el}}{(3.6\times 10^6)} + \frac{Q_h}{H_u \eta_s}C_g\right) \tag{21.5}$$

$$C_t = C_{enr} + C_i = PWF\left(\frac{Q_c}{COP}\frac{C_{el}}{(3.6\times 10^6)} + \frac{Q_h}{H_u \eta_s}C_g\right) + C_{ins}L_{ins} \tag{21.6}$$

Table 21.3 Annual loads including heating and cooling (calculated with IESVE) for the five cases

Cases	Annual cooling load (MWh)	Annual heating load (MWh)	Total annual energy load (MWh)	% Improvement—annual cooling loads (%)	% Improvement—annual heating loads (%)	% Improvement—total annual energy loads (%)
Case1	59.4931	40.4489	99.942	72.77	88.66	78.89
Case2	218.4933	263.6767	482.17	Baseline		
Case3	83.383	102.1224	185.5054	61.84	61.27	61.53
Case4	44.2974	28.2179	72.5153	79.73	89.30	84.96
Case5	45.294	30.7593	76.0533	79.27	88.33	84.23

The inflation rate effect on energy cost was determined by Eq. (21.7)

$$\mathrm{PWF} = \frac{C_i}{A_s} \tag{21.7}$$

From the calculated results, the payback periods for cases 1, 3, 4 and 5 were 10.5, 7.8, 15.7 and 13.1 years respectively. Sullivan et al. [8] considered the payback period to be acceptable economically if it is within five years. Therefore, neither of the selected cases evaluated were profitable or economically viable as all payback periods were longer than five (5) years. The main reasons for the long payback periods are that the Syrian tariff for household energy consumption is extremely low while the cost of the imported insulation materials is very high [5]. This does not translate into affordable housing as developers aim to sell at a market price regardless of construction cost savings.

21.5 Multiple-Criteria Optimization Analysis

Determining the best building envelope solution towards nZEBs requires consideration of many design variables and factors, such as building thermal performance, CO_2 emissions, construction and running costs etc. This is challenging as these variables affect each other and their individual optimisation goals can change significantly. Figure 21.2 shows a phased approach towards decision making in the transition to nZEBs. The simplified criteria shown are targeted to guide decision making towards nZEBs in Syria. This phased approach can be applied to the concept of nZEBs and assigned with values and weights to assess the post-war reconstruction. It can incorporate a synthesized list of energy efficient indicators associated with post-war housing to enable decision makers to undergo a Multi-Criteria Decision Making (MCDM) process that considers their objectives and priorities. The MCDM in Fig. 21.2 consists of the following phases: (a) objective identification; (b) criteria development; (c) alternative generation, evaluation, and selection; (d) implementation and monitoring [8]. It can enhance the handling of the energy sector uncertainty, the demand for housing, deal with multiple project requirements and address conflicts amongst stakeholders [9]. The framework in Figure (2) considers nZEBs' key decision makers such as regulators/policy makers, project managers, contractors (private, public, PPP), consultants, designers, and property developers/owners. Other major industry stakeholders, out of this study's scope, include building material manufacturers, suppliers, international partners, and new buyers. Their opinions could be integrated into a more comprehensive approach in future research.

nZEBs should be scheduled in a precise order based on each country priorities, assessing the possibility of any knock-on effects. Seminara et al. [9] suggests a cost-effective method, with an approach that aims to improve building envelop first

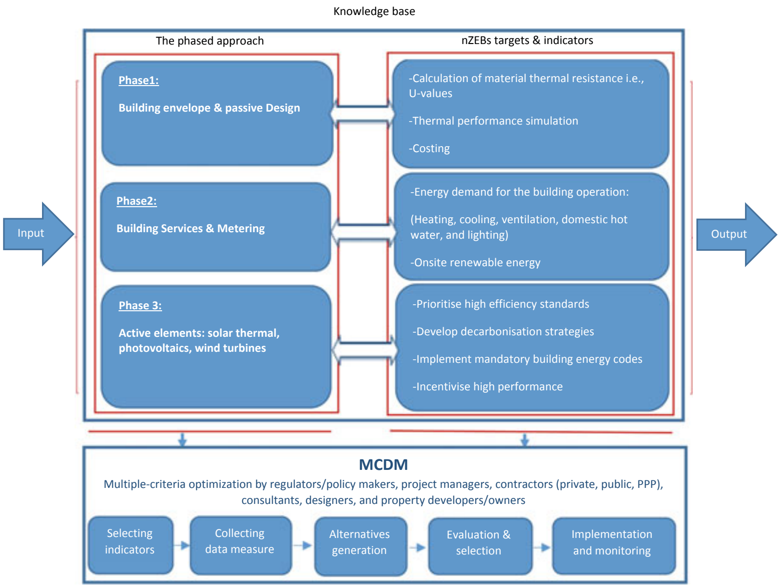


Fig. 21.2 Simplified multiple-criteria optimization analysis of residential buildings envelope

followed by building services then more active elements. In this sense our framework in Figure (2) has three levels (Phases) with the following roles: **Phase 1**—Building envelope and passive design. This could start form the Pre-design phase to assist the owner, planner and others involved at the planning (pre-design) stage of the project. This phase's main indicators are calculation of material thermal resistance i.e., U-values, using thermal performance simulation and costing analysis). **Phase 2**—Building services and metering offers a self-assessment check system that allows architects and engineers to raise nZEBs under consideration during its design process. Assessments here is based on the design specification and the anticipated performance of building operations (heating, cooling, ventilation, domestic hot water, and lighting and potentially onsite renewable energy). **Phase 3**—Active elements. This has the highest cost implications as it involves the inclusion of solar thermal, photovoltaics, and wind turbines etc. The main indicators at this phase are prioritising high efficiency standards, developing decarbonisation strategies, implementing mandatory building energy code for high nZEBs performance.

The key inputs are climate zones data and design specifications. The knowledge base in Figure (2) is to assist in grasping measurable nZEBs indicators such as the thermal performance, cost estimate, payback period at the Pre-design stage. The framework output indicators help to evaluate/rate the level of impact of nZEBs targets for decision making. The MCDM follows each phase developed criteria and indicators to evaluate the alternatives based on collecting data, cost calculations, and thermal performance simulation. The monitoring stage allows decision making by

Client/Owner via monitoring of the overall construction status (by contractor) and building risk register updates (by project team).

Considering the economic and technical challenges associated with the post-war reconstruction of Damascus, improving building envelope insulation appears to be an effective approach towards nZEBs. To apply the simplified multiple-criteria optimization framework in Figure (2) to the five cases studies, output indicators were outlined as shown in Table 21.4. The incorporation of the insulation material in the envelope structure resulted in a reduction in heat losses. Each envelope (material and construction) costs were calculated, according to 2020 market prices in Syrian pounds per square meter (SP/m^2). This resulted in cost increases ranging between 27.3 and 54.5% above baseline levels. Case 4 was found to have the best thermal performance improvement but the highest increase in material and construction cost whereas the cheapest compliant solution, case 3, had the lowest thermal performance. The payback calculated showed that none of the four compliant cases met the 5-year payback threshold hence all were considered unacceptable economically for affordable housing as developers aim to sell at a market price regardless of energy cost savings. Despite it's the cases being BIC compliance, none of them proved the cases to be optimal solution.

To reach an optimal envelope solution a couple of considerations need to be made. Firstly, it may be necessary to generate alternative envelope solutions based on the locally available materials that can be cheaply accessed in significant quantities. This is because, the availability and installation capacity for insulation material, is a dominant factor in the selection of appropriate building envelope under post-war reconstruction condition. Despite compliant buildings higher initial cost, the simplified analysis shows that there is the need to minimize the total cost over building lifetime which includes the insulation (purchase and installation) and the energy (consumption and maintenance) costs. Secondly, the BIC will benefit from a rating scale to drive building envelope selection. Various internationally recognized building rating and certification systems value the improvements in building envelope performance in relation to thermal performance and reductions in energy/emission

Table 21.4 Simplified multiple-criteria optimization analysis applied for the five cases

Building Envelop Output Indicators						
Cases	Annual cooling load (MWh)	Annual heating load (MWh)	Total annual energy load (MWh)	Envelope cost (Syrian pounds SP/m^2)	Payback period (Years)	BIC compliant
Case 1	59.4931	40.4489	99.942	30,000	10.5	Yes
Case 2	59.4931	40.4489	99.942	22,000	–	No (baseline case)
Case 3	218.4933	263.6767	482.17	28,000	7.8	Yes
Case 4	83.383	102.1224	185.5054	34,000	15.7	Yes
Case 5	44.2974	28.2179	72.5153	32,000	13.1	Yes

consumption. The USA's LEED, for example, offers one credit point for buildings that offer good level of thermal comfort system control by personal occupant [10]. The UK's BREEAM offers two credits for thermal comfort system control by personal occupant [11]. Japan's CASBEE rating identifies five levels of control [11] and Australia's Green Star offers two points for buildings that facilitate individual control of thermal comfort [12]. These credits and ratings are non-existent in the BIC hence a compliant building may still consume significant amounts of energy and emit significant CO_2 yet will pass compliance. This obviously will not help with the transition of post-war reconstruction buildings to nZEBs in Syria as cost challenges may unlikely encourage investors to spend toward nZEBs when they are BIC compliant [13–15]. In comparison to previous research on multi-approach decision making toward energy-efficient buildings [16–18], the results obtained by this research can be replicable for multi-target decision-making-objectives and optimisation goals so that different actors can decide between optimal solutions for different objectives. In this sense, BIC no doubt can be considered as the first steps towards a low carbon future for Syria however it will need to be reviewed and improved with low carbon targets to push newly constructed buildings towards nZEBs.

21.6 Conclusion

A simplified building envelope selection approach using multi-criterion optimization methodology, simulated thermal loads (IESVE heating and cooling) and cost-energy trade-off, for a pilot project in Damascus, Syria has been investigated.

- The results obtained from the IESVE simulation shows that for BIC compliant cases 1, 3, 4 and 5 respectively, the % improvement in annual cooling loads ranged between 62 and 79% depending on the envelope structure. For the same cases in winter, the % improvement ranged between 61 and 89%. Overall, combined % improvement of annual total energy utilized for the cases (1, 3, 4 and 5) were 78.89%, 61.53%, 84.96% and 84.23% respectively.
- The payback analysis for the investment in the envelope structures represented by the BIC compliant cases, 1, 3, 4 and 5 returned 10.5, 7.8, 15.7 and 13.1 years respectively. These long payback periods were deemed unacceptable economically as they exceeded the typical 5 years threshold of acceptable economic payback period.
- The results obtained were also applied to multiple objectives and optimisation goals for a multi-target decision-making framework so that different actors can decide between optimal solutions for different objectives. The findings yielded no singular optimal solution from all the cases investigated. However, the Multi-Criteria Decision Making (MCDM) framework developed offers opportunities for regulators/policy makers, project managers, contractors (private, public, PPP), consultants, designers, and property developers/owners to address conflicts and consider their objectives and priorities in a structured manner.

Occupant behaviour can influence the performance of nZEBs especially when they embark on modification to have control on buildings. Hence, we recommend that future studies consider the influence of occupants' behaviour in developing effective nZEBs indicators in post war reconstruction.

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