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ORIGINAL PAPER

Comparative analysis of residential building envelopes newly implementing the building insulation code in Damascus

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Abstract
The selection of envelope construction technique has the highest impact on sustaining indoor thermal comfort while reducing energy consumed for heating and cooling. Numerous insulation codes are implemented worldwide to improve building envelope modification. Each country has set envelope transmittances criteria, materials, techniques and simulation tools differently based on its climate zones and construction sector adaptability. The housing sector in Syria is the focus of energy conservation being responsible of half of the energy consumption in the country. Syrian post-conflict residential buildings are challenged by the new implementation of Building Insulation Code. This code has opted for a "fabric first" dwellings design approach with mandatory *U*-value standards. Hence, like many energy-related regulations in Syria it has been dropped because the construction sector has not been able to cope with them, forced by speculators to keep costs low. Another reason is that building thermal performance modeling has not been used to comply with the new insulation code in Syria. The research aims to examine the potential relevance of the Insulation Code in informing post-war social housing envelope structures in Damascus. It evaluates compliant building envelope structures compared to conventional building in terms of transmittance properties, simulated thermal loads (IESVE) and cost–energy trade-off. The research findings reveal an improvement in *U*-values of 78.5%, 31.5%, 92.7% and 90.2% achieved in compliant cases 1, 3, 4 and 5, respectively, compared to conventional case-2. The simulation demonstrated best improvement in total heating loads up to 85% achieved in case-4. Hence, the improved *U*-value lead to improvement in winter heating loads but overheating in summertime. The simulation was found useful but not enough to optimize envelope performance through interdisciplinary decision that contributes positively to Syrian post-war circumstances. The cost analysis found an increase in wall initial construction costs, amounting to 36.4%, 27.3%, 54.6% and 45.5% in cases 1, 3, 4 and 5 with long payback periods. These findings spark a new agenda for Insulation Code improvement. The proposed simplified criteria offer practitioners more understanding to customize their own list of envelope structure parameters based on the climatic zone resulting in a shift in envelope selection from input to a more output oriented.

Keywords Thermal insulation code · Building envelope · Residential buildings · Energy efficiency · Syria

Introduction

Syria is facing serious energy crisis. The energy sector is not able to meet the housing sector demand for electricity, even for few hours per day (Khaddour and Yeboah 2022). Syria's post-war reconstruction has experienced significant growth in demand for energy efficient affordable housing. This is because the residential sector accounts for 65% of Syrian war total damages. The energy sector is the second-hardest hit sector with estimated damages of $1445 billion till 2016 (WBG 2017). The Syrian energy sector is characterized by the dominance of fossil fuels and the absence of a renewable role (Hassan and Beshara 2019). In fact, the total energy demand exceeded 23.2 million tons of equivalent oil consumption (kWh/year) in 2010 compared to 16.64 million tons of oil in 2000. With the growth rate of more than 7.5% annually, the Syrian energy demand is expected to reach 63.8 million tons of oil by 2030 driven by the spread of energy-intensive housing applications and state energy policies, e.g., low electricity tariffs (Hatahet and Shaar 2021).

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Syria energy supply used to depend on national oil and natural gas means. Since the beginning of the current conflict, Syria's energy sector is in chaos, with oil and natural gas production decreasing dramatically mainly due to the sanctions imposed by USA, the war damages to energy infrastructure and the government losing control of many oilfields (Hassan and Beshara 2019). Beside the destruction of the main power generation plants and transmission infrastructure during the conflict, the currently in service power plants are working beyond their capacity and over their life span with very high maintenance and repair cost (Khaddour 2021b). For example, Banians and Tishreen plants are about 50-year-old plants and need more than 15 billion dollars each for maintenance only without adding the operational cost (Hatahet and Shaar 2021). In April 2021, Ghassan al-Zamil, the Minister of Electricity, announced the integration of the electricity-saving program, so that power would be delivered for one hour for every minimum 5 power cut hours. Electricity availability varies considerably among cities, and between urban and rural areas. Schedules are changed, in an unpredictable manner, with short notice, depending on fuel availability.

The main function of residential buildings is to provide occupants with thermally comfortable internal environment. This will not only result in increasing occupants comfort level, but it will also determine its energy efficiency and consequently will influence buildings' sustainability targets (Lotfabadi and Hançer 2019). Residential buildings consume about 31% of energy demand and emit about 23% of carbon emissions worldwide (Schwarz et al. 2020). In Syria, these figures are even higher as residential buildings contribute to 49% of the country energy consumption and up to 40% of the country's energy-related carbon emissions (Guidelines for Green Architecture 2013). These figures highlight the significant potential of reducing residential buildings energy consumption and therefore carbon emissions in Syria post-war reconstruction. Furthermore, it is vital to focus on minimizing thermal loads which contribute to 55% of Syrian residential sector energy consumption (Khaddour 2021a). In this regard, the building's envelope construction technique has a major effect on heating loads, energy consumption and construction cost.

There is a growing concern about the impact of building envelope construction techniques on building energy consumption (Kumar et al. 2012; Yüksek 2015). Energy efficiency is identified by the energy consumption of the building services and by the envelope thermal losses (Khaddour et al. 2023). The thermal losses are mainly controlled by the envelope thermal transmittance (Kandya and Mohan 2018). The selection of building envelope construction techniques is important to reduce energy consumption by decreasing heat gain/loss while reducing heating/cooling (air-conditioning) loads (Akadiri 2012). According to the Global Energy Assessment report, heating and cooling energy consumption of residential buildings can be halved by 2050 by implementing up-to-date building envelope construction techniques and energy efficient technologies (GEA 2012). Research revealed that several best-practice envelope construction techniques can save 30–90% in operational energy consumption (Kumar et al. 2012; Chang 2010; Kumar et al. 2012; Yüksek 2015).

Numerous energy policies and insulation codes have been recently implemented worldwide to achieve this goal. The main aim of these codes is improving building envelope modification. Hence, each country has set envelope transmittances criteria differently based on climate zones, temperatures and degree-day variations. Previous studies revealed variations between actual verses code predicted building's thermal and energy performances. For example, the achievements and challenges of the EU's building envelope regulation, in terms of compliant building envelopes' thermal performance, were analyzed by Papadopoulos (2016). O'Brien et al. (2020) compared various building insulation codes across the globe. Another comparative review by Lu and Lai (2019) focused on building insulation and energy efficiency codes in different countries, e.g., EN 832, German Regulations, ISO 9164, TS 825 of Turkey and Code 19 of Iran. Also, Wang et al. (2019) evaluated Chinese compliant houses according to building insulation and energy code of China GB 50189. Additionally, different codes and initiatives of buildings' insulation in the Arab Countries were evaluated by Hanna (2010). One common limitation found is focusing on narrow requirements for separate building parts, such as thermal transmittance of windows (Schwarz et al. 2020). Another limitation is the performance gap caused by focusing on regulating planned values in building envelope construction techniques while neglecting the actual post-occupancy energy consumption (Lotfabadi and Hançer 2019). As previous studies have highlighted the limitations of different insulation codes around the world, argument turns to original approaches and modeling to overcome such limitations for continuous improvement based on each region circumstances.

Struggling to meet the growing energy demand of the housing sector, the Syrian Government had put forth several initiatives to encourage private investment in renewable energy and housing energy efficiency. Hence, numerous energy efficient prospects in housing are not realized to date, despite being economically superior to the post-war status quo. The Government of Syria initiated the Building Insulation Code (BIC) in addition to the Energy Conservation Law, in 2009, to enhance insulation and energy saving in housing sector. These initiatives focus on aspects of building envelope construction techniques that minimize heat loss with the minimum insulation required. The Syrian conflict, which has escalated since 2011 to date, has prevented the implementation of these initiatives. In the light of post-war energy deficiency and resource limitations, energy efficiency is a key factor in Syria post-war re-construction and socioeconomic restoration (Khaddour 2021a). In fact, "improving energy efficiency" was found to be a key factor in Syria post-war re-construction with 4.06 rank on Likert scale according to recent survey conducted on Damascus construction companies (Khaddour and Deng 2023). Thus, a few studies were found regarding building insulation impact on building energy efficiency in Syria. Salkini (2017) developed criteria for selecting building envelope materials for improving post-war housing thermal comfort and environmental impact in Aleppo. More recently, Khaddour (2021b) have compared between traditional and contemporary housing from operational energy consumption point of view. However, the study did not include how BIC compliance buildings are expected to be improved in terms of thermal performance.

Appropriate building insulation codes are essential not only for providing comfortable thermal conditions but also for energy saving. The applicability of the building insulation codes has been broadly studied worldwide. Out of the identified codes limitations, it was felt that there was a lack of empirical research on building envelope construction techniques impact on thermal comfort, energy consumption and cost in Syria which is essential for building insulation code correct definition and implementation. This research provides transmittance calculation, thermal simulation, parametric analysis, simplified approach for selecting envelope construction as well as recommendations for better energy efficient and climate responsive buildings. This study took place in Damascus from December 2018 to January 2020.

Research gap and objectives

Selecting building envelope construction technique that complies with insulation code (thermal comfort, energy efficiency, low building thermal loads and cost saving) is a new challenge for Syria post-war re-construction of new affordable residential buildings. Residential sector practitioners, stakeholders and researchers are challenged with interdisciplinary factors, such as policies; climate change; shortage of fossil fuel stocks; poor flexibility of the local traditional construction companies; post-war sanction; economic downturn; and occupants' awareness (Khaddour 2021b). Considering all these aspects, an integrated simplified approach for envelope selection is required to address post-war housing demands and to achieve energy efficient affordable housing target. Hence, the Syrian construction sector has not shown any improvement in this area (Hassan and Beshara 2019; Khaddour 2022).

In response to the energy deficiency challenges that Syria is facing, the Syrian Ministry of Energy in cooperation with the newly established National Energy Research Centre (NERC) has issued the ambitious BIC initiative in 2009, BIC set an objective of 20% reduction of energy demand, 20% reduction of CO_2 emission and 20% increase of renewable energy introduction by 2020. Because of the war, BIC has been lately enforced, since early 2020, as a requirement to gain building planning permission by the Central Engineering Syndicate. Hitherto, a limited number of envelope techniques were proposed to handle buildings thermal performance, in general, and the external walls' multilayer, in particular.

BIC is the first step toward more practical and much ambitious targets. The current housing re-construction practices are struggling to comply with the minimum immature BIC standards. BIC lacks any thermal performance evaluation method, model or tool which allow analyzing building thermal performance according to its climatic zone (Khaddour 2021b). Achieving BIC targets requires developing further guidelines on the development of building envelope construction techniques. In addition to BIC limitations, post-war housing re-construction challenges requires special consideration on cost implications, resource limitation and on underlying building envelope standards bottlenecks.

The demand for interdisciplinary and user-friendly numerical approaches for envelope selection was highlighted for further research so that architectures and engineers can integrate innovative envelope techniques in housing designs (Khaddour and Yeboah 2023; De Gracia et al. 2015). This is considered vital approach from energy, economical and sustainable point of view. Previous research recommended envelope construction techniques present significant differences in various countries as the simulated annual thermal loads are the main inputs required for evaluating envelope techniques. The data used for calculating energy in previous research are different to those used in Syria, and so, the findings are of limited value.

This research aims to examine the potential relevance of BIC standards in informing post-war social housing design in Damascus. The main themes are the compliant envelope structures improved performance compared to conventional building envelope, on the one hand, and, the selection criteria for efficient envelope structure for Damascus climate, on the other hand. In this regard, the research objectives are:

- To investigate BIC standards in terms of envelope techniques variables associated with comfort, thermal, energy and cost for Damascus climate.
- To evaluate compliant building envelope structures compared to conventional building in terms of envelope thermal properties, building simulated thermal loads (heating and cooling) and cost–energy trade-off.
- To endorse the lessons in developing simplified criteria that informs the selection of building envelope construction technique for Damascus climate.

Literature review

Many countries around the globe have developed building insulation codes to enhance housing energy saving and environmental impact. This section comprises a broad literature review covering the evolution of insulation and thermal comfort standards in different countries, the development of envelope materials and the building insulation code considered in this study.

Historical context

The evolution of insulation and thermal comfort standards has been frequently evaluated in recent years (e.g., de Dear et al. 2013; Nicol and Humphreys 2010; Yu et al. 2012; Cao et al. 2011a, b). Around the world, most governments have realized the impact that housing has in terms of energy consumption and greenhouse emissions. Increasing the heat transfer resistance of the building envelope is one of the approaches toward reducing building energy consumption (Hao et al. 2022; Zhang et al. 2010a, b, c, d).

To ensure pursuing appropriate building envelope construction, building legislations have evolved during the years. The cods provide the minimum energy performance requirement for new housing. The UK Government, for example, has recognized the impact of building envelope on building energy efficiency since 1985 when "Part L" was introduced into the UK Building Regulations. These regulations focus on building envelope construction and material. More amendment was conducted in the 2006 edition of Part L, as Section 1 Design Standards was modified. A more comprehensive building energy efficiency method was emerged in Building Regulations (2006), as it set the carbon dioxide (CO_2) target emission rate (TER) and the proposed dwellings carbon emission rate (DER) were provided for the housing sector. The building envelopes conductivity was calculated via the following method, according to the UK Building Regulations (1995) edition:

A) Elemental method: estimated *U*-values were provided for different envelope components.
B) Target *U*-value method: average *U*-values were calculated by means of the total floor area, the total area of walls, the proportion of windows and heating efficiency.
C) Energy rating method: ventilation amount, fabric losses, water heating consumption, internal heat and solar gains were simultaneously.

In 2008, the UK Government sat ambitious emission reduction targets, with an aim of 80% reduction in carbon emissions by 2050. In 2010, an update of the Part L1A was formulated, with a carbon emissions rate calculation from the Government Standard Assessment Procedure (SAP) (2009). Additionally, the SAP indicates a cost-effective method aiming to improve the building envelope fabric first. Improving envelope insulation is the most effective Environmental Resource Management (ERM) approach, with heat loss reduced up to 40% with cavity wall insulation and up to 50–80% with external wall or roof insulation (Jones et al. 2017). In the 2013 version, the target fabric energy efficiency (TFEE) was created alongside target emission rate (TER) as the minimum building energy performance requirement (The Building Regulations 2013). The next update was announced in 2016 without any additional technical changes. The near-zero-energy requirements for new buildings indicate that "where a building is erected, it must be a nearly zero-energy building" (The Building Regulations, 2021). The UK Net Zero Strategy (2021) points the post-pandemic demand to improve affordable energy efficient housing. One of the main benefits is to prevent Sick Building Syndrome (SBS) symptoms experienced during the quarantine (Lan et al. 2019). More recently, the actual target is net zero by 2050. As a result, the UK Building Regulations have been modified to reach the UK Government's plan.

More international building envelope standards have been developed with the main intention of maximizing benefits of integrated, cost-effective adoption of green design and building envelope construction to overcome the problems related to energy consumption and GHG emissions, and to monitor building thermal performance. However, Building Research Establishment Environmental Assessment Method (BREEAM) published in 2020 called Ecohomes, an environmental rating for houses. Ecohomes was updated over a year, built the fundamentals for the Code for Sustainable Homes, by the UK Government. In 2008, two stages were introduced in the assessment (BREEAM 2008): 1. design stage (DS) for an Interim BREEAM Certificate and 2. post-construction stage (PCS) for a final BREEAM Certificate.

In the USA, in 1998, the Leadership in Energy and Environmental Design (LEED) was launched as a system to evaluate and certify buildings. Similar to BREEAM, LEED is centered on a credit system. Consequently, a credit weighting system has been developed by the US Green Building Council (USGBC), following the specific rating criteria (Kubba 2010). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) implemented thermal comfort approach into construction practice in the mid-1990s. de Dear (2011) divided the adaptive thermal comfort processes into two categories: (1) behavioral (using operable windows, fans, doors, sunshades, etc.) and (2) psychological (developing building envelope insulation toward climatic conditions). The American National Standards Institute (ANSI) in charge of the ASHRAE 55-2004R Thermal Insulation Environmental Conditions.

In Europe, a project named SCATS replicated the ASHRAE by conducting a survey on 26 buildings located in 5 EU countries, over 1 year (Nicol and Humphreys 2010). This survey formed the base for the EU insulation standard, 1EN15251, announced in 2007 (de Dear et al. 2013). Some similarities between the insulation standards of EN15251 and ASHRAE 55-2004 contain the conductivity equations and acceptable temperatures inside buildings to the outdoors temperature (de Dear et al. 2013). Other differences between the insulation standards of EN15251 and ASHRAE 55-2010 2004 are: 1) the geographical scope of ASHRAE 55-2004 standard was global, whereas

EN15251 is EU focus and 2) the different methods used to evaluate thermal loads in each of the database's constituent buildings were identified (Nicol and Humphreys 2010).

To this point, envelope construction techniques appear to have major influence on residential building's thermal comfort, cost and energy saving. In order to decrease the heat transfer to the required limits, many thermal insulation codes around the globe concentrate on external wall insulation techniques. External walls may be constructed in various ways to meet insulation standards providing that the structural requirements are met. To achieve low thermal conductivity suitable wall construction technique is required (e.g., increasing material thickness, improving insulation material properties or adopting the hollow wall construction).

The evolution of building envelope materials

This section reviews the evolution and the importance of the main commercialized building envelope materials. The energy consumption of housing depends on the characteristics of its envelope. The thermal performance of building envelope material directly influences the energy efficiency of buildings. Therefore, the building envelope's thermal insulation is a key factor for reducing the energy consumed for both winter heating and summer cooling. Insulation materials play an important role in terms of: the selection of the building envelope material, its thickness and its position, allow to obtain good indoor thermal comfort conditions and energy efficiency (Khaddour and Yeboah 2022). Envelope materials thermal properties, sound insulation, resistance to fire, water vapor permeability and impact on the environment and on human health need to be carefully considered when designing a building envelope.

Heat flows through building envelope units (walls, roofs and windows), as heat transfers form hotter zone to cooler area in building (Daouas 2011). For that, the building envelope construction technique should be selected based on this law of heat transfer. This property is measured in "thermal transmittance *U*-value." The main advantage of thermal insulation here is the retuning of temperature within the building regardless of the outside temperature. It retains the thermal comfort for occupants; in summer (cooling season) when envelope should not allow heat gain from outside and in winter (heating season) when the heat should not be allowed to leave the building (Lotfabadi and Hançer 2019). As a result, appropriate building envelope construction technique is responsible for indoor comfortable conditions by keeping buildings cool in hot summer and warmer in cold winter.

Heat transmission in buildings has many ways: (1) heat transfer through material depending on the difference in temperature between indoors and outdoors, (2) insulation thickness, (3) external exposure area, (4) heat flow time duration and (5) material conductivity (Lotfabadi and Hançer 2019). For that, the envelope insulation material main properties should be: (1) thermal resistance, (2) fireproof, (3) insect proof, (4) durability, (5) non-absorbent of moisture, (6) economic and (7) availability (Thapa and Panda 2015).

Envelope thermal insulation materials have many forms: (1) insulation slab (2.5 mm thickness boards) or blocks (60 cm × 120 cm), (2) flexible fibrous blanket rolls made from wool, cotton, animal hair, etc. (12–80 mm thickness), (3) bat insulating material (similar to the previous blanket insulation type but greater in thickness) (4) board insulation (for interior lining of walls), (5) reflective sheets (for high heat resistance) (Lotfabadi and Hançer 2019). Simultaneously, the choice of building envelope construction technique depends upon: (1) material cost (2) exposure area to be covered (3) required insulation code standard and (4) heating and cooling coat (Lotfabadi and Hançer 2019).

Building envelope is normally realized using insulation materials acquired from polystyrene processed with high energy consumptions (e.g., glass and rock wools) or from natural sources. These envelope materials' impacts on the environment depend on its production stage (e.g., the use of non-renewable materials and fossil energy consumption) and its disposal stage (Asdrubali et al. 2015). The introduction of sustainable buildings has encouraged researching advanced thermal insulation using natural or recycled materials.

Building envelope technical specifications (e.g., the thermal properties of building envelopes components), is provided and presented by manufacturers, with its certified laboratory tests. In the laboratory tests, building envelope components' thermal insulation properties are calculated in compliance with each country codes and standards. Asdrubali et al. (2015) examined a state of the art of building envelope insulation made of natural or recycled materials that are not commercialized. The study performed comparative analyses taking into account thermal conductivity, specific heat and density. Building envelope local materials and even industrial byproducts are encouraged as these material limit transportation and disposal impacts.

Although the life cycle assessment (LCA) approach was recommended to evidence the environmental advantages of envelope's materials (Khaddour et al. 2023), most of the available studies focus on either the design phase or the occupancy phase. For the design phase, building energy modeling tools were widely used in previous relevant research. Building envelope components *U*-values are calculated at this phase based on building envelope materials' quantity and specifications (i.e., mortar, block, stones, insulation material) (Kelly et al 2012). At the occupancy phase, the on-site *U*-value and heat losses are measured on-site using thermal flux equipment for infrared surveys (Asdrubali et al. 2014). In this case, sensors are placed on both sides of the envelope and the outcomes are monitored for a minimum duration of 72 h, while the indoor temperature is fixed (Kosmina 2016). Despite the long time needed to undertake an on-site test and the costs involved, differences have been found between design phase *U*-values and the on-site one. Therefore, diagnostic tests are important to examine the actual energy efficiency of existing buildings (Berardi 2013).

Another cradle-to-gate approach by Skullestad et al. (2016) found that timber buildings had significantly lower embodied carbon (9–56%) than their mineral counterparts. The authors compared cradle-to-gate impacts for timber and RC alternatives for four envelopes. The outcomes were in the range 111–121 $kgCO_2e/m^2$ for mid-rise RC structures and 26–40 $kgCO_2e/m^2$ for timber. In comparison, another research by Spear et al. (2019) conducted a sensitivity analysis found a narrow gap between concrete and timber when higher emission factor is applied.

Purnell and Black (2012) investigated the embodied carbon of envelope materials as a function of their load capacity. The importance of material selection was found to be dependent on the context and general conclusions were drawn that timber should be preferred for very light duty columns and longer, light duty beams, while other cases needed more careful assessment. Simultaneously, it was found that the RC made from a concrete mix optimized for low embodied carbon (C50/60 with 40% of cement replaced by pulverized fuel ash) achieved the lowest embodied carbon (Purnell and Black 2012).

Some researchers found that timber construction has many advantages over mineral alternatives considering the displacement factor. Sathre and O'Connor (2010) used meta-analyses to investigate displacement factor of 2.1 tons of carbon emissions prevented per ton of carbon in the timber. Geng et al. (2017) found a range of 0.25–5.6 tC/tC, comparing wood framed buildings to steel and concrete options, for which the range was 0.9–2.2 tC/tC.

While buildings are currently dominated by few insulation material categories such as mineral wool, extruded and expanded polystyrene, the demand for more sustainable material outlines developing opportunities for new insulation materials. Several research examined thermal, acoustic and environmental performance of building envelope materials. Future research is directed toward unconventional material that can be manufactured using natural sources such as residues of agricultural production and processing industries. Other sources are represented by recycled products or industrial plants byproducts. This research will focus on thermal issues-related building envelope material for Syria reconstruction post-war context.

The building insulation code considered in this study

In Syria post-war re-construction, the quality of new affordable homes dropped as building as many new homes as possible became a higher priority than quality. In Syria, the process was initiated through the introduction of: Building Insulation Code (BIC) (which is the focus of the current study), Energy Efficiency for Homes Labels in addition to the Energy Conservation Law in 2009 by the National Centre for Energy Research (NCER). This section elaborates on BIC, envelope trade-off compliance and multiple previous studies. The Building Insulation Code (BIC) contains 5 Chapters and 7 Appendices. It comprises the following chapters: (1) general requirements (definitions, abbreviations and acronym), (2) building envelope scope and thermal compliance, (3) building insulation material (selection and implementation), (4) humidity in buildings and (5) operational energy efficiency.

2021 International Energy Conservation Code (IECC) defined envelope as all building elements enclosing the conditioned space (e.g., basement walls and ground, exterior walls, floors, roofs). Thermal performance evaluation approach is required for establishing building insulation codes as building envelope construction techniques impact thermal transmittance. Thermal performance is calculated based on heat loss and is usually expressed in buildings as U-value (reciprocal of R-value) (Lotfabadi and Hançer 2019). U-value is defined as the rate of thermal transmittance across a structure (which can occur through one material or multiple-layer envelope), divided by the difference of temperature (ΔT) between inside and outside air across that structure, in units of W/m^2K (O'Brien et al. 2020). The envelope thermal transmittance (U-Factor) is defined as the factor of heat flux through an envelope elements per unit area and unit temperature variation between the warm side and cold side ($W/(m^2\,K)$) (Kamel and Memari 2022). Heat flux, Φ, is measured in power units [W] (e.g., energy units per second) as presented in (Eq. 1):

$$\Phi = \left({}^{\sigma}A_i \times U_i\right) \times \Delta T \tag{1}$$

A = Heat transfer area [m^2].

U = Thermal transmittance [W/m^2k].

ΔT = temperature difference [k] between the two sides of the envelope. $\sigma\, Ai \times Ui$ = sum of all heat transfer areas (walls, roof, windows, etc.) times the corresponding U-value

Therefore, the better building envelope construction technique is, the lesser the U-value will be. The range of the operating temperature defers depending on each country considerations. The thermal comfort index is provided by the insulation codes measured as the percentage of people dissatisfied (Kamel and Memari). Given the anticipated post-war re-construction growth in housing stock across Syria, BIC sets the minimum standards for envelope components compliance parameters. The code provides the maximum allowable limit to: the ratio of openable window to floor area, windows thermal transmittance (U-window), roof thermal performance (U-roof) and external wall thermal transmittance (U-wall). The thermal envelope transmittance depends on two factors: the construction type which regulates the transmittance limit (U-max) and the climatic zone which controls the average transmittance limit (U-med). It is worth noting that some insulation codes regulate only the U-max parameter, e.g., German, British, Passivhaus and BIC standards. In contrast, the USA insulation code regulates only the *U*-med parameter. In BIC, the envelope transmittance value limits are specified for better thermal performance and energy saving. The code applies to new dwelling and specifies minimum requirements such the ratio of windows area to the floor area based on the climate zone. The BIC recommended building envelope *U*-max are: *U*-wall = 0.8 W/m^2/k (several composite external walls were presented), *U*-roof = 0.5 W/m^2/k (upwards heat flow direction) and *U*-window of 3.5 W/m^2/k (double-glazed windows).

BIC *U*-value is used as a key parameter to feature building envelope thermal performance. This parameter, calculated in (Eq. 2), symbolizes the heat loss/gain through the structure components per unit area.

$$U = \frac{1}{R_T} = \frac{1}{R_{Se} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + R_{si}} \tag{2}$$

U: heat transmission W/(K m^2).
R_T: thermal resistance (K m^2)/W.
R_{Se}: heat transfer resistance (externally) (K m^2)/W.
R_{Si}: heat transfer resistance (internally) (K m^2)/W.d_i: layer thickness mλ_i: thermal conductivity W/(K m)di/lambda..sub.i = Ri: thermal resistance (K m)/W

Equation (2) demonstrates the thermal properties of the building envelope components, available in Annexure-4 of BIC. It represents the thermal performance of different building envelope components (external wall (*U*-wall), window glazing (*U*-window) and roof (*U*-roof)). Therefore, BIC requirements include the maximum *U*-values allowed for each climatic zone.

The code should ideally regulate envelope selection criteria (cost, space requirement, esthetic, embodied energy). The advantage of implementing this study simplified criteria along with building energy and thermal performance software is to select a viable envelope structure. Considering the massive number of post-war residential projects, these simplified criteria are essential to mitigate the peak loads which can in turn minimize the total energy consumption and cost. Although BIC prescriptive of energy efficiency measures encourages several envelope design approaches, it does not include any whole-building thermal performance method. For deciding on envelope design, building must be simulated using a thermal performance or energy analysis software, i.e., IESVE, VDOE or Energy +.

To conclude, the phenomenal global growth in sustainable buildings, energy crises and the need to build back better for Syria post-war construction have driven the interest in the concept of adaptive building envelope material. BIC comprises general principles of thermal insulations to ensure envelope's heat resistance. This thermal performance of envelope materials depends on its properties and thickness (Thapa and Panda 2015). BIC standards attempt to identify building envelope solution at the design phase. Hence, limited improvements have been made over the years regarding the building thermal performance in Syria (Khaddour 2021b). According to BIC, building envelope components should have sufficient thermal insulation and a minor heat conductivity. Therefore, envelope material thickness and thermal performance are important parameters for selecting the sufficient building envelope construction technique. There are few research comparing of traditional vs contemporary BIC compliant buildings are expected to be different in terms of post-occupancy energy efficiency and thermal comfort.

Previous studies

This section elaborates on the previous related research results and methods. To an extent, previous research defined thermal loads as the heat to be supplied from a building's interior to maintain thermal comfort conditions. In this sense, thermal load on residential building depends on many variables, e.g., outside solar radiation, occupancy rate and equipment being used inside (Khaddour 2021b). Several available methods of thermal load calculations are summarized by Thapa and Panda (2015) as follows:

A) Approximate methods: these methods are helpful at the planning phase. In this case, then change to the average of energy requirements is analyzed (e.g., the degree-day method and bin method).
B) Correlation methods: this method focuses on thermal relationship in format of a correlation coefficient (e.g., the ratio of solar load and the ratio of load collector).
C) Simulation models: in this method various simulation software are used for evaluating envelope heat conduction equations (e.g., Energy Plus, Trnsys, IESVE, RetScreen, Hot2000).

For example, Vivian et al. (2020) analyzed the effects of envelope structure, occupants' behavior and temperature on the energy consumption and thermal comfort for three reference dwellings in Europe. The research findings revealed that during winter (heating season) the thermal energy lost, through envelope, increases from new to old dwellings resulting in lower efficiencies for old building envelope construction techniques especially in severe cold weather conditions.

Andreasi et al. (2010) conducted a comparative study on ISO/FDIS 7730:2005 compliance buildings in Brazil's hot and humid climate. The research survey, on the selected occupants, revealed differences among actual thermal performance, predicted insulating material thermal properties and the thermal conditions calculated according to ISO standard.

Langevin et al. (2012) analyzed three centrally HVAC building case studies from the ASHRAE compliance perspective at the post-occupancy phase. The authors found important correlations between thermal loads and building envelope layers for controlling the thermal environment. Similar research outcomes from a study conducted in Japan on six buildings; based on thermal load modeling (Goto et al. 2007). The research found that the occupants in the case studies had more opportunity to control their thermal conditions (i.e., operable windows or controllable HVAC) than normally expected in centralized HVAC buildings.

Hasan (1999) developed a simplified approach for the optimization of thickness of insulation material optimization in Palestine Mediterranean climate. Hasan's proposed a life cycle cost analysis in order to select external wall thickness as a function of its thermal resistance. The results indicate the possibility of savings up to 21 $/m^2 of wall area with payback periods between 1 and 1.7 years for sandwich rock wall with wool insulation in the middle. The payback periods were between 1.3 and 2.3 years for a sandwich rock wall with polystyrene insulation in the middle.

The same methodology was also used by Mohamed (2020) who investigated building heat loads for two types of walls and ceiling with and without thermal insulation in Egypt. The cooling load temperature difference method was used to estimate the building heat load during a year. The results indicate an average of yearly saved energy of about 33.5%. The research findings recommended an optimal insulation thickness between 7 and 12 cm with a payback period of 20–30 months for Egypt according to the latitude and annual degree-days.

To an extent, the previous studies developed fragmented approaches for evaluating building envelope construction techniques. These approaches were limited to the consideration of inner wall surface temperature and heat flux across various types of wall structure.

These methods were extended by Daouas (2011) to determine external wall thickness for a typical residential building in Tunisia. The researcher used simulated annual thermal loads as inputs based on complex finite Fourier transform method. The research recommended that external walls can be constructed more economically with 10.1 cm insulation thickness, 71.33% energy savings and 3.29-year payback period.

Some researchers measured annual heating and cooling loads independently. For example, Lotfabadi and Hançer (2019) conducted a comparative analysis between traditional and contemporary envelope structures in Cyprus' hot and humid climate. The research modeling results demonstrated achieving thermal comfort levels only for limited duration of the year. Also, the research found that increasing building height resulted in an increase in thermal comfort but it rose the total energy consumption of the building between 6 and 9%.

Another comparative study between conventional and energy efficient housing in Damascus by Khaddour (2021b) evaluated the operational energy saving and identified the technical, economical and organizational barriers for implementing the building energy efficiency law (Law No. 18 2009). The energy efficient building achieved a 63% of overall savings in energy consumption but a 35% increase in initial cost resulting in a payback period of 10 years. The study recommended further research on building envelope construction techniques for the newly implemented building insulation code in the light of national effort for reconstruction.

Seminara et al. (2022) suggests a cost-effective method, with an approach that aims to improve building envelope first followed by building services and then more active elements. This approach provides a precise order based on each country priorities, assessing the possibility of any knock-on effects. Similar three-phase approach was detailed by Khaddour and Yeboah (2022) for Syria post-war reconstruction. Given the post-war reconstruction situation, the quality of new affordable homes dropped as building as many new homes as possible became a higher priority than quality. Therefore, building envelope and passive design (phase 1) is viewed as the most appropriate focus for the post-war settings. This phase starts form pre-design stage to assist the owner, planner and others involved at the planning and pre-design stages of the project. This phase's main indicators are calculation of material thermal resistance, e.g., *U*-values, using thermal performance simulation and costing analysis (Khaddour and Yeboah 2022). Phase 2 building services and metering and phase 3 active elements are viewed as overreaching technology and high-cost implications.

To this end, the recommended envelope construction techniques present significant differences in various countries. Additionally, the simulated annual thermal loads are the main inputs required for evaluating building envelope construction techniques. Most of the previous research calculated thermal load by the degree-days means. Hence, the variety of results is mainly due to the wide range of housing design, insulation materials, housing life span and climatic conditions. Hitherto, the data used for calculating energy in previous research are different to those used in Syria, and so, the findings are of limited value.

For Damascus climate, to reach comfort levels both winter heating loads and summer cooling loads should be analyzed. In this research study, the IESVE method is used for simulating the thermal loads through various compliant external wall structures in Damascus specific periodic outdoor temperature. This research will estimate summer annual cooling loads and winter annual heating loads which will be computed for several BIC compliant external wall construction techniques and will be compared to conventional building envelope construction. The methods and materials used in this research are explained further in the next section.

Materials and methods

This research aims to tackle the BIC envelope insulation data shortage problem and to boost the performance of thermal comfort prediction in Syrian Housing reconstruction. As shown in Fig. 1, the research methodology can be exemplified in four stages: stage one: parametric analysis for five envelope construction techniques (building details and methodological details), stage two: sensitive analysis simulating the annual heating and cooling loads, stage three: cost–energy trade-off analysis and stage four: a simplified criteria will be developed and recommendations on possible BIC improvement will be outlined. This study took place in Damascus from December 2018 to January 2020.

Input parameters and preliminary considerations

IESVE modeling is commonly used to simulate envelope thermal performance, to evaluate envelope elemental heat loss and to examine indoor comfort. IESVE utilizes inputs from building design, envelope elements' thermal properties and climatic zone data (Khaddour and Yeboah 2022). A variety of input and output reports are generated for analysis. In this study, IESVE thermal load modeling is used to determine the building thermal load for different envelope insulation systems. The common chart dialog is used to accommodate the different displays and manipulation for the displayed output.

Site location and weather data of the building and the weather to which it is exposed are specified according to BIC. The selected location records include the latitude and longitude of the site while the climate data cover the conditions of both the heat loss and heat gains estimates and the thermal modeling (Khaddour 2021b). The preliminary considerations about Damascus (36° 13′ N, 33°29′ E), the capital of Syria, are chosen as the study area. The city is in the southern part of Syria, about 80 km from the western side of the Mediterranean Sea, separated from it by long mountain borders between Syria and Lebanon.

In Damascus, to reach thermal comfort levels, buildings demand both heating in winter season and cooling in summer. In summer season, the cooling system starts operating from the 1st of June until the 31st of September (annually 120 days). In winter season, the heating system starts operating from the 15th of November and continues until the 15th of April (annually 150 days). According to Syria map climate zones, Damascus highest recorded temperature is 40 °C, whereas its lowest temperature is − 2 °C. Table 1 shows the external surrounding environmental parameters that should be considered for Damascus buildings design according to BIC. The input climate records used in the thermal performance analysis must reflect whole year temperature, solar radiation, humidity and wind speed for the climatic region, as given in Table 1. Hence, BIC lacks any simulation consideration. In the current study, different compliant building envelope techniques parameters will be evaluated in three specific performance levels (U-values, thermal loads and energy–cost trade-off).

In the present study, the given parameters are the inputs of the simulation to provide accurate results (e.g., building location and orientation; envelope thermal properties, occupant load, HVAC systems type, energy consumption, conditioning capacities and operational profiles). Five types of envelope construction techniques will be evaluated based on material conductivity, simulated cooling and heating loads and associated cost.

Choice of the buildings

The residential area under study, Qudsaya's residential project for post-war youth housing, covers an area of 240 hectares, offering 11,300 apartments with areas of 60, 70 or 80 square meters each. Qudsaya is at the Northwest edge of Damascus (Fig. 2).

Qudsaya residential project will contain overall 515 buildings distributed among: 52 (10%) ten floors buildings, 313 (61%) four floors buildings and 150 (8%) two floors buildings. Therefore, the selected four-story conventional building type represents 61% of buildings in Qudsaya's project. This building type represents 43.4% of Damascus residential buildings height classification (Alhourani and Koike 2013). Two existing building types were selected first. A pilot project case-1 is a thermal insulated compliant building with central solar heating system for heating in winter and conditioning system for cooling in summer, as shown in Fig. 3. Case-2 is the conventional baseline building (with no insulation and similar central heating system for winter and conditioning system for summer).

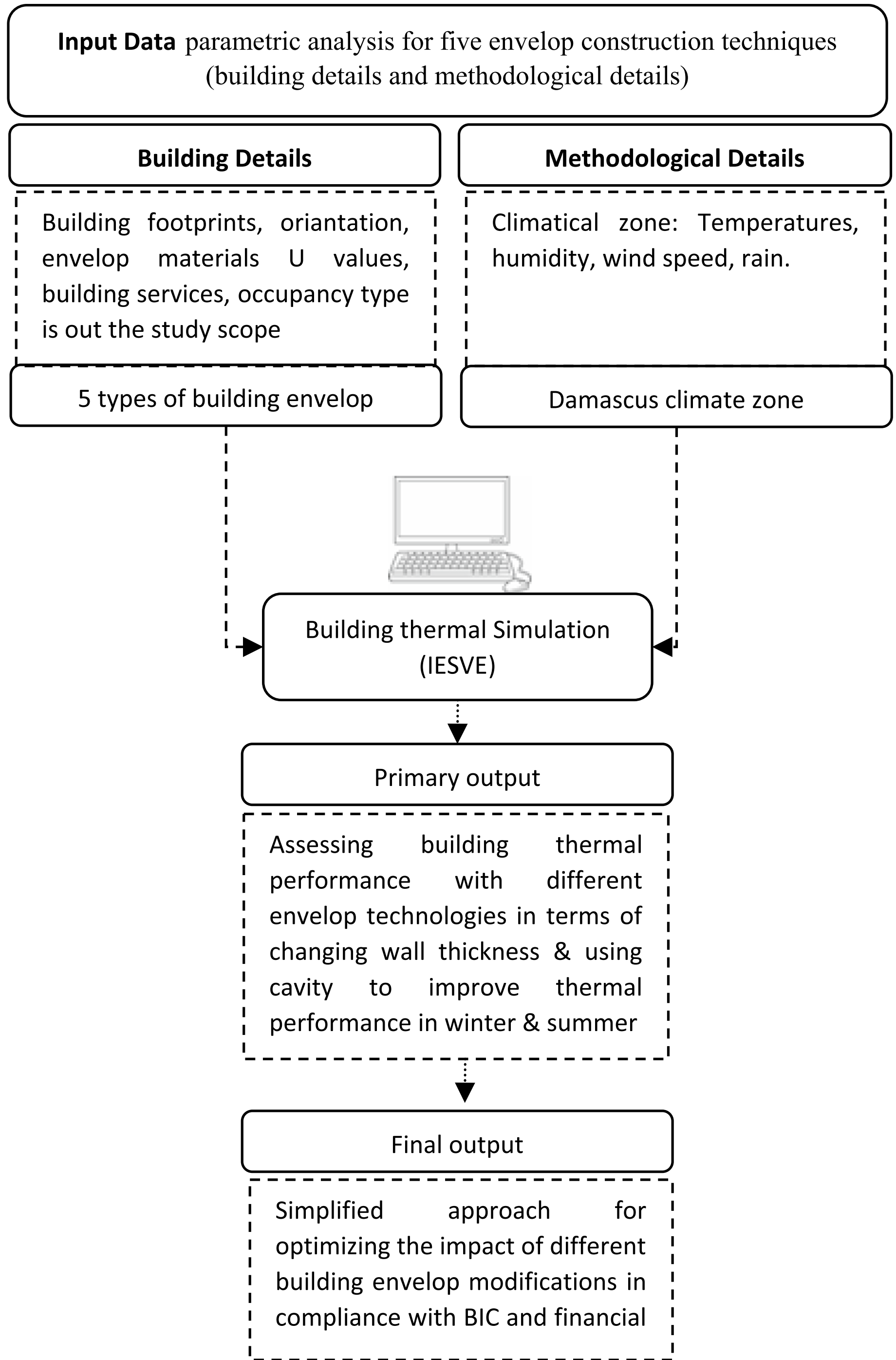
The buildings under study are assumed to be in same climate location with the same layout and orientation. Buildings case-1 and case-2 were constructed in 2010 by the same crew: the General Company of Housing (the owner), the General Company for Engineering and Consulting (GCEC) (the design company) and LAMA company (private contractor). Additionally, consultants were invited onboard for the pilot project design and monitoring (case-1) namely, the National Energy Recourse Center (NERC) (local consultant) and Medenec (European energy consultant). Since the focus of this study is on the influence of envelope construction techniques on building thermal performance, energy consumption and cost–energy trade-off, more BIC compliant building envelope construction techniques will be simulated for the same building design.

Comparison of the thermal envelope transmittance

This section highlights the compliance with BIC specifications in terms of windows, roof and external walls.

1. Compliance with BIC window-to-floor ratio (WFR) specifications: the value of WFR is calculated for the selected buildings. The 16.66% operable window area is compliant with minimum code specified value of the facade area of 20%. An acceptable ratio is typically considered in most Damascus apartments reflecting a conservative Islamic cul-

Fig. 1 Methodology flowchart



ture. Some of the positive design measures are the selected buildings orientation (45° southeast (S45°E)) and the courtyard southwest orientation (Tables 2, 3, 4, 5).

2. Compliance with BIC roof thermal transmittance (*U*-roof) specifications: the methods of calculating *U*-roof is explained in BIC Annexure-4. Case-1 and case-2 *U*-roof values are given in Tables 3 and 5. The envelope materials thickness (ti) is taken from typical constructions practiced in Damascus. Each envelope material resistance thermal conductivity is taken from material specifications records, before multiplying it with the surface area calculated from building elevation; then, all the layers *U*-values are added up for total *U*-roof.
3. Compliance with BIC external wall thermal transmittance *U*- wall specifications: the method of calculating *U*-wall is explained in BIC Annexure-4. Case-1 and case-2 *U*-wall values were calculated accordingly as given in Tables 2 and 4.

Table 1 Damascus climatic zone

City	Lat, oN	Log, oE	Eleva, m	Wind direction		Wind Ws (m/s)	Designed sun radiation [wh/m^2.day]		Daily range Co	Designed H (%)		Designed Co	
				Winter	Summer		Winter	Summer		Winter	Summer	Winter	Summer
Damascus	36°13	33°29	729	W	NW	5.5	2820	7700	19.69	75	30	−2	40

Fig. 2 Location, Qudsaya youth residential project

Furthermore, Table 6 presents different types of external wall construction techniques which will be evaluated in terms of *U*-value improvement, heating and cooling loads and cost saving.

Table 7 presents window types and glazing attributes available in Damascus for parametric simulations.

All cases under study have the same external wall surface area of 398 m^2 each. Further, cooling and heating loads will be simulated using IESVE using the same building design for the five envelope types, as highlighted in the next section.

Results and discussion

This section comprises description of the comparative study, data collection and analysis. The research has been assessed by means of computer monitoring, field visits and computer energy simulation.

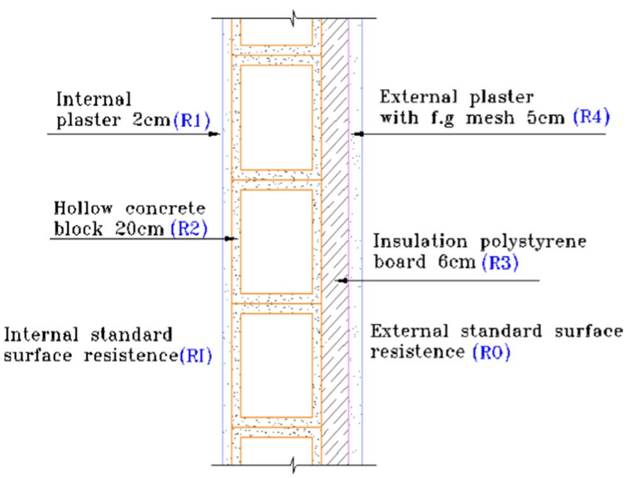
Parametric study

For carrying out the parametric study, 5 types of residential buildings envelope were selected as per a study carried out by Khaddour and Yeboah (2022). The five typical buildings were analyzed to represent most of the housings constructed in Syria post-war. Detailed architectural, functional and operational data of the houses were obtained from project drawings, specifications, utility bills and reports provided by the General Company of Housing (the owner), the General Company for Engineering and Consulting (GCEC) (the design company) and LAMA company (private contractor). The glazing and the roof attributes are assumed to be adiabatic for parametric simulations. This uniformity is seen essential to priorities external walls while the middle floors of multi-storied residential buildings have no heat transmitted from adjacent floors.

Applying external building material insulation layer	**Solar energy system for backing up under floor heating**	**Solar energy system for heating water**
		

Fig. 3 Compliant building case-1

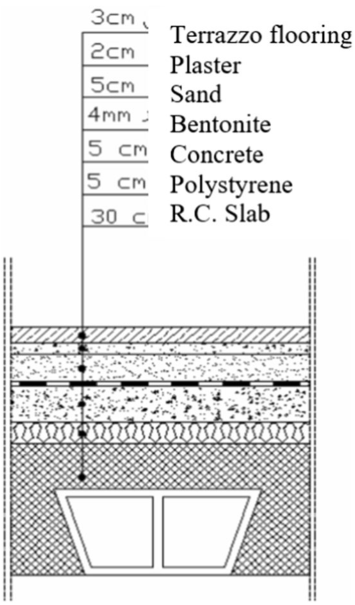
Table 2 Building (case-1) external wall material with insulation, U-value = 0.4 W/m^{2}K



Material	Thickness	Conductivity	Resistance
Symbol	ti	ki	R
Unit	m	W/(m k)	(m^2 k)/W
Internal standard surface resistance Ri	–	–	0.12
Internal plaster	0.02	0.720	0.028
Hollow concrete block	0.2	1.173	0.171
Insulation polystyrene board (30 kg/m^3)	0.06	0.032	1.875
External plaster with f.g mesh	0.05	0.100	0.050
External standard surface resistance Ro	–	–	0.02
Total R value (m^2 k)/W 2.264			
Overall wall thermal transmittance: U value W/(m^2 k) 0.4			

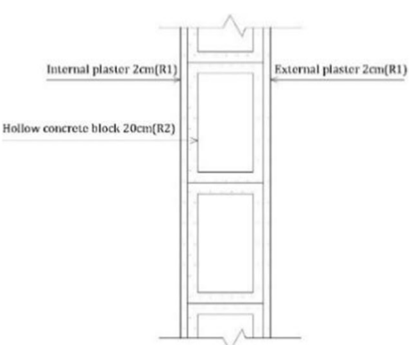
The input of envelope structures, technical specifications and U-values of the external walls, roof and glazing for the selected envelopes are presented in Table 8. Case-3 is similar to case-1 in design and in roof and window types but with different external wall structure: double concrete block (7 cm and 10 cm), 5 cm empty space in the middle, 2 cm internal cement mortar and 3 cm external cement mortar. Case-4 is similar to case-1 in design and in roof and window types but has a sandwich wall structure: double concrete block (7 cm and 15 cm), 5 cm polystyrene layer in the middle, 2 cm internal cement mortar and 3 cm external mortar. Case-5 is similar to case-1 in design and in roof and window types but with compliant external sandwich walls which consist of double concrete block (7 cm and 10 cm), 5 cm Styropor layer in the middle, 2 cm internal cement mortar and 3 cm external mortar (Table 8).

Table 3 Building (case-1) roof material with insulation, U-value = 0.4 W/m^2



Material layer	Thickness	Conductivity	Resistance
Symbol	ti	ki	R
Unit	m	W/(m k)	(m^2 k)/W
Internal standard surface resistance Ri			
Tile	0.03		0.01
plaster	0.020	0.720	0.028
Sand	0.05	0.578	0.086
Protection concrete layer	0.05	0.71	0.070
Bitumen waterproof layer	0.004	–	0.030
Extruded Polystyrene (30 kg/m3)	0.05	0.032	1.562
Bevel Concrete layer	0.05	0.71	0.070
Combined (concrete + block)	0.3		0.250
Plaster	0.020	0.720	0.028
External standard surface resistance			0.020
Total R value (m^2 k)/W 2.254			
Overall wall thermal transmittance: U value W/(m^2 k) 0.4			

Table 4 Building (case-2) conventional building external wall material, U-value = 2.045 W/m^{2}K



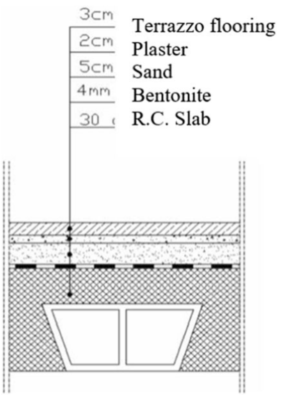
Material	Thickness	Conductivity	Resistance
Symbol	ti	ki	R
Unit	m	W/(m k)	(m^2 k)/W
Internal standard surface resistance Ri	–	–	0.12
Internal plaster	0.02	0.720	0.028
Hollow concrete block	0.2	1.173	0.171
External plaster with f.g mesh	0.05	0.100	0.050
External standard surface resistance Ro	–	–	0.02
Total R value (m^2 k)/W 0.489			
Overall wall thermal transmittance: U wall value W/(m^2 k) 2.045			

The number of occupants was taken as 25.5 m^2/person, as mentioned in BIC. Default schedules (occupancy, lighting and equipment) in the IESVE software were used. Damascus climate zone was selected for the study. Five residential buildings were modeled using the IESVE software with the following Syrian typical residential space occupancy patterns according to BIC:

- Density of lighting power = 7.8 W/m^2
- Density of equipment power = 8.0 W/m^2
- 25.5 m^2/person is the average occupancy density level.
- 22 °C is the set-point temperature in the cooling period.
- 19 °C is the set-point temperature in the heating period.
- The selected design WFR is 16.66% for all cases.
- Estimated wind speed is 5.5 WS (m/s).

Hence, several parameters vary in the selected cases when it comes to estimate the annual heating and cooling loads

Table 5 Building (case-2) conventional building roof material U-value = 2.69 W/m^2



Material layer	Thickness	Conductivity	Resistance
Symbol	ti	ki	R
Unit	m	W/(m k)	(m^2 k)/W
Internal standard surface resistance Ri			
Tile	0.03		0.01
plaster	0.020	0.720	0.028
Sand	0.05	0.578	0.086
Bitumen waterproof layer	0.004	–	0.030
Combined (concrete + block)	0.3		0.250
plaster	0.020	0.720	0.028
External standard surface resistance			0.020
Total R value (m^2 k)/W 0.37			
Overall roof thermal transmittance: Uroof value W/(m^2 k) 2.69			

due to the different wall constructions and different glazing types used, as given in Table 7. This study applies several envelope techniques in order to find out its different impact on heating and cooling loads. Table 6 presents the five selected external wall structures. Each wall has (n) layers of different materials and thicknesses. Building envelope is subjected to fixed design temperature Ti on the inside surface. The outside surface is exposed to the periodical temperature variation (t). Assuming that envelope inside and outside surfaces has same temperature as the surrounding air, the envelope thermal conductivity coefficients comprise convection and radiation properties (Kamel and Memari 2022). The fixed indoor comfort design temperature is 22 °C in the cooling period and 19 °C in in the heating period, according to BIC. These temperature values are expected to increase energy efficiency, but it may result in low occupants' comfort satisfaction.

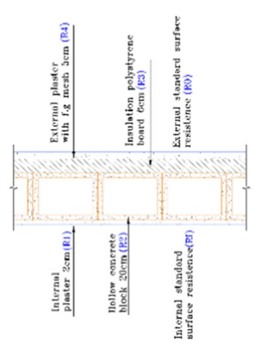
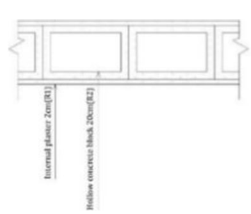
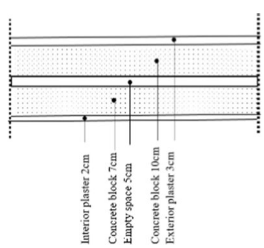
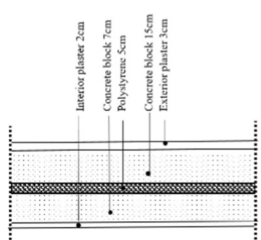
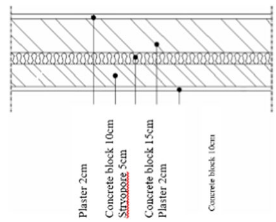
All selected cases are exposed to the same climatic and boundary conditions. Table 2 shows a noticeable improvement in case-1 U-wall of 0.4 W/m^{2}K compared to Table 4 which represents case-2 U-wall value of 2.045 W/m^{2}K. Also, Table 3 reveals a significant improvement in case-1 U-roof value of 0.4 W/m^{2}K compared to Table 5 that shows case-2 U-roof value of 2.69 W/m^{2}K. Therefore, case-1 provides improvement in U-values of building envelope components; walls, roof and windows with 85%, 75% and 50%, respectively, compared to case-2. Table 8 summarizes the five selected cases envelope component U-values. These values are used as inputs for the next section simulation and analysis.

Building energy simulation and thermal performance

The thermal performance for each of the five cases, are assessed through the whole-building thermal simulation. Cooling load and heating load are simulated using IESVE after modeling the building. The floor plan of these buildings is shown in Fig. 4, while the wall and glazing attributes for parametric simulations are given in Table 8. The roof is assumed to be adiabatic, assuming common construction practice of multi-storied residential buildings. IESVE simulate the yearly thermal loads to provide an accurate solution for heat transfer through building envelope under steady periodic conditions. The simulation process is repeated for each day of the summer cooling season (June–September) and for winter heating season (November–April). Then, daily thermal loads are added up for each season to get the annual cooling and heating loads.

In this sense, heat gain determines cooling requirements in summertime temperatures. Heat loss calculation determines heating requirements in winter temperature. Figures 5, 6, 7, 8 and 9 present the combined annual cooling (in blue color) and heating (in red color) transmission loads per square meter for both cooling and heating seasons versus different envelope structures. The simulation outputs show significant impact of envelope structure on building thermal performance. Case-2, the baseline building with no insulation, has the highest heating and cooling loads with a total of 345.1 MWh, as shown in Fig. 6). Out of the four compliant cases (1, 3, 4 and5), the best improvement was achieved in case-4 with total loads of (72.5153 MWh) (Fig. 8). The polystyrene insulation in case-4 achieved slightly better results than the Styropor insulation layer

Table 6 Different types of external wall construction techniques

Case-1: Pilot compliant building with external polystyrene board insulation	*Case-2*: conventional baseline building with no insulation	*Case-3*: BIC compliant option: sandwich wall with empty space in the middle	*Case-4*: BIC compliant option: sandwich wall with polystyrene insulation layer in the middle	*Case-5*: BIC compliant option: sandwich wall with Styropor insulation layer in the middle
				

in case-5 (Fig. 9). The worst envelope performance among the selected compliant cases is case-3 with higher values of annual transmission loads (185.5054 MWh) due to the sandwich walls with an empty space in the middle, U-value of 1.4 W/m^2/k, as shown in Fig. 7.

During case-2 simulation, a warning message popped up at the end of the simulation as the thermal zone in the building has more than 150 cooling unmet load hours. Figure 6 presents unmet load hours for combined cooling and heating load-sensitive analysis of case-2 conventional baseline building with no insulation. This explains the increase in energy demand for cooling and heating in conventional buildings and nictitates the need for BIC to consider not only new building but also existing buildings retrofitting.

Table 9 summarizes the annual cooling and heating loads for the five envelope structures cases. The average improvement in annual total thermal load, compared to case-2, are 77.40%, 61.53%, 84.96% and 84.23% for case-1, case-3, case-4 and case-5, respectively. If BIC standards can be questioned for indoor thermal environments, Damascus social housing cases present more complexity. It is noteworthy, in summers, the placement of external wall exterior insulation layer (i.e., case-1) has the third best cooling load in summer season following the case-4 and case-5. Case-4 and case-5, with the insulation material installed in the middle of the wall, have better performance in winter compared to case-1 with 84% and 83% heating load improvement, respectively.

To this point, BIC should provide total performance evaluation method in order to select building envelope structure that can maintain acceptable thermal comfort for Damascus' climate. Furthermore, residential building energy usage and cost saving can still be optimized by building envelope construction techniques, as discussed in the next section.

Energy–cost trade-off

This section compares between to conventional building case-2 and the pilot project case-1 in terms of annual energy and cost saving in cooling and heating seasons, according to BIC instructions.

1. Heating system (winter season):

The heating system starts operating from 15th November and continues until 15th April; 150 days annually. Additionally, the average operating hours of the central heating system is 12 h per day. Therefore, it operates for 1800 h during the entire winter. The price of fuel liter locally is 215SYP (2019 prices). During the time of the study, Syria's economic crunch has witnessed fuel prices hike by more than 50%, whereas the Global fuel price has dropped dramatically during coronavirus crisis. However, 2019 prices will be considered. For winter heating

Table 7 Window types *U* value comparison chart

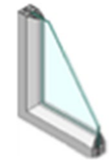
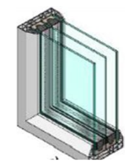
Window types		UK Window energy rating	
Window type	*U*-value W/m^2/k	*U*-value W/m^2/k	
Single-glazed (base case)	5.6	5.2	
Double-glazed	1.9	2.6	
(C) rated windows	–	1.6	
Rated windows	–	1.4	
Eco-choice triple-glazed	–	1.0	

Table 8 Building envelope structures and components U-values

	External wall construction techniques	Wall thickness cm	Wall *U*-value W/m^2/k	Glazing *U*-value W/m^2/k	Roof *U*-value W/m^2/k
Case-1	20 cm Concrete block, 5 cm polystyrene and 2 cm internal and 3 cm external cement mortar	30	0.44	1.9	0.4
Case-2	20 cm concrete block and 2 cm internal and 3 cm external cement mortar	25	2.045	5.6	2.69
Case-3	(7 cm and 10 cm) double concrete block, 5 cm empty space, 2 cm internal and 3 cm external cement mortar	27	1.4	1.9	2.69
Case-4	(7 cm and 15 cm) double concrete block, 5 cm polystyrene and 2 cm internal and 3 cm external cement mortar	32	0.15	1.9	2.69
Case-5	(7 cm and 10 cm) double concrete block, 5 cm Styropor, 2 cm internal and 3 cm external cement mortar	27	0.2	1.9	2.69

Fig. 4 Plan of the selected building design model

season, the following figures were calculated for the compliant building case-1:

- Annual heating loads = 40.4489 MWh.
- Annual fuel consumption for heating is 11,081 L.
- The initial cost for the central heating system (including Boilers, pumps, radiators, tubes …) = 800,000 SYP.
- The total costs of the heating system within 15 years (the lifetime recommended by BIC) = the setup cost + (mainte-

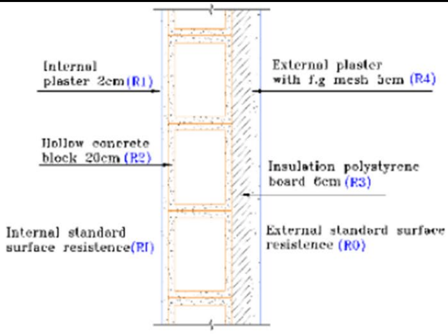
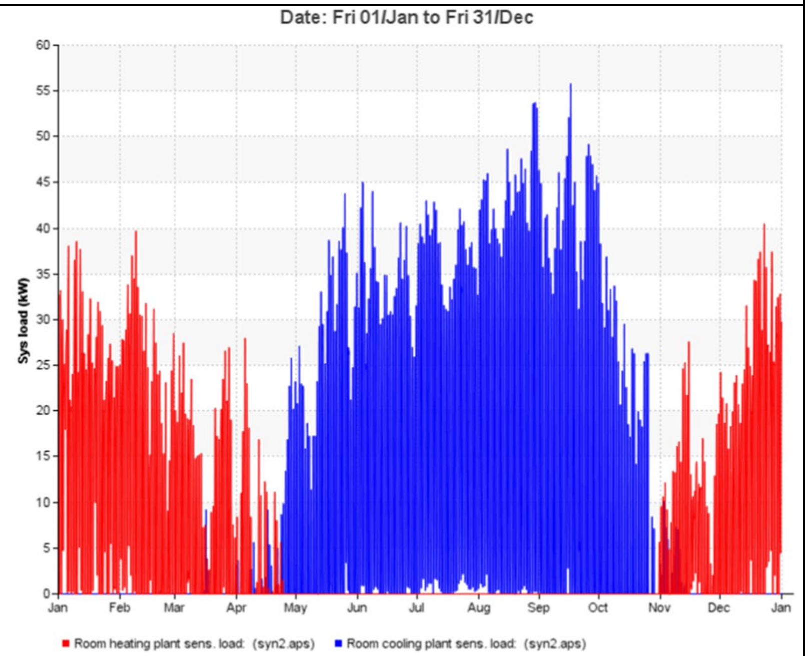
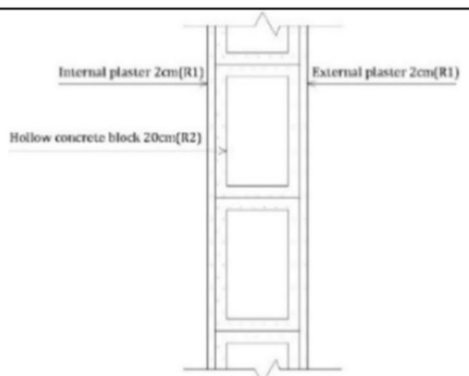
External wall type	Heating load (in red) and cooling load (in blue)
	

Fig. 5 Combined cooling and heating load-sensitive analysis of case-1 pilot compliant building with external polystyrene board insulation. Total loads 101.8MWh



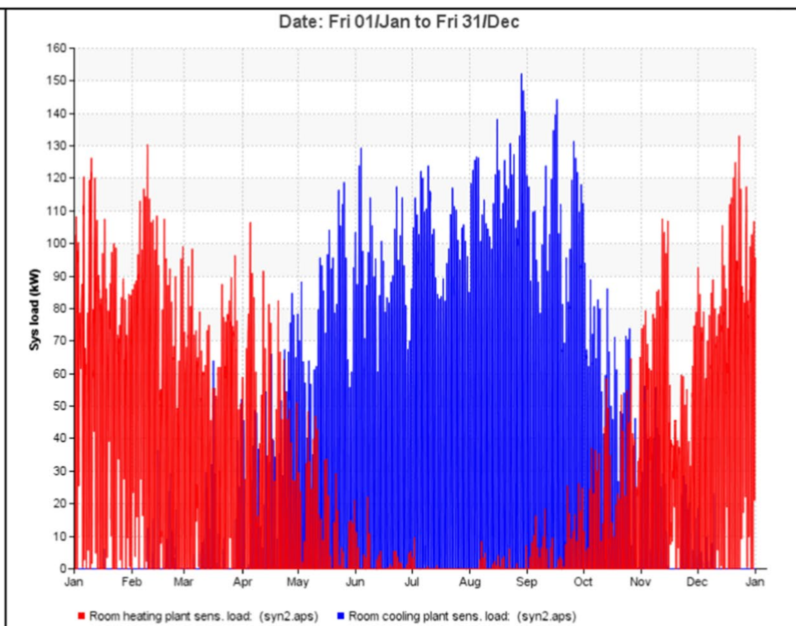


Fig. 6 Combined cooling and heating load-sensitive analysis of case-2 conventional baseline building with no insulation. Total loads 345.1MWh

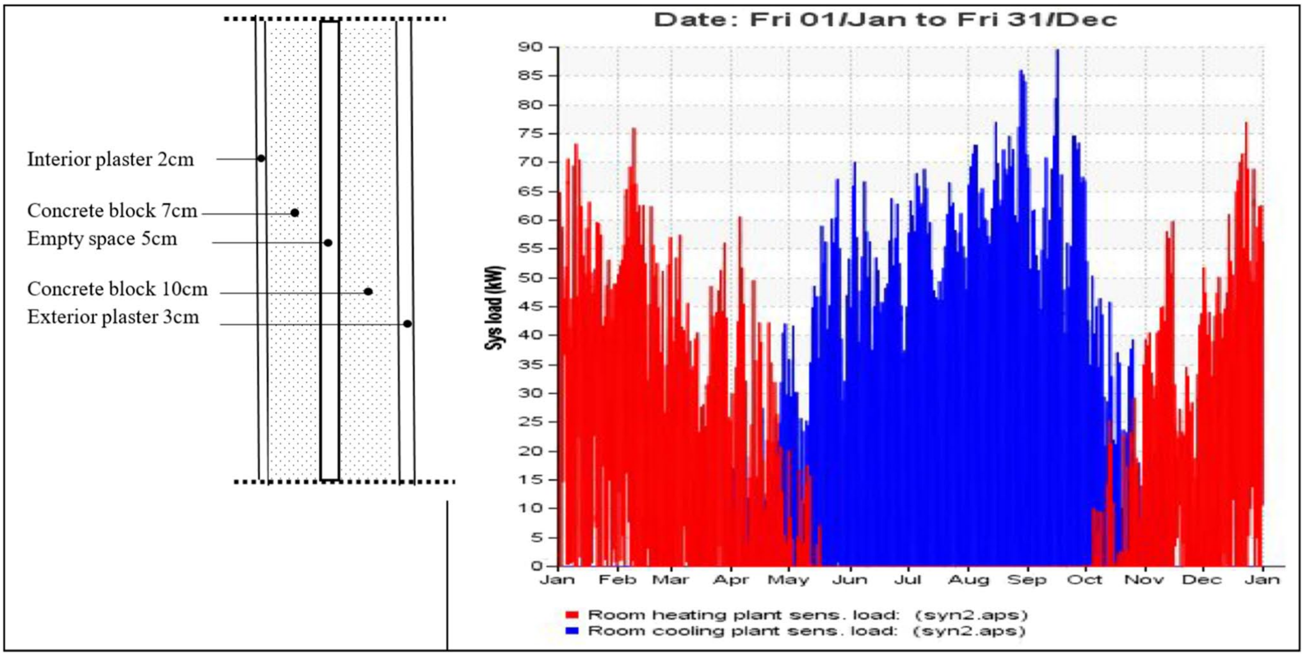


Fig. 7 Combined cooling and heating load-sensitive analysis of case-3 double block wall building with empty space in the middle. Total loads 185.5054 MWh

nance and operating costs) = 15 × (81,445 + 25,000) + 800 ,000 = 2,396,675 SP + 462,675 (total costs for the heating system and building insulation) = 2859,350 SP

For the conventional building, case-2, the following numbers were calculated in winter (heating season):

- Annual heating loads = 263.6767 MWh.
- Annual fuel consumption on heating is 22,042 L.
- The initial cost for the central heating system (including Boilers, pumps, radiators, tubes …) = 1325,000 SYP
- The annual cost of fuel consumed for heating = 162,010 SP.
- The total costs of the heating system within 15 years = the setup cost + (maintenance and operating costs = 15 × (162, 010 + 40,000) + 1,325,000 = 435,152 SP.

There is 50% annual saving in the amount of fuel consumed for heating in case-1 compared to case-2. Hence, according to BIC method, the annual cost savings in case-1 (insulated building) compared to case-2 (conventional building) over15 years = [(the total costs of the heating system during the 15 years for case-2)—(the total costs of a heating system within 15 years case-1)]/15 = 99720SP.

Therefore, 34% total cost saving was achieved over 15 winters, in building case-1 compared to case-2 (which equals 99,720 SP per year). Despite of the higher initial cost (insulation material purchase and installation) of case-1 compared to case-2, case-1 appear to be economically feasible, according to BIC method.

2. Air-conditioning system (summer season):

The cooling system (air-conditioning system) starts operating from 1st June until 31 September, (120 days annually). The average operating hours of the cooling system is 10 h per day. Therefore, it operates for 1200 h during the entire summer. The Syrian household average annual electricity consumption cost is 3820 KW/h, based on data provided by the National Energy Recourse Center (NERC 2019). This is equivalent to 640 KW/h per cycle (two-month period) that costs 14,560 SP at worldwide fuel prices for 2019, of which the consumer pays only 390 SP. This is due to the Syrian low electricity household prices as the average tariff level is 0.004SP which is equivalent to 0.0000031814 US$ (according to www.exchange-rates.org) as per of currency exchange rate on 12/31/2019 (1 Syrian Pound = 0.001942 US$).

For summer cooling season, based on the above, the following figures were calculated from case-1:

- Annual cooling loads = 59.4931 KWh.
- Electricity consumption of an air conditioner with a capacity of 1 ton (3517 W) = 1.25 KW/h.
- Annual electricity consumption on air-conditioning cooling 29,124 KWh.
- Annual cost of the electricity consumption on air-conditioning cooling 72,809 SP.
- The initial cost for the conditioning system (HVAC) is 384,000 SP
- Annual maintenance costs = 12,000 SP.

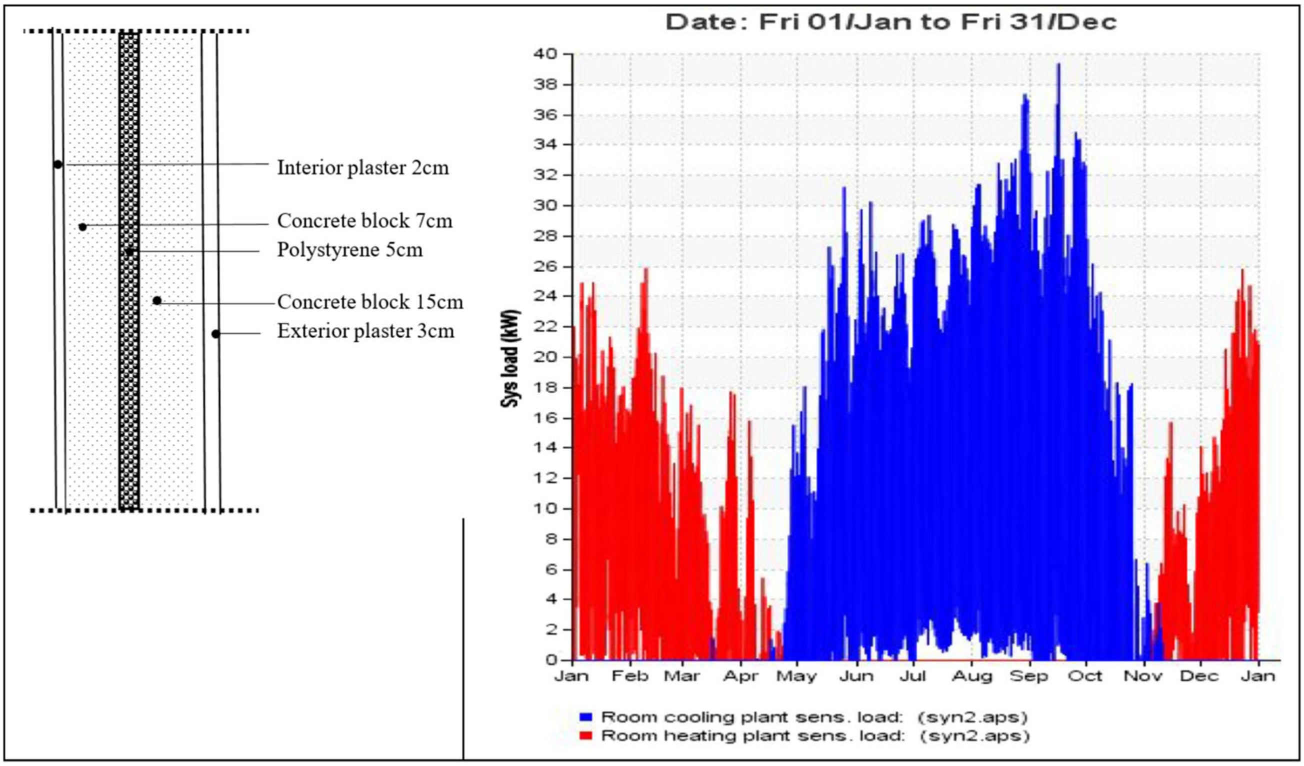


Fig. 8 Combined cooling and heating load-sensitive analysis of case-4 sandwich walls with polystyrene insulation in the middle. Total loads 72.5153 MWh

Table 9 Annual loads including heating and cooling (calculated with IESVE) for the five cases

	Cooling load in summer	Heating load in winter	Total load	Improvement in cooling loads in summer	Improvement in heating loads in winter	Total improvement
Case-1	59.4931	40.4489	101.79	60.92%	78.28%	78.89%
Case-2	218.4933	263.6767	482.17	Baseline		
Case-3	83.383	102.1224	185.5054	61.84%	61.27%	61.53%
Case-4	44.2974	28.2179	72.5153	79.73%	89.30%	84.96%
Case-5	45.294	30.7593	76.0533	79.27%	88.33%	84.23%

- The total costs of the cooling system within 15 years = the setup cost + (maintenance and operating costs = 1,656,133 SP

From case-2, the following figures were calculated in summer cooling season:

- Annual heating loads = 218.4933 KWh.
- Annual electricity consumption on air-conditioning = 44,249 KWh.
- Annual cost of the electricity consumption on air-conditioning cooling 110,623 SP.
- The initial cost for the conditioning system (HVAC) = 428,000 SP.
- Annual maintenance costs = 12,000 SP.
- The total costs of the cooling system within 15 years = the setup cost + (maintenance and operating costs = 2,267,351 SP.

Compared to conventional building case-2, case-1 achieved 34% annual cost saving in electricity consumption (air-conditioning system). 27% total cost saving was achieved, in building case-1 compared to case-2 (which equals 40748SP per year). Importantly, the insulation appears to be more economically viable in winter heating season.

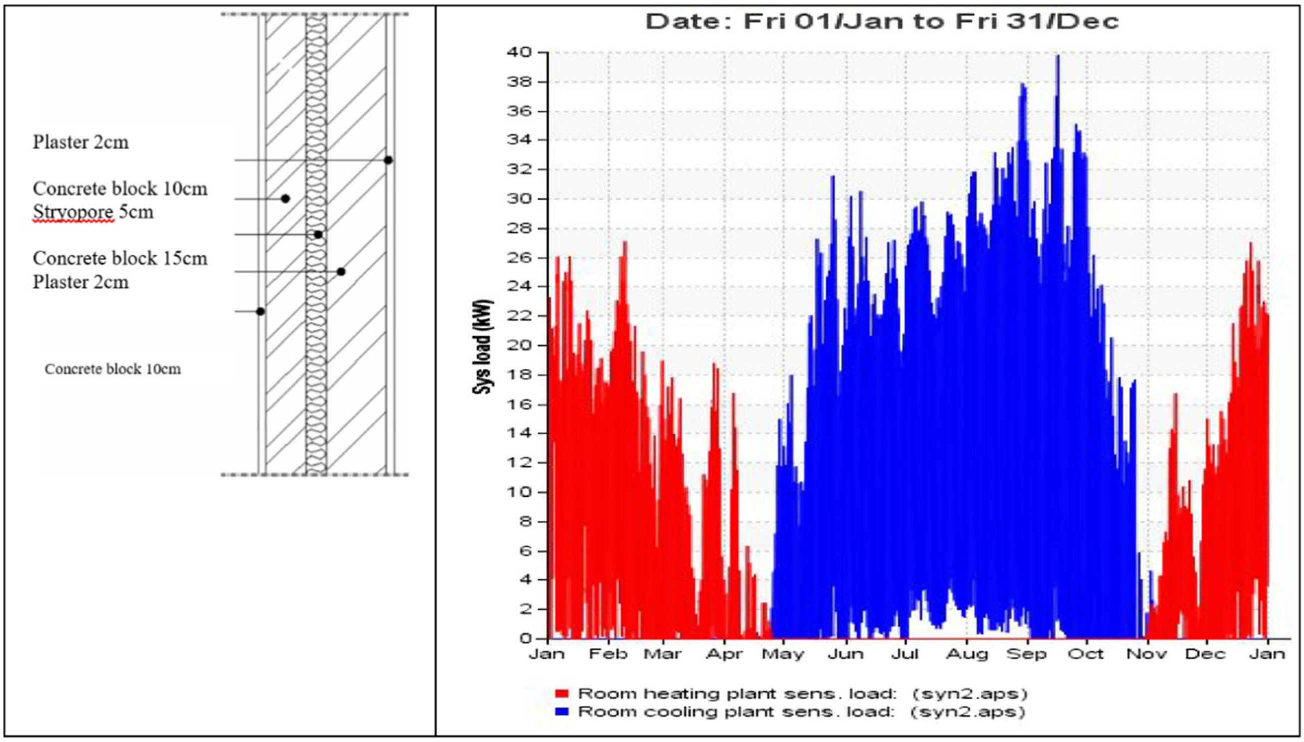


Fig. 9 Combined cooling and heating load-sensitive analysis of case-5 sandwich walls with Styropor insulation in the middle. Total loads 76.0533MWh

This does not translate into more affordable housing mainly because of to the low electricity prices which has increased the supply–demand gap. The government should revise the eight-block tariff structure for better leveling low-income residential customers. Additionally, BIC should be revised to extend its energy–cost trade-off method with 50-year life cycle payback period calculation as it contradicts the 50-year residential buildings life cycle requirement of the Syrian Buildings Code. Further simplified criteria that uses the input of building energy/thermal performance simulation for early design evaluation in specific climate zone is highlighted in the following section.

Simplified comparative approach

The discussion in this research shows differences and similarities among the five cases. This section proposes a simplified criteria to answer this research question: Which building envelope construction technique of the five cases under study is most effective? To an extent, BIC thermal insulation layers decrease the demand for indoor heating and cooling which in turn decreases the energy consumption cost. Simultaneously, the high additional cost of insulation, the limited availability of insulation material locally, the lack of local experience required for installation and maintenance as well as BIC methodology shortcomings appear to be the main barriers for BIC implementation (Khaddour 2021b). Thus, further simplified criteria is required to analysis the annual pattern simulation, generate alternatives, guideline the selection of new residential building envelope structure as follows:

Impact of wall construction techniques

The external wall structure selection has the top importance due to its high thermal conductivity through whole facade surface area. Previous research by Khaddour (2021b) revealed 85% *U*-wall improvement achieved through insulated external walls compared to conventional building. One can note that the cases with lower U-value (case-1, case-4 and case-5) have higher cooling transmission loads in summer than heating loads in winter. This reflects the Insulation over heating effect compared to case-3 which has the highest heating load peak in January is 25.63 MWh, whereas the cooling load peak is the highest in August with 19.47 MWh (Fig. 7). Figure 8 illustrates the combined cooling and heating loads for case-4 where fluctuations are significantly reduced for this sandwich walls with polystyrene insulation in the middle. This is mainly due to the sandwich walls, with polystyrene insulation in the middle, considerable heat storage property. In contrast, the brick wall in case-3 has less heat storage property which permits good heat flux release for summer season nighttime in Damascus climate. Therefore, the prevention of heat transmission from outside to inside in summer cooling season was achieved best in case-4 through envelope structure that comprises sandwich walls with polystyrene insulation in the middle, insulated roofs in addition to the double-glazed windows.

To this point, increasing the thickness of the insulation layer is recommended. The research findings indicates that BIC compliant standards of 5 cm insulation layers are found to be rather thin compared to previous research. Hasan (1999) recommended a sandwich rock wall with 7 cm polystyrene or wool insulation in the middle, in Palestine climate (Hasan 1999). In Egypt, the recommended sandwich rock wall has 7–12 cm thermal insulation thickness in the middle (Mohamed 2020). In Tunisia, Daouas (2011) recommended a sandwich rock wall with 10.1 cm of polystyrene insulation in the middle.

Impact of glazing type and roof construction

Table 7 illustrates the *U*-value of glazing types. Triple-glazed window type is not mentioned by BIC as it is not available in the country. BIC focuses on narrow requirements for separate building parts. Hence, BIC *U*-values for double-glazed window was found to be close to the C rate windows in UK standards (Table 7). Single-glazed windows (*U*-value of 5.6 $W/m^2/k$) are the mostly used types in Syrian residential buildings. No evidence was found on the use of eco-choice triple-glazed windows in Damascus. A massive decrease in thermal loads can be achieved by replacing the commonly used single-glazed windows with double-glazed ones due to *U*-window value improvement by 66%. This result is close to Khaddour research findings that demonstrated 50% *U*-window improvement between conventional and compliant residential building (Khaddour 2021b). The area of outside windows should be minimized. This is because heat transfer of windows is three time that of the walls (Thapa and Panda 2015). Therefore, for the recommended case-4, the prevention of thermal transmission in winter heating season from inside to outside depends on controlling the air flow through windows, doors and ventilation. In turn, this will prevent the flow of outside cold air from replacing the hot air indoors in order to sustain a comfortable temperature and to save the energy consumed for heating. Therefore, BIC should encourage more passive and adaptive techniques for the building envelope construction, e.g., innovative glazing, shading and solar radiation control, design orientation and green roofs and walls.

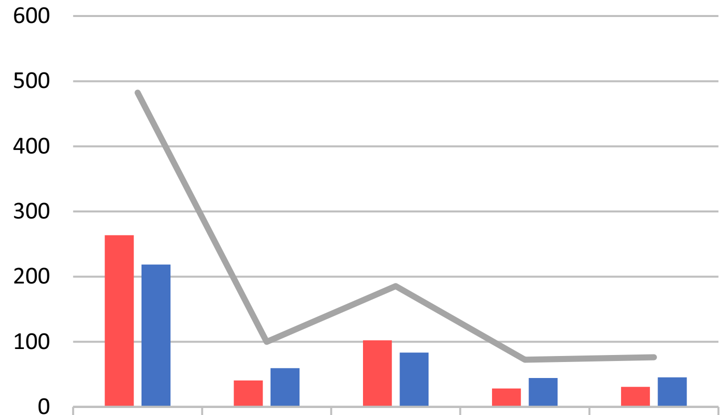
Impact of simulated thermal performance

This key parameter affects the selection of building envelope construction techniques as the simulated thermal performance results are the main input for analysis and selection. The simulation findings indicate stronger relationship between external wall type and winter heating loads compared to summer cooling loads. This is because the heat gain in summer is not much influenced by the external wall structure as much as by thermal gains from sunshine, solar radiation and ventilation. In fact, improving the building envelope insulation, especially walls, appear to have negative effects on summer cooling loads as it causes overheating in summer, as shown in Fig. 10. BIC relaying on envelope materials *U*-values could mislead designers to more heat storage envelope structure. For that, BIC should adapt a thermal/energy simulation software; as shown in Fig. 10, the impact of different envelope construction techniques on cooling, heating and total loads is demonstrated for the five cases. In this sense, the best thermal performance building envelope construction technique among the selected cases is case-4 followed by case-5.

Impact of insulation material (availability, purchase and installation)

This is a dominant parameter affecting the selection of building envelope construction technique in the post-war social housing reconstruction. Despite compliant buildings higher initial cost, the simplified analysis should consider minimizing the total cost over building lifetime which includes the insulation (purchase and installation) and the energy (consumption and maintenance) costs. As shown in Fig. 10, the cost per square meter of each external wall construction technique in relation to its thickness and its U-value thermal performance. It is noticeable that as long as the wall thermal properties are improved, its cost are increased. Where the insulation material had been added to the external wall structure in case-1, case-4 and case-5, a 36.4%, 54.6% and 45.5% increase in cost have resulted, respectively, compared to case-2. Simultaneously, 78.24%, 92.7% and 90.2% improvement in *U*-value were achieved in case-1, case-4 and case-5, respectively, compared to case-2. These values are calculated based on Syrian local market prices at the time of the research study. Importantly, determining composite walls' thermal insulation thickness is vital for controlling the thermal conductivity and consequently the heat transmission. Hence, the increase in insulation thickness will increase the initial building cost, on the one hand. On the other hand, it will reduce the energy consumption running cost.

In the light of Syria post-war situation, BIC should encourage the integration of local renewable building envelope materials. Insulation material availability is an important factor



	Case2	Case1	Case3	Case4	Case5
Heating load MWh	263.6767	40.4489	102.1224	28.2179	30.7593
Cooling load MWh	218.4933	59.4931	83.383	44.2974	45.294
Total load MWh	482.3	99.94	185.5054	72.5153	76.0533

Fig. 10 Impact of different envelope construction techniques on cooling, heating and total load of five cases

to be considered when selecting envelope structure due the country post-war economic downturn. For example, in case-1 and case-4 insulation layers of polystyrene were installed. It should be noted that the manufacturing of polystyrene emits 7 kg CO_2-Eq/kg on average with high energy consumption (Bribián et al. 2011). Furthermore, BIC does not consider any insulation of natural origin, i.e., wool. The use of local material implies lower embodied energy and higher thermal resistance compared to the popularly used cement bricks which means it is a greener option due to its low carbon footprint (Khaddour et al. 2023). Also, using sheep's wool as insulation layer has the advantages of being CO_2 free as it is 100% recyclable at the end of its life cycle. Therefore, it is recommended to establish local factories for wool as building thermal insulation material which will provide sustainable raw material; cheap, abundant, profitable and create job opportunities in ruler areas).

Impact of the payback period

A payback period method presents the connection between the initial cost (insulation purchase, installation and other building energy efficient means) and the savings in the running energy consumption cost. Sullivan et al. (2015) developed Eqs. (3), (4) and (5) to evaluate the cost efficiency of installing envelope insulation regarding the payback years. The authors considered the envelope structure acceptable economically if the payback is within five years (Sullivan et al. 2015). Sullivan et al. (2015) approach is used to calculate the payback years for the four selected cases (1, 3, 4, 5) compared to case-2 baseline using the following equations:

$$\mathrm{PWF} = \sum_{u=1}^{n} \left(\frac{1+i}{1+d}\right)^{u} = \begin{cases} \frac{1+i}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^{n}\right] & i \neq d \\ \frac{n}{1+i} & i = d \end{cases} \tag{3}$$

$$C_{\mathrm{enr}} = \mathrm{PWF}\left(\frac{Q_c}{\mathrm{COP}}\frac{C_{el}}{(3.6\times 10^{6})} + \frac{Q_h}{H_u \eta_s}C_g\right) \tag{4}$$

$$C_t = C_{\mathrm{enr}} + C_i = \mathrm{PWF}\left(\frac{Q_c}{\mathrm{COP}}\frac{C_{el}}{(3.6\times 10^{6})} + \frac{Q_h}{H_u \eta_s}C_g\right) + C_{\mathrm{ins}}L_{\mathrm{ins}} \tag{5}$$

PWF the present worth factor.i the inflation rate effects on energy cost$d$ time value of money during $n = 50$-year housing life cycle

Cenr the energy cost actual value over $n = 50$-year housing life cycle.

Ct the total cost per wall surface square meter which includes and Ci the insulation purchase and installation costs.

The annual savings in running energy consumption (As) are considered for 50-year lifetime and then divided by the PWF. In Fig. 10, the wall total cost per square meter includes the energy cost present value and the insulation purchase and installing cost. The inflation factor (i) is considered in the payback (b) calculation, as can be seen below (Eq. 6).

$$\mathrm{PWF}(b) = C_i / A_s \tag{6}$$

Accordingly, the payback periods are 10.5, 7.8, 15.7 and 13.1 years for case-1, case-3, case-4 and case-5, respectively. These periods indicate that neither of the selected cases is profitable or economically viable as all payback periods are longer than five years (Daouas 2011). The main reasons for the long payback periods are: the Syrian tariff for household energy consumption is extremely low and the cost of the imported insulation materials is very high. This does not translate into affordable housing as developers aim to sell at a market price regardless of construction cost savings.

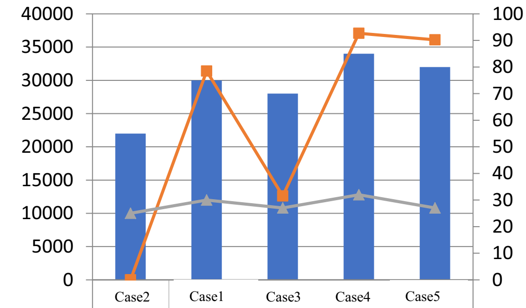
All calculated payback periods appear rather long compared to previous research. Hasan (1999) indicated the possibility of savings up to 21 $/m^2 of wall surface area for sandwich rock wall with wool insulation in the middle (payback periods between 1 and 1.7 years). For sandwich rock wall with polystyrene insulation in the middle the payback periods were found to be between 1.3 and 2.3 years in Palestine climate (Hasan 1999). In Egypt, the optimal thermal insulation thickness was 7–12 cm with payback period of 20–30 months (Mohamed 2020). For a typical residential building in Tunisia, Daouas (2011) recommended an optimum insulation thickness of 10.1 cm with 3.29-year payback period.

Thus, several factors appear to influence the possibility of reducing compliant building payback period in Syria post-war context: (1) revising the energy tariff structure by the government, (2) reducing the initial cost by using wool or locally manufactured insulation materials, (3) adopting one carefully analyzed building design as a replicable solution for decreasing new youth housing initial construction costs and (4) supporting this type of buildings by government, i.e., compliant building discounts in taxes and planning permission fees in order to reduce the payback time. Considering these suggestions could drop the payback period to be within 5 years.

Simplified comparative statistics

The results IESVE model are used as primary input for this analysis in order to select a multilayer external wall solution for Damascus climate. Figure 11 reveals significant differences among the cases in U-value improvements divided by cost increase with 2.3, 1.77, 1.73 and 2.04 for case-1, case-3, case-4 and case-5, respectively. Although case-4 has the achieved the best simulated thermal performance, it has the worst indicators through the total life cycle cost analysis. Results show that case-1 and case-5 envelope constructions are the most economical cases with respect to thermal performance improvement. Therefore, the significant higher price of case-4 wall structure represents a challenge for this structure implementation in post-war situation. Therefore, the study simplified comparative analysis recommended case-1 and case-5 structures based on U-value improvement, cost and thermal performance.

Heat gains might come from large, glazed areas in Damascus warm/hot climate. Therefore, building envelope should ideally regulate temperature and moisture levels of indoor spaces. Shading devices in line with the cladding can greatly help mitigate solar gains. Contrary, in winter, insulated building envelope tries to prevent that indoor heating from going out. Hence, imply adding extra layers of insulation might not be



	Case2	Case1	Case3	Case4	Case5
Cost SP/m2	22000	30000	28000	34000	32000
Wall-U improvement %	0	78.48	31.54	92.67	90.22
Wall thickness	25	30	27	32	27

Fig. 11 Simplified comparative analysis of external wall construction techniques

the preferred option (cost, space requirement, esthetic, embodied energy. These observations support the adaptive comfort approach, by de Dear et al. (2013), of allowing indoor temperatures to drift with outdoor seasonal temperature instead of being firmly regulated around a fixed indoor design temperature. Thus, BIC should integrate further characteristics of building envelope specification, e.g., minimal/low thermal bridge levels for excellent levels of thermal comfort and low energy demands.

To conclude, BIC, as the mandated standards from the Syrian government, is an influential tool which articulates building insulation, thermal performance and energy efficiency outcomes. Thus, BIC implementation is suffering post-war situation where technical, economical and organizational barriers exist (Khaddour 2021b). However, BIC poorly articulated standards could misguide engineers during design phase when selecting building envelope construction techniques. Therefore, BIC should integrate the previously discussed simplified comparative analysis in order to select optimum envelope construction through: calculating building envelope thermal performance (U-values), simulating thermal loads, energy–cost trade-off and payback period analysis.

Drawbacks of and barriers to BIC implementation

In line with the empirical evidence and theoretical opinion presented in this study, it is expected that more post-war affordable housing projects have inflexible design due to the traditional nature of the Syrian construction system. All design aspects, including building envelope construction techniques, must be planned ahead as any adaptations in design are not possible once project's execution starts. This limited design adaptability has consequential impact on building's thermal and energy efficiency performance. The lack of clear standards in BIC also affects developers who perform most efficiently when they have clear output. Additionally, BIC is limited to newly built construction. Further insulation standards require future research on improving building envelope selection criteria for existing buildings and renovation projects.

Another BIC implementation barrier is the speed of post-war reconstruction of affordable housing. This speed is driven by the increasing demand on affordable housing on the one hand and the developers' keen interest in a higher return on investments on the other hand. BIC was found to be focusing on narrow requirements for separate building parts, such as *U*-values for windows. Further drawback is the performance gap caused by focusing on regulating planned values in new building envelope construction techniques while neglecting the actual post-occupancy energy consumption.

Key recommendation is improving the envelope construction quality control tools and machinery to allow higher consistency of construction execution. Additionally, BIC will benefit from implementing building energy simulation and thermal performance software to drive building envelope selection. BIC should ideally regulate envelope selection criteria (cost, space requirement, esthetic, embodied energy). Therefore, BIC should integrate an advanced envelope rating guide for pre-design as well as for post-occupancy phases. Various internationally recognized building sustainability rating and certification systems value the improvements in building envelope performance in relation to reductions in energy consumption for heating and cooling. These rating systems are also supported with further consideration to occupant thermal control. The USA's LEED, for example, offers one credit point for buildings that offer good level of thermal comfort system control by personal occupant (USGBC 2009). The UK's BREEAM also offers two credits for thermal comfort system control by personal occupant (de Dear et al 2013). Also, Japan's CASBEE rating identify five levels of individual control (JSBC 2011). Another example is Australia's Green Star offering two points for buildings that facilitate individual control of thermal comfort (GBCA 2010).

As selecting envelope structure is a multi-criterion and multi-participant procedure, it was necessary to limit the scope of this research and to concentrate on BIC most neglected areas of: envelope thermal performance, thermal simulation and advocacy and cost parameters. Reservation of views from case-1 and 2 engineering teams and residents in sharing their views on thermal comfort satisfaction and energy-saving perception level is addressed as research limitations. Additionally, only essential climate data parameters are measured as the local weather station did not hold records for sunshine, solar radiation and cloud cover. Investigating the results of living behavior assessment is recommended for further research.

This research study provides better understanding of the potential of more efficient envelope form and its implementation in achieving better thermal comfort, thermal loads, energy efficiency and cost saving. The main benefit from this study simplified approach is setting guidelines for BIC improvement and implementation in Damascus post-war affordable residential buildings. This simplified approach demonstrates the logic of which envelope structure output assessment can be conducted, resulting in a shift in the control from input oriented to a more output oriented. Implicitly, the research findings will be beneficial in further development of a comprehensive criteria for Syria different climatic zones. Hence, this research explicitly views climatic responsive design as a form that surpasses technical issues alone. The proposed simplified comparative analysis offers practitioners a novel approach to customize their own list of envelope structure parameters based on the climatic zone.

Further research on energy sensitivity analysis is recommended in order to show the relationship among various parameters: insulation cost, inflation and discount rates, thermal comfort, environmental impact and consumed energy savings through building lifetime cost. Adopting an effective building energy/thermal performance simulation by BIC facilitate providing affordable design solution, reducing energy use, decreasing the environmental impact, improving indoor thermal comfort and facilitating future innovation and technological progress in post-war re-construction.

Research novelty

There is currently a lack of harmonization in the BIC requirements that are mandated in Syria. BIC has opted for a "fabric first" dwellings design approach, having mandatory *U*-value standards for new housing. Hence, like many energy-related regulations in Syria it has been dropped because the construction sector has not been able to cope with them, forced by speculators to keep costs low. Another reason is that building thermal performance modeling has not been used as an alternative approach to comply with the new insulation code in Syria.

Within BIC, the thermal transmittance is the only aspect that is used to evaluate envelopes' thermal insulation. However, this research demonstrates that the thermal transmittance is not a valid parameter for comparative analysis of the envelopes' thermal losses. Alternatively, this study proposes a simplified methodology that can be used to regulate housing insulation in Damascus as a pilot project replicable to ultimately harmonize the envelope thermal losses across different climates.

This research evaluates the potential of various building envelope modifications for improving the thermal performance, reducing energy consumption, thereby mitigating climate change for Damascus climate. Since, building envelope insulation layer is responsible for thermal efficiency, this research investigates the new BIC measures, e.g., increasing the thickness of the wall and constructing a cavity wall.

In addition, this research will use thermal simulation for compliance with BIC standards. BIC standards lack to thermal modeling has prevented reproducing the envelope design based on specifications and operational assumptions. This research will explore building thermal simulation to demonstrate compliance to BIC construction standards. This model is generated for five types of with standard construction material, lighting and HVAC systems.

Hence, the thermal simulation is not seen sufficient by itself as decision making tool to optimize a building envelope, an interdisciplinary simplified approach is developed to contribute positively to Syria reconstruction circumstances. The calculations of the transmittance values and the thermal modeling are usually done at the end of the design phase in order to apply for the planning permissions. However, although thermal modeling can contribute to envelope selection, achieving better thermal performance must be reached at a lower investment cost. This research simplified criteria will support BIC regulatory body incentives based on percentage improvement compared to the reference base conventional envelope model.

This research simplified approach main benefits are allowing design flexibility and BIC compliance using more efficient envelope material and construction techniques. In Syria post-war circumstances, construction costs need to be reduced while being compliant using local insulation material, passive design. Consequently, this will lead to reduction in energy consumption and operating costs, improvement in thermal comfort and occupants' satisfaction; decrease in Green House Gas GHG emissions, therefore enabling future net-zero design at a lower cost.

Conclusion

There are an increasing number of research on adaptive thermal comfort reflecting the global keen interest in sustainable buildings. Little research, however, has been performed to investigate BIC compliant building thermal and energy performance in Syria. This research study has investigated the concept of building envelope construction techniques in Damascus post-war affordable residential buildings.

Housing is an important component of the 2030 Agenda for Sustainable Development. With this research outcomes, housing practitioners and developers alike will benefit from improving building envelope practices' impact on achieving the 2030 Agenda for Sustainable Development. This can be a starting point for action in Syria post-war re-construction. This is mainly because energy efficient and affordable housing leads to benefits in health, education and economic opportunities (Housing and the Sustainable Development Goals Report 2021). Improving building envelope thermal performance is a key factor for improving housing energy efficiency which is in turn an integral part of the following SDGs: a) SDG1: building resilience and reducing vulnerability to economic-, social-, health- and climate-related disasters, b) SDG3: securing occupants physical and mental health and well-being, c) SDG5: elevating the standard of living which is linked to entire communities and gender equality, d) SDG7: ensuring energy efficiency with its social, environmental and health impacts on wider community, e) SDG11: achieving safe, resilient and sustainable cities and f) Goal13: reducing contributions to drivers of climate change.

In this sense, by highlighting areas of improvement for BIC in the Syrian context, this research benefit other war-shattered countries adapting the amended BIC settings to build back better considering the need for sustainable socioeconomic development. Hence, future research should focus on BIC potentials for building envelope construction through interdisciplinary analysis of housing typologies in the post-war era, involving advanced local building material, life cycle analysis and energy systems.

BIC standards should integrate special considerations for the selection of building envelope construction techniques based on a variety of parameters, e.g., envelope materials *U*-values, simulated thermal loads and energy–cost trade-off. In this research, the impacts of five different building envelope construction techniques were investigated and simulated. It is evident from the present study that IESVE modeling has sufficient prediction capability to determine the thermal conductivity, using simple variables, e.g., outdoor temperature, indoor comfort design temperature, building envelope materials parameters characteristics. Then, the daily thermal loads were added up for each season to get the annual cooling and heating loads.

To an extent, BIC compliant thermal insulated buildings is proved to reduce the space heating and cooling demand and consequently decreases the running energy consumption cost. The three recommended envelope structures are case-1, case-5 and case-4 according to: the improvement in U-value, the simulated building thermal performance, the cost–energy trade-off. Hence, this research findings revealed that neither of the selected cases is profitable or economically viable as all payback periods are longer than five years. The main reasons for the long payback periods are: the Syrian tariff for household energy consumption is extremely low and the costs of the imported insulation materials (purchase and installation) are very high. BIC was found to be focusing on narrow requirements for separate building parts, such as *U*-values for windows. Another limitation is the performance gap caused by focusing on regulating planned values in new building envelope construction techniques while neglecting the actual post-occupancy energy consumption. This research suggested recommendations based on the developed simplified criteria for selecting building envelope construction technique.

Post-war BIC compliant residential buildings are suffering energy deficiencies. The main building envelope construction techniques presented by BIC were investigated. Syrian housing envelope structure technique could be improved by; considering sandwich wall structure, increase insulation layer thickness and installing improved local natural origin insulation layer. BIC should be revised to include clear guidelines on the proposed simplified criteria accompanied with approved building energy/thermal performance simulation for early design evaluation in specific climate zone. This research findings have sparked a new agenda for BIC improvement focusing on the effectiveness of thermal performance simulation through simplified comparative analysis. In an attempt to fill part of the energy demand–supply gap, this research highlighted the need to revise the BIC standards and proved the possibility to lower the energy use, considering post-war limited resources, in the future compliant housing compared to the conventional housing in Damascus climatic region.

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Declarations

Conflict of interest The author has no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval This article does not contain any studies with human participants or animals performed by the authors.

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