Environment, Development and Sustainability (2024) 26:7105–7128
https://doi.org/10.1007/s10668-023-03001-w

Optimisation of energy and life cycle costs via building envelope: a BIM approaches

Muhammad Altaf[1] · Wesam Salah Alalaoul[1] · Muhamamad Ali Musarat[1,3] · Abdelaziz Abdelmahmoud Abdelaziz[1] · Muhammad Jamaluddin Thaheem[2]

Received: 24 January 2022 / Accepted: 2 February 2023 / Published online: 17 February 2023

Abstract

A surge in energy demand driven by the growing number of buildings and insufficient attention to sustainable and optimised energy-saving procedures are likely to threaten the economy and the environment. The building envelope is a significant component that influences energy requirements, directly affecting the operations costs. Thus, the current study considers the envelope to optimise the building's Life Cycle Costing (LCC) and enhance energy efficiency. Therefore, to achieve the aim of the study, Building Information Modelling (BIM) with the integration of Life Cycle Cost Analysis (LCCA) is adopted to assess the building envelope and optimise energy use and relevant costs. Three alternatives of wall system: brick wall with rockwool insulation, brick wall with polystyrene insulation and curtain walls system, are considered for the building envelope to enhance energy-saving potential by analysing and comparing the energy demand. To determine LCCA, the Net Present Value (NPV) approach was adopted for the initial expenditure and the associated future costs. It was found that utilising insulation material with low thermal conductivity reduces heating and cooling energy resulting optimised LCC. Compared to curtain walls, the results show that the rockwool insulated wall reduces 17% of energy demand while the polystyrene wall reduces 12.7% of the energy. Similarly, rockwool insulated walls save 5% energy relative to the wall system with polystyrene insulation. Thus, integrating LCCA with the BIM approach at the conceptual design stages promotes energy and LCC optimisation.

Keywords LCCA · BIM · Energy efficiency · Building performance · Wall system

---

✉ Wesam Salah Alalaoul
wesam.alaloul@utp.edu.my

[1] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia

[2] School of Architecture and Built Environment, Deakin University, Geelong, VIC, Australia

[3] Offshore Engineering Centre, Institute of Autonomous System, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia

1 Introduction

Several techniques are adopted to lower the total Life Cycle Costing (LCC) of a construction project and increase the revenue (Durdyev et al., 2018; Levy, 2018). The LCC of a project consists of capital cost, operation and maintenance (O&M) cost, replacement cost and disposal cost (Gholami et al., 2020; Kabeel et al., 2019). In practical approaches, the primary attention is only given to the initial construction cost, although the O&M cost contributes more than the initial construction cost (Kerzner, 2017; Meredith et al., 2017). Globally the building sector consumes around 40% of the total energy during the operational period (Robinson et al., 2017; Wei et al., 2018). The rise in the operating cost of a building is associated with energy demand and consumption (Amasyali & El-Gohary, 2018; Hu et al., 2017; Junker et al., 2018; Wei et al., 2018).

The rise in operating cost is attributed to the expense of sustaining thermal comfort, which is influenced by various variables, including climate, occupant behaviour, and energy systems, all of which contribute to the building's energy demand and consumption for heating and cooling (Al-Saggaf et al., 2020; Verbeke & Audenaert, 2018; Yao et al., 2018). The heating and cooling energy for the building contributes 17–73% of the total energy consumption (Hernández et al., 2022; Ürge-Vorsatz et al., 2015). Another significant factor affecting the overall energy consumption of a building is its external insulation. External thermal insulation of the building envelope is considered one of the most efficient techniques to be adopted to optimise energy requirements, which decreases the LCC of a building (Sharif & Hammad, 2019). The building envelope is the external skin of the structure, which prevents the conduction of heat from the building to the surrounding. Efficient insulation optimises energy consumption, consequently demanding less energy for cooling in summer and heating in winter (Aditya et al., 2017). The insulation optimises space heating and cooling by reducing the solar absorption and heat conduction to the outside, thus minimising the energy burden and cost (Beyhan & Ersan; Chwieduk & Chwieduk, 2020).

Compared to a conventional building envelope, the energy-saving potential of a thermally insulated building envelope ranges from 50 to 90% (Louanate et al., 2022). Likewise, Hassan et al. (2014) stated that a well-insulated building could reduce energy consumption by 64% compared to conventional buildings. The thermal insulation of a building consists of materials that possess thermal resistance capacity, which decreases thermal conductivity. In hot regions, the cooling of the buildings causes significant energy consumption to sustain thermal comfort for the occupants. Using efficient materials for the thermal insulation of building envelopes can help reduce the energy burden for cooling (Feehan et al., 2021).

Building envelope insulation enhances the potential for a thermal comfort level with optimum usage of cooling systems such as Air Conditioning (AC) systems (Lotfabadi & Hançer, 2019). For proper thermal insulation procedures, energy-efficient materials are adopted to reduce heat gain and loss. Various insulation materials such as brick walls, wooden walls, fibreglass and metals are primarily used to find optimum conductivity, reducing energy consumption to save operational costs during the life cycle (Pásztory, 2021; Tushar et al., 2022). However, wood or brick wall has better insulation than fibreglass and metals (Amran et al., 2020; Elfayoumy et al., 2020). Likewise, insulation materials such as rockwool and extended polystyrene (EPS) insulation save energy, costing up to USD 2.5 per m^2 of walls (Kumar et al., 2020). Furthermore, another parameter for building insulation considers the insulation thickness of the envelope, which is usually assessed by deploying the Life Cycle Cost Analysis (LCCA) approach. Optimum insulation thickness was measured for the colder places of Turkey, where LCCA was adopted to assess energy cost optimisation and energy savings of up to USD 12 per m^2 of the wall was recorded (Çomaklı & Yüksel, 2003). As the thickness of the insulating medium increases, the need for cooling loads decreases, resulting in a reduction in energy cost. In practice, this is only true to a certain degree since if the building is insulated too much, it will end up with a hotter building that requires more cooling (Lomas & Porritt, 2017). Moreover, increasing insulation thickness increases the design and installation cost (Amirifard et al., 2019; Monteiro et al., 2017; Solgi et al., 2019).

Considering both energy savings and life cycle costs, value engineering (VE) and building information modelling (BIM) technologies are used to improve the envelope of green buildings, which may drastically lower their energy consumption. To emphasise the significance of energy efficiency, the energy performance of 20 Zurich residential buildings was investigated using the Life cycle and BIM simulation technique, and it was revealed that the forecast of operational energy usage helps significantly to obtain higher levels of energy efficiency (Althaus et al., 2005). Using DeST energy simulation software, a college building in Chengdu was studied for the impact of material type and thickness of the thermal insulation layer, and it was revealed that adding insulation materials to the building envelope had less influence on the cumulative yearly cooling load. Even yet, the cumulative yearly heat load has a bigger effect when compared to no insulation; it may save 21.52% heat load, 3.78% total load, and 25.34% total cost per unit area. Optimal economic thickness is shown to have an anti-parabolic connection with the varying insulation thickness and overall cost trends. However, various insulating materials also have to vary economically viable thicknesses (Zhang et al., 2019); similarly, the optimum thickness for the insulation of external walls in Malaysia was found to be between 18 to 126 mm (Basrawi et al., 2013). Therefore, outside walls should be insulated with sufficient insulation materials and appropriate thickness per the outside environment (Biseniece et al., 2018).

The rise in the energy demand due to the growing rate of building construction and minimum attention to economic and optimised energy efficiency techniques are supposed to be risky for the economy and environment (Zhang et al., 2022). In addressing the issue, research tends toward adopting optimised energy alternatives with the help of integrated BIM in the conceptual design phase (Teng et al., 2022). Whereas, to determine the optimised LCC of a project, the integration of BIM and LCCA can facilitate the ability to implement economically sustainable projects (Altaf et al., 2022). BIM is a widely used approach that integrates key details for project planning and design, development, and operation and maintenance (O&M) (Cao et al., 2022). In construction projects, the information delivery among different databases for energy measurement and environmental assessment, BIM is used to simplify data flow between the databases (Dalla Mora et al., 2020; Jalaei et al., 2021; van Eldik et al., 2020). Furthermore, the emerging aspects of BIM have implications for building systems and operations activities dataflow, but they can also bring additional dimensions to current and future problems. Moreover, BIM determines energy efficiency and enables the optimisation of energy costs by adjusting the structure's orientation using a graphic representation (Singh & Sadhu, 2019). Tang et al. (2013) used BIM to model and monitor the efficiency of the heating, ventilation and air conditioning (HVAC) and observed a 27% decrease in the cost during conceptual modelling. It is evident from the results that BIM integration is very useful in optimising the layout, LCC and energy performance of a building. The BIM consists of automatic quantity take-off capability, which is used to estimate the area and volume of a project and generate a Bill of Quantity (BoQ). While linking the developed BoQ to life cycle evaluation resources can help stimulate economic sustainability (Aibinu & Venkatesh, 2012; Hollberg et al., 2020).

It has been discovered that the take-off tool cannot process data independently and must be combined with other software for data exchange between the management and architecture models to conduct LCCA and other assessments (Hollberg et al., 2020). LCCA is an efficient approach that compares different alternatives of materials and systems to optimise operational energy requirements and reduces the capital cost of energy systems (Luerssen et al., 2020; Saafi & Daouas, 2018). Studies show that the implementation of economic optimisation and LCC evaluation impact cost reduction (Elkadeem et al., 2020; Streicher et al., 2020; Xiang et al., 2020). The idea behind the LCCA method is that the initial decisions should be based on costs over the lifetime of the project, considering the construction and operation costs. LCCA is a common tool that can quantify for a relatively long period, considering the fluctuation of future project prices (Zhivov, 2022).

The energy demand and consumption of the building raise the total LCC of a project. The building envelope is the primary part of the building which is affecting energy efficiency; hence, various materials and systems could be used as a building envelope that provides a similar function but varying thermal conduction and emission (Ascione et al., 2019; Sadineni et al., 2011). Moreover, thermal insulation seems to be one of the best approaches to optimising operational energy requirements and costs by reducing heating and cooling demand in cold and hot seasons. In the current study, a methodology is developed to optimise the overall LCC by integrating the economic assessment approach, i.e. LCCA with BIM and energy simulations, in the conceptualization and design stage of a building. The methodology is supported by the investigation of three alternative building envelope systems, i.e. a brick wall with rockwool insulation, a brick wall with polystyrene insulation and a curtain wall system to improve energy-saving potentials. To achieve the aim of the study, the BIM Autodesk Revit and Ecotect are adopted for modelling for energy analysis with the integration of LCCA. BIM enables integrative information to be modelled inside a single model. It offers the potential for sustainability reforms and predictive analytics to be carried out during the design phase. The current methodology identifies sustainable mechanisms that could have beneficial impacts on energy conservation and assess the LCCA output of the building in terms of its thermal component of energy usage at the operating phase.

2 Methodology

The current study investigates energy requirements and evaluates the optimised energy cost for various building envelope alternatives and economic evaluation for optimal LCC decision-making. Three types of building envelope alternatives, i.e. brick wall with rockwool insulation, brick wall with polystyrene insulation, and curtain wall system, were considered as they are commonly used insulation materials in Malaysia (Basrawi et al., 2013). Figure 1 shows the methodology adopted consisting of a BIM approach with the integration of LCCA to analyse energy requirements and assess the optimised energy cost for building envelopes with different wall systems and insulation materials. A three-dimensional (3D) visual model was generated in Autodesk Revit 2021, assigning different planes, allocating materials, allocating spaces and zones and developing an energy model, as it helps users to create 3D BIM models in digital form (Wu et al., 2014). Revit is also useful for construction documentation, quantity and cost estimation, and coordination for a BIM process to run efficiently. BIM captures, organises and systemically exchanges data among the stakeholders and various software to evaluate further decision-making. The data transfer from

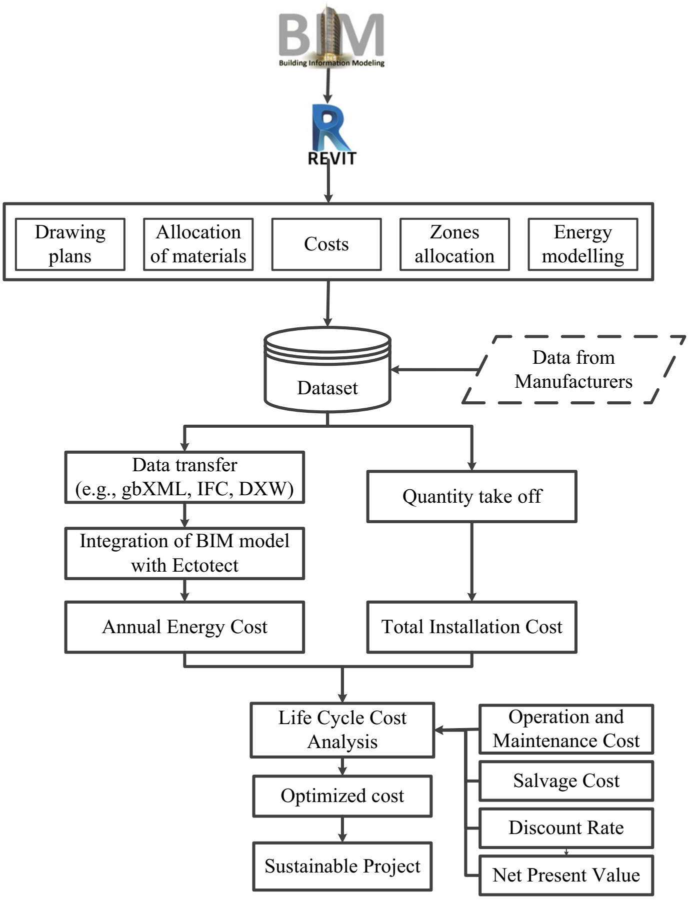


Fig. 1 Research flowchart

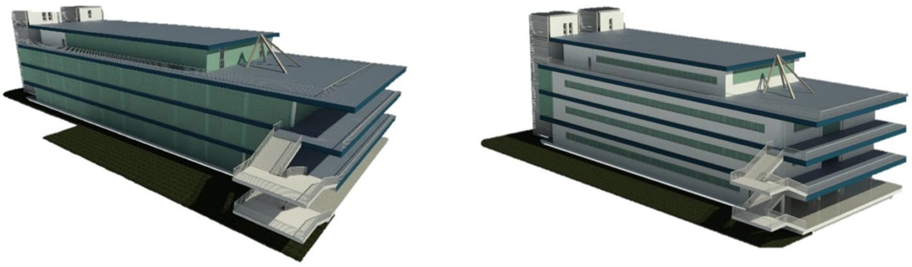
one platform to another can be accomplished in various formats, depending on the need of that platform (Altaf et al., 2022). Two datasets were created, one from the BIM database and the second by the companies and manufacturers. In the current research, Ecotect was used as an energy simulator for which data were transferred from Autodesk Revit in the form of gbXML. The transferred BIM dataset was integrated with the Ecotect environment to analyse the annual energy demand and cost. Moreover, BIM allows quantity take-off for materials and the components used in the model, which were used to extract the quantities of building alternative envelope materials. The results were interpreted with the data gathered from the manufacturers. For sustainable economic assessment, the energy cost and material installation cost were incorporated with cost parameters, i.e. Net Present Value (NPV), the life cycle of 20 years and discount rate to calculate the LCC of the building.

2.1 Case study

A newly built four-storey institutional building in University Teknologi PETRONAS, Malaysia, was used as a case study to examine the energy requirements and economic evaluation of the building envelope with various wall types and insulation. The total area of the building is about 1,855 m^2 for each storey. The case building is located in Malaysia, which has hot weather throughout the year, resulting in higher indoor temperatures that necessitate more resources to provide thermal comfort in the workplace by artificial cooling. Therefore, there was no need to consider the heating load. Moreover, for the case, energy system such as air conditioning system was also investigated to determine and compare optimised energy cost for the different alternatives. Twenty (20) years long building life is considered for determining LCCA, and the discount rate is taken at 3.262% (CEIC, 2018).

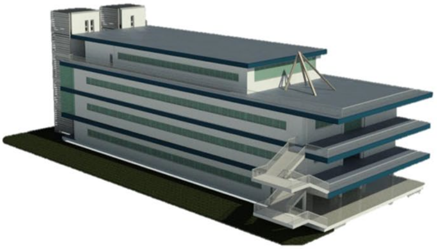
2.2 Building information modelling (BIM)

BIM is a better planning, design, and O&M process utilising a standardised machine-readable information model for any new or existing facility. Besides the advanced use of BIM, it performs an efficient flow of data between different libraries in creating the Information Delivery Manual (IDMs) for energy measurement, environmental assessment and LCCA (Andriamamonjy et al., 2018; Li et al., 2017). 3D visualised BIM models of the three alternatives with changing envelope materials, i.e. curtain walls (Fig. 2a), rockwool insulated brick walls (Fig. 2b), and polystyrene insulated brick walls (Fig. 2c), were generated. Autodesk Revit interface was used for modelling, which is considered the best interface to create authentic architectural and detailed, high-quality designs (Read et al., 2011). Inside Revit, different plans were assigned to the stories and 3D elevations were designed, followed by materials allocation to the different components of the building model.



(a) Building with Curtain walls

(b) Building with Rockwool Insulated brick wall



(c) Building with Polystyrene insulated brick wall

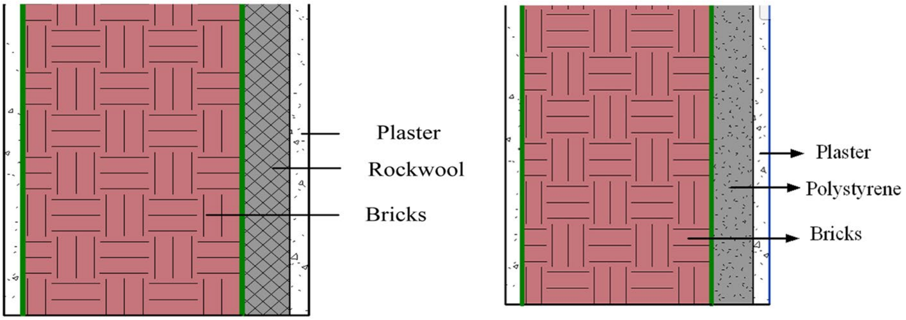
Fig. 2 Alternative building models

2.3 Materials selection

In this study, three types of wall systems, a typical brick wall with rockwool insulation, a brick wall with polystyrene insulation, and a curtain wall system, were considered to be studied as building envelopes. First, a typical brick wall with rockwool insulation material was assigned to the external envelope of the 3D-modelled building in Revit, as shown in Fig. 3a. Rockwool is a non-metallic, inorganic product made from a carefully managed mix of raw materials, consisting mainly of stone or silica, heated until molten to a high temperature (Dias, 2020). The molten glass or stone is then spun and moulded into a flexible and fibrous mat for further processing into finished goods. Mineral wool's thermal efficiency is primarily due to preventing convection by trapping air in the open-cell and woolly matrix of the fibre (INDiaTHerMOcAre, 2020). Conduction is decreased because there is very little solid material to provide pathways, and there is poor thermal conductivity in the trapped, static air (Dias, 2020). The thickness of rockwool is kept at 50 mm for the current model.

Secondly, a typical brick wall with polystyrene insulation material was assigned to the model in Revit, as shown in Fig. 3b. Polystyrene foam is used as insulation as it contains tiny air bubbles trapped within it. The heat energy does not flow through it, making polystyrene a good insulator (Samanta et al., 2021). In the cavity of the building walls, insulators such as fibreglass and plastic foam are placed to trap the air and reduce the transfer of heat energy. Foamed polystyrene contains millions of tiny air bubbles trapped in the foam, and since polystyrene has a high thermal resistance, it is very effective at preventing heat transfer (Lohtander et al., 2022). The thickness of the polystyrene is also kept at 50 mm.

Thirdly, a curtain wall was considered which is a non-structural facade system for the exterior skin of buildings usually associated with multistorey buildings. The curtain wall is a popular choice by designers and clients to adopt for a beautiful architectural appearance (Almerino, 2022). In contrast, the curtain wall offers poor thermal performance with unwanted heat gain or loss (Li et al., 2022). To improve thermal performance, the typical curtain wall is re-engineered with time. With glazing facades, the thermal conductivity and performance can be improved, which can be measured with thermal insulation (R-Value) and heat transfer coefficient (U-Value). Thus, a glass glazing curtain wall with a higher insulation value (R) and lower heat transfer (U) has good thermal performance (Huang et al., 2021). The curtain wall system with double-glazing glass was considered another alternative for the outer building envelope.



(a) Brick wall with Rockwool insulation (b) Brick wall with Polystyrene insulation

Fig. 3 Materials cross section

Table 1 Properties of the materials

Material	Thermal mass Kj/k	Heat Resistance (m k)/W	Thermal Conductivity (U) W/ (m.K)
Brick wall with rockwool insulation	34.12	1.94	0.033 (Annibaldi et al., 2019)
Brick wall with polystyrene insulation	34.13	1.94	0.040 (Klarić et al., 2016)
Curtain wall (double glazed)	34.84	1.19	0.60 (Architecture, 2007)

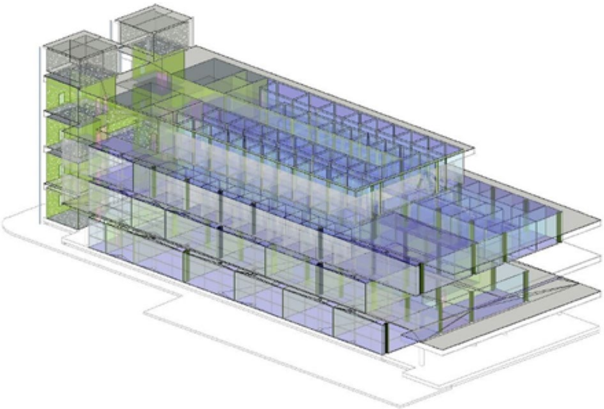


Fig. 4 Energy visualised model in Revit

To assess the thermal properties of the building envelope, thermal conductivity was mainly considered for the three alternative insulation systems, as some of the values of the parameters remain the same for the alternatives. Thermal conductivity is the capacity of a material to conduct heat. Highly conductive materials can efficiently conduct heat and quickly absorb heat from their surroundings. Poor thermal conductors restrict heat transfer and slowly absorb heat from their surrounding environment, causing them to become cold. The characteristics of the building envelope alternatives are given in Table 1.

2.4 Data Transfer

To analyse building energy properties with the three types of building envelope, energy models were created in the Revit, as shown in Fig. 4. This process consists of creating rooms and zones in the different portions of the building. Revit uses the space portion to hold details on the location. Space keeps values for a set of parameters that influence the analysis of a project's heating and cooling load. Rooms and spaces are distinct elements for various purposes. Rooms are architectural elements used to keep occupying locations updated. Spaces are used solely for volume measurement in the categories. Revit contains parameters that keep knowledgeable data about the locations and areas in which it is located (Thabet et al., 2022). The whole data are used in the study of heating and cooling loads. The heating load is the energy applied to maintain an appropriate temperature range. However, the cooling load is the energy used to drain heat from a room to retain a comfortable temperature. The heating and cooling loads depend on height, the shadows on the building, the insulation of the building and the components of the building, such as floors, walls, roofs and ceilings (Duraković, 2020).

The heating and cooling loads can be controlled with heating or air conditioning systems. In Ecotect, the case study building was analysed for cooling and heating load. The parameters of working hours from 8 am to 5 pm were assigned since the academic building operates typically during this time. After considering all criteria, the amount of cooling energy needed to sustain the building temperature between 22 and 26 °C was calculated.

On the other hand, Autodesk Ecotect was used to analyse the energy model. Ecotect is a convenient software that is free of material restrictions. It can analyse any project orientation, solar systems annual projection and calculate energy load for an entire year. Moreover, Ecotect differs from most analytical tools because it focuses on the early planning phases, where essential decision-making may have many further consequences on the result. The data from Revit can easily be imported to the Ecotect interface in the form of DXW and gbXML (Fu, 2022). In the current case, the data of the energy model from Revit was imported in gbXML format. It is the language of the building which enables the sharing of information between the different 3D building information models and the research tools for architecture and engineering (Bastos Porsani et al., 2021).

2.5 Life cycle cost analysis (LCCA)

The LCCA method was used to measure the cost-effectiveness of the different building envelope alternatives. To assess the LCCA of the building, the energy cost and material installation cost were integrated with cost parameters such as Net Present Value (NPV), a 20-year life cycle, and a discount rate. The data regarding the initial construction cost were determined by the quantity take-off of material which is a proficient application of BIM. The capital cost of the energy system used in the building, such as the central air conditioning system, was determined according to the building area and different suppliers provided the cost. In the following research, the components related to optimising energy and the energy systems, i.e. building envelope and cooling system, are considered only. For this purpose, the initial construction cost of the envelope system is added to the installation cost of the cooling system for the total initial cost.

Furthermore, the operation cost is the cost of energy used to operate a project which can be calculated by dividing the total annual energy cost by the total annual energy consumption. The operation and maintenance costs occur in a uniform series of payments utilised every year, which can be found with the help of equivalent annual costs. Equivalent Annual Costs (EAC) are the annual ownership, service and maintenance expenses of the property over the lifetime and the overall cost of the property throughout its lifetime. The EAC was found by Eq. (1), where NPV = net present value, i = discount rate and n = years of expenditure.

$$\mathrm{EAC} = \mathrm{NPV}\ \left((1+i)^{\mathrm{n}}\right) \Big/ ((1+i)^{n} - 1) \tag{1}$$

Moreover, the salvage value was determined, which is a single payment compound cost. A single payment compound amount factor is used to compute the future worth (F) accumulated after "n" years from the known present worth (P) at a given interest rate "i" per interest period. It is assumed that the interest period is in years and the interest is compounded once per interest period. The single payment value was calculated using Eq. (2).

$$\mathrm{NPV} = \text{present cost} / (1 + \mathrm{i})^{\mathrm{n}} \tag{2}$$

In the last, the total LCCA was determined, which includes all the costs associated with the construction, service, and repair over a given period. For the dynamic decision-making process, optimising the LCCA for a project, building, or equipment is necessary. LCCA was calculated using Eq. (3).

$$\mathrm{LCCA} = \text{ initial Cons. Cost } - \sum (\mathrm{O\&M})\text{ cost }(\mathrm{P/A},\ \mathrm{i},\ \mathrm{n}) + \text{ Salvage value }(\mathrm{P/A},\ \mathrm{i},\ \mathrm{n}) \tag{3}$$

The uniform series of payments is shown by P/Ai,n, where “A” is the uniform series of equal amounts, which happened at the end of each time period for “n” number of periods at the compound interest rate of “i” and “P” is the cumulative present value. The unknown parameter “P” is often accompanied by known values for A, i and n.

3 Results and analysis

This section provides a detailed energy analysis, followed by LCCA of building envelope alternatives. The energy model was first analysed in Ecotect, which evaluates the energy absorption by the building surfaces, the annual and daily orientation of the sun, and the annual heating and cooling load of the case building. After that, a detailed LCCA of the building envelope was analysed and a comparison between the present worth of the alternatives was provided.

3.1 Energy model analysis

The Ecotect can simulate the components created in gbXML file format transferred from the Revit. The software interface recognises the spaces and zones in the gbXML file and creates an energy model in its interface, as shown in Fig. 5.

In simple and single-storey buildings, the exterior surfaces, particularly the larger roofs, are exposed to the sunlight, creating heat gains. In a multistorey building, the envelope is the major surface exposed to sunlight, which affects the total energy gain and loss of the internal environment. The roof surface is a minimum area exposed to sunlight compared to the rest of the envelope. Therefore, focusing on the building envelope is more effective in overcoming the solar heat gain, which helps in energy optimisation. In the case study building, the thermal analysis gives a detailed overview of the surface exposed to sunlight. The building heat map can be seen in Fig. 6.

The colour indicator mentions the amount of heat absorbed by the building surfaces. Similarly, in Fig. 7, the annual and daily orientation of the sun is demonstrated, which

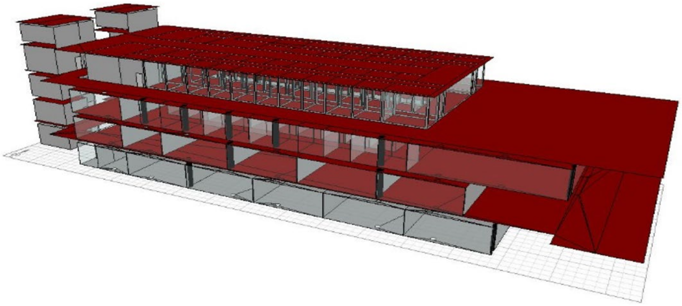


Fig. 5 Energy visualised model in Ecotect

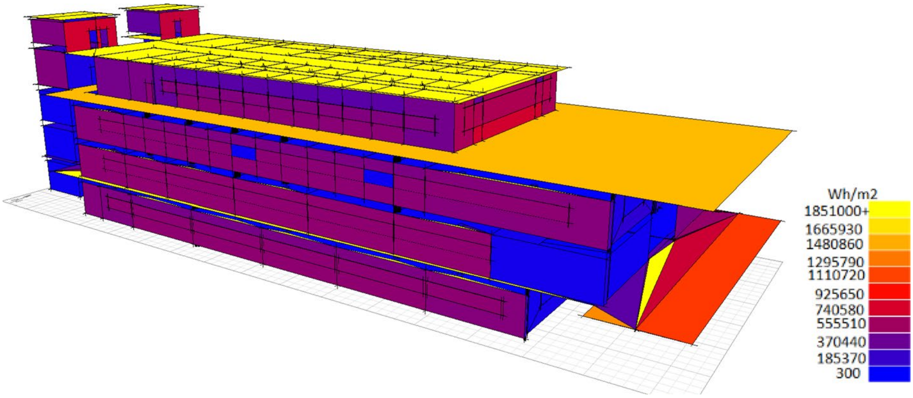


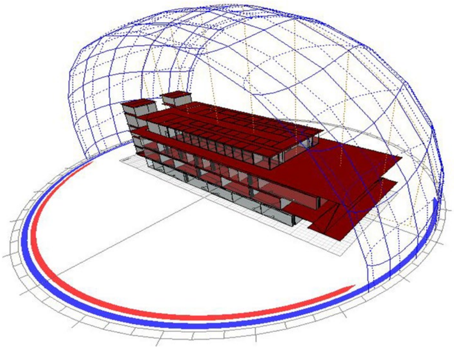
Fig. 6 Energy absorption by the building surfaces

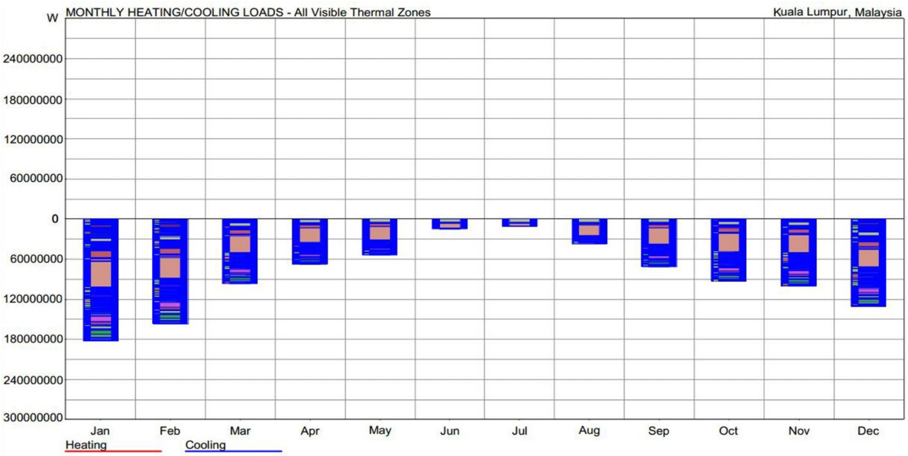
analyses the projection of the shadow of the building due to the position of the sun. The following simulation is a powerful application of BIM technology that identifies the heating and cooling load of the building. BIM offers every range of locations; thus, the location was set according to the requirement of the study.

3.2 Cooling and heating load analysis

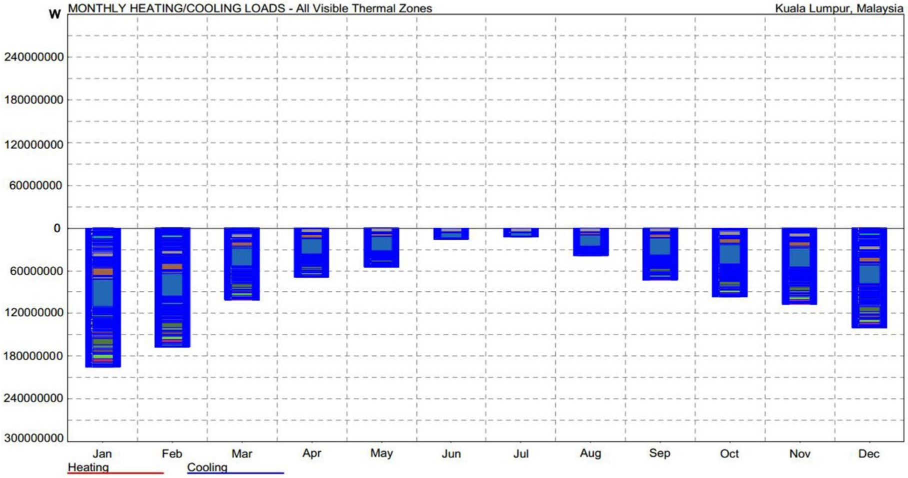
Energy consumption was estimated based on building materials to analyse their effect on decreasing and/or increasing energy usage. Figure 8a and b demonstrates the simulation results from Ectotect software for the heating and cooling load of brick walls with rock-wool insulation and the brick wall with polystyrene insulation. The analysis was specifically based on the weather database of the Ecotect. In the model, only blue colours are visible, indicating that only the cooling load was required due to the hot and humid Malaysian climate. Thus, there is no heating load evident because no heating was required. It can be seen that from Nov to Feb, the energy demand is higher, whereas June and July are hotter months that require minimum cooling energy. Similarly, Fig. 9 represents the heating and cooling load of the models for the curtain wall system. Again, no evidence of heating load is visible due to the local climatic conditions.

Fig. 7 Annual and daily orientation of the sun





(a) Rockwool Insulation



(b) Polystyrene Insulation

Fig. 8 Monthly Heating and Cooling load

Besides this, a detailed summary of the heating and cooling load of the three models is demonstrated in Table 2 to determine an optimised insulation option that will lead to a reduction in energy usage.

Similarly, the total energy demand for the three models is presented in Fig. 10. The energy load for the building having curtain walls as an envelope recorded the highest value of 1,218,415 KWh. While the load of the building having a brick wall with rockwool insulation was the lowest at 1,018,301 KWh. The wall having rockwool insulation saves 17% energy demand compared to the curtains wall, whereas the wall having polystyrene insulation saves 12.7% energy demand compared to the curtain walls. Similarly, walls with rockwool insulation save 5% energy as compared to polystyrene insulation material. Thus, the analysis also indicates that building walls with low U-values can minimise heat gain and loss for the building.

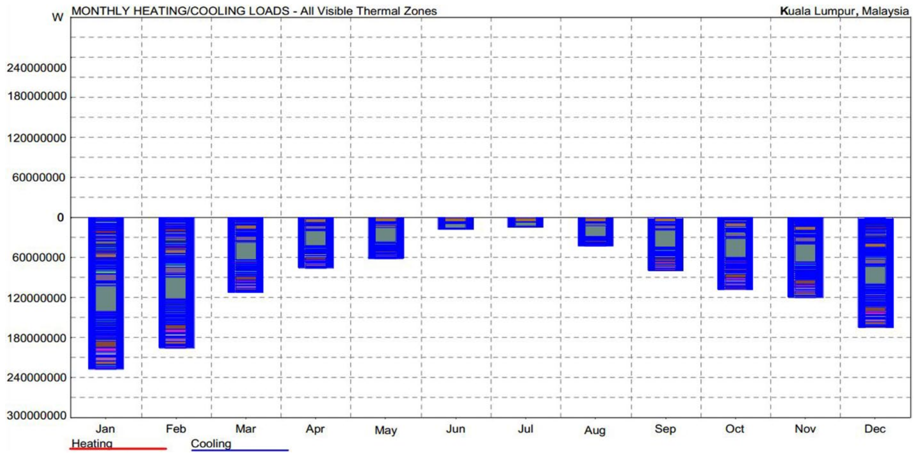


Fig. 9 Monthly Heating and Cooling load for Model with Curtain walls

Table 2 Summary of monthly heating and cooling load of the alternatives

Month	Curtain wall		Bricks wall with rockwool		Bricks wall with polystyrene	
	Heating load (KWh)	Cooling load (KWh)	Heating Load (KWh)	Cooling load (KWh)	Heating load (KWh)	Cooling load (KWh)
Jan	0	226,550	0	182,869	0	195,373
Feb	0	195,444	0	156,902	0	167,148
Marc	0	112,495	0	96,686	0	101,068
Apr	0	75,809	0	67,369	0	69,398
May	0	61,388	0	53,609	0	55,341
Jun	0	18,122	0	14,957	0	15,703
Jul	0	14,682	0	11,689	0	12,273
Aug	0	42,392	0	37,492	0	39,146
Sep	0	79,342	0	71,237	0	72,961
Oct	0	107,973	0	93,542	0	96,605
Nov	0	119,774	0	100,744	0	106,811
Dec	0	164,444	0	131,205	0	140,648

3.3 Power consumption analysis

3.3.1 Building envelope cost

The building envelope is the external skin of the building exposed to sunlight and thermal conductivity. The building envelope cost, as shown in Table 3, is calculated according to the Construction Industry Development Board (CIDB), Malaysia (CIDB,

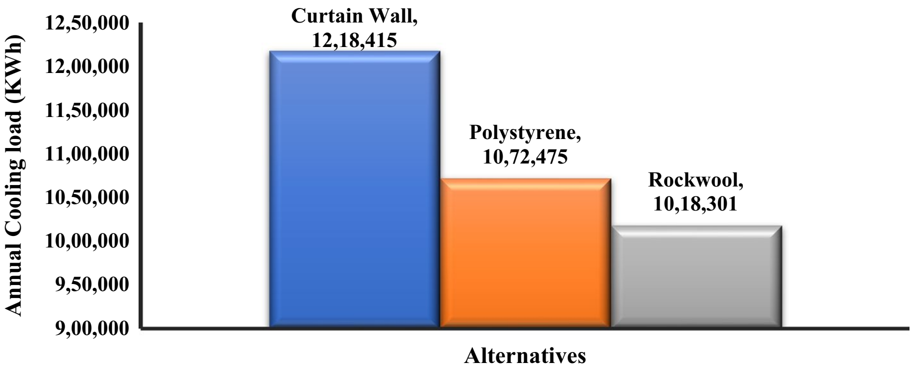


Fig. 10 Cooling load comparison

2019). The table determines the thickness of material layers individually in millimetres, whereas the total cost is found by the product of the total area and unit cost of materials.

3.3.2 Installation cost of AC system

The data regarding the central AC installation cost were determined according to the building area, and the cost was determined from different supplier websites (ACSON, 2021; Carrier, 2021; DAIKIN, 2021). The total area of the considered building was 1855 m^2 for each storey. Moreover, the installation cost for an area between 1500 m^2 and 2000 m^2 is between USD 3500 and 4300, as shown in Table 4. Thus, the air conditioning system cost of 2.5 tons for each storey was estimated to be USD 4300 and a total of USD 17,200 for the four stories.

Table 3 Initial cost of the wall systems

Material	Thickness (mm)	Cost (USD/m2)	Total area (m2)	Cost (USD/m2)	Total cost (USD/m2)
	1	2	3	4 = 2*3	5
Brick wall with Rockwool insulation					
Brick	228	22.60	2,646	59,799.6	99,412
Rockwool	50	4.42	2,644	11,686.48	
Plaster	20	5.28	5,289	27,925.92	
Brick wall with Polystyrene insulation					
Brick	228	22.60	2,646	59,799.6	96,556
Polystyrene	50	3.34	2,642	8,830.96	
Plaster	20	5.28	5,289	27,925.92	
Curtain wall					
Double glazing	6.35	127	771	97,917	97,917

3.3.3 Total initial cost

For the total initial cost, the initial construction cost of the envelope system was added to the installation cost of the cooling system, as shown in Table 5.

3.3.4 Operation and maintenance cost

Operation cost is the cost of energy used to operate the building properly. In this study, the air conditioning system cost was considered operation cost per KWh, which can be calculated by multiplying the total annual energy demand in KWh by the unit price of the electricity. The capacity or power of an AC unit is measured in British Thermal Units—BTUs (the amount of heat it can remove from space in one hour). The operation of the considered institutional building was from 8 am to 5 pm. The unit size of the AC system determined for each floor of the building was 2.5 tons, equal to 30,000 BTU (RapidTables, 2021). As the building was in Malaysia and the operation was 8 h per day, the cost of the electricity per kw/h was considered USD 0.412 according to Tenaga Nasional Berthed, Malaysia (TNB, 2021) for commercial buildings, as shown in Table 6, whereas the total operation cost can be found using Eq. 4:

$$\text{Total operation cost per month} = \frac{\text{Watt usage per hour (Wh)}}{1000} \times \text{price of kw/h} \quad (4)$$

The total annual cost for the three alternatives was calculated as shown in Table 7 based on the energy demand analysed by Ecotect. The model having curtain walls as an external envelope had an energy demand of 1,218,415 KWh per year, having an electricity cost termed as operation cost of USD 126,715 per year to keep the building cool 8 h per day. Likewise, the annual energy demand for the brick wall with rockwool insulation was calculated to be 1,018,301 KWh, for which the operation cost was USD 105,903 per year. In

Table 4 AC unit size and installation cost according to the Area

Area (m2)	Unit Capacity (BTU)	Unit Size (Tons)	Installation Cost (USD)
700–1000	1800	1.5	2,200–3,300
1200–1400	21,000	2	3,000–3,800
1500–2000	30,000	2.5	3,500–4,300
2000–2500	34,000	3	4,500–5,000
3000–4000	48,000	4	5,200–5,800
5000+	60,000	5	6,000

Table 5 Total initial Cost

Wall type	Cost of wall type (USD)	Cost of the cooling system (USD)	Total initial cost (USD)
Brick wall with rockwool insulation	99,412	17,200	116,612
Brick wall with polystyrene insulation	96,556	17,200	113,756
Curtain wall	97,917	17,200	115,117

Table 6 Malaysian Electricity Rates

Malaysian electricity prices	Household (kWh)	Business (kWh)
Malaysian Ringgit (MYR)	0.244	0.412
US Dollar (USD)	0.059	0.104

contrast, the total energy demand for the bricks wall with polystyrene as insulating materials was 1,072,475 KWh and the entire operation cost to keep the building cool 8 h per day was USD 111,537 per year. On the other hand, the total annual maintenance cost for the AC system was USD 173 provided by the suppliers. The annual maintenance cost was added to the annual operation cost to obtain combined operation and maintenance costs.

3.3.5 Salvage value

Salvage value is the value after the usable life of an asset. It is sometimes called scrap value which is used to calculate the average asset depreciation cost. Firms generally estimate a "reasonable" salvage for the commodity in consideration. The worth depends on how much time and how much the company uses the asset. The salvage value of the wall systems is not considered in the following analysis as the focus is on energy optimisation with LCCA. The average system useful life for the ACs is between 15 and 20 years, for which the salvage is estimated to be USD 6129, according to the suppliers (ACSON, 2021; Carrier, 2021; DAIKIN, 2021).

3.3.6 Discount rate

The costing of the life cycle approach typically includes simple discounting and financial estimation methods. It considers the balance between original costs and future investments using a set of economic analyses. The basis for the alternatives to be tested is similar. This can be described as applying the chosen interest rate to change the distribution value to a common point of reference, typically when decisions must be made. This approach guarantees an equivalent comparison of the alternatives. The discount rate in Malaysia in October 2018 was 3.262% which is considered for this study (CEIC, 2018).

Table 7 Total Operation and Maintenance Cost (O&M)

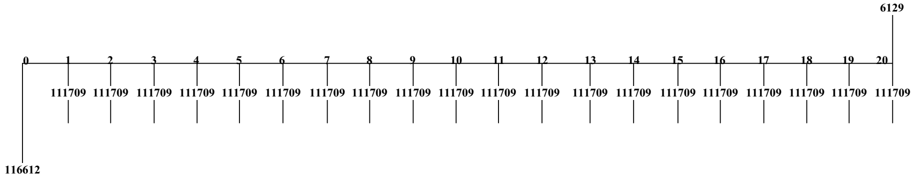
Wall system	Energy (KWh)	Electricity cost per Unit	Operation cost (USD/year)	Maintenance cost (USD)	O&M cost (USD)
	(1)	(2)	(3 = 1*2)	(4)	(5 = 3 + 4)
Bricks Wall with Rockwool	1,018,301	0.104	105,903	173	106,076
Bricks Wall with Polystyrene	1,072,475	0.104	111,537	173	111,709
Curtain wall	1,218,415	0.104	126,715	173	126,888

3.3.7 Net present value (NPV)

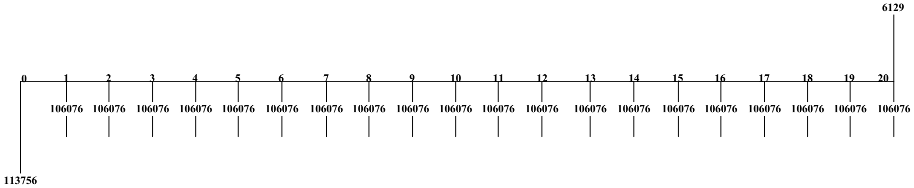
The cash flow diagram is developed for the 20 years, as shown in Fig. 11, for the alternatives to understand the phenomena of future cash. Present value is the current value of future money or cash flow stream given a specific rate of return. Future cash flows are discounted at the discount rate of 3.262%. The higher the discount rate, the lower will be the present value. The total LCCA of the three alternatives with the air conditioning unit as an operating system was calculated as shown in Fig. 12 using Eq. (3). The present worth of the building with the curtain wall was estimated as USD -1,887,963, and the wall with polystyrene insulation was USD -1,676,995. In contrast, the present worth of the wall having rockwool as insulation material was USD-1,601,744.

4 Discussion

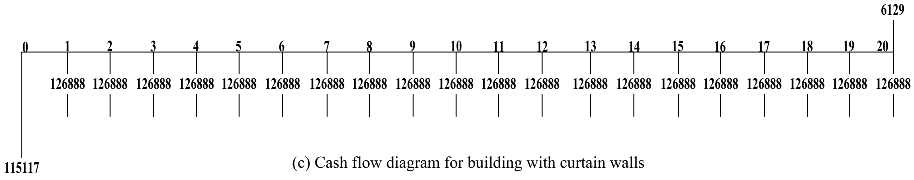
The energy consumption of the building raises the total LCC for a project. The key component of the building that impacts energy demand and use is the building envelope. In high-rise buildings, the envelope is the primary solar radiation barrier, impacting the average energy gain and loss in the interior atmosphere. The external surfaces, especially the roof area, are exposed to sunlight in simple and single-storey projects and therefore, obtain heat. Whereas, the roof surface of high-rise buildings receives less sunlight than the rest of the envelope, which impacts energy efficiency and must be dealt with for optimum energy costs. The building envelope is a component that substantially influences the building's energy consumption under the same building orientation, the area ratio of window to wall,



(a) Cash flow diagram for building with a brick wall having Rockwool insulation



(b) Cash flow diagram for building with a brick wall having polystyrene insulation



(c) Cash flow diagram for building with curtain walls

Fig. 11 Cash flow diagram

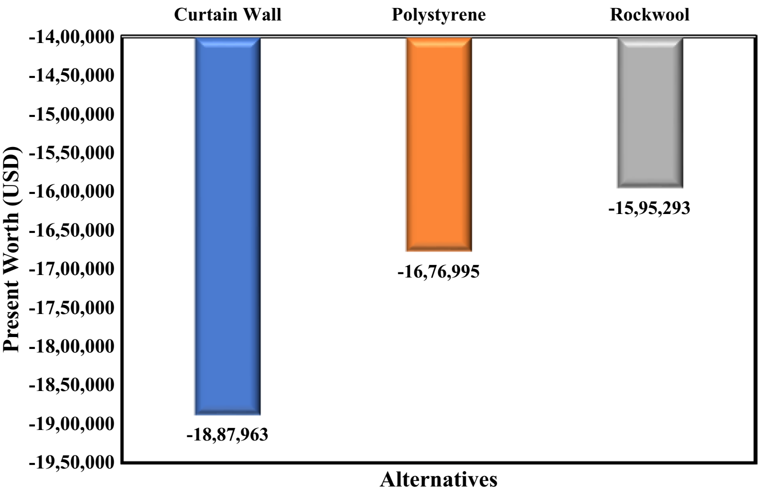


Fig. 12 The present worth of the alternatives

and the geometric size of components (Yuan et al., 2020). Different materials and structures could be used as energy envelopes with a similar purpose but differing thermal conductivity and emission.

The application of BIM to find sustainable mechanisms has beneficial impacts on energy efficiency, enabling the optimisation of the building's overall life cycle performance during the conceptual design phase of a project. Advanced BIM is an adequate data flow between numerous libraries for energy analysis, LCA and LCCA. Standards have been defined that show how software and systems should interact when utilising the same data formats. gbXML, created by Green Building Studio, and IFC, an object-based, open file format developed by building SMART and approved as an official International Standard ISO 16739–1:2018, are widely used for data sharing within the AEC industry (Durdyev et al., 2021; Panteli et al., 2020).

Evaluation of BIM and energy modelling capabilities (AlizadehKharazi et al., 2020) found that switching out low-performance traditional envelope materials for high-performance alternatives reduced LCC by 28% and increased performance by 31%. Similarly, Sandberg et al. (2019) determined that the optimal design solution could yield savings of 13% Life Cycle Energy (LCE) and 12% LCC relative to the conventional design building envelope. They also assessed the building envelope and concluded that increasing the insulation in the roof and external walls would provide the greatest LCE and LCC benefit of all building components.

In the current study, a convenient way to determine total energy use and LCC and how to assess decision-making of optimum alternatives with BIM simulation is adopted. Revit was used to create an energy model for this investigation. Data were exported in gbXML format and imported into the Autodesk Ecotect software to determine the optimal building envelope for education institutions and calculate their HVAC loads. The cooling load of a 4-storey educational building was calculated for three types of building envelope alternatives. The highest energy load for the building with curtain walls was 1,218,415 KWh. However, a building load with a brick wall with rockwool insulation was the lowest at 1,018,301 KWh. Compared to the curtain wall, the wall with rockwool insulation saves

17% energy, while the wall with polystyrene insulation saves 12.7% energy compared to the curtain wall. In comparison with the insulation of polystyrene, walls with rockwool insulation save 5% energy. This is because insulating materials with lower thermal conductivity result in energy savings by allowing less heat conduction from the surrounding. Moreover, the total LCC of the alternatives demonstrated in Fig. 13 elaborates on the comparison between the impact of using different types of wall systems as a building envelope. Results show that the rockwool insulation has the highest cost during the installation phase, followed by the curtain wall and the lowest initial cost is with polystyrene insulation materials. The wall with rockwool has the lowest cost during the operation and maintenance phase, followed by polystyrene insulation and curtain wall. Adopting the LCCA approach, all the future costs associated with the project were discounted to the present worth to compare all the alternatives together and to identify the best-optimised alternative. According to the total costs for all alternatives after discounting them to the present values, it was evaluated that the curtain wall has the lowest present worth, i.e. USD -1,894,413, followed by polystyrene insulation having a present worth of USD -1,683,445, whereas the highest present worth calculated was USD -1,601,744 for rockwool insulation. The LCCA demonstrates that the best alternative is rockwool insulation. Although the initial cost could be higher than other alternatives, the 20 years of O&M costs are low, playing a significant role in total LCC optimisation. In all cases, rock wool is the material that allows obtaining the lowest O&M cost, unlike other insulating materials chosen in the study. Rockwool is a very effective insulating material because it has a very low heat conductivity value; the lower the thermal conductivity, the better the insulator the material is (Annibaldi et al., 2019).

Thus, the energy efficiency model of a building cannot just rely on the recommended and practical values. Better performance may be achieved in buildings if these kinds of materials are used and the economic thickness of insulating materials in the outer walls is determined in the light of the actual conditions of the building and the environmental consequences. The economic thickness of the thermal insulation layer is determined using the life cycle cost analysis method, which considers all aspects of building construction and uses more objectively and scientifically (Zhang et al., 2019).

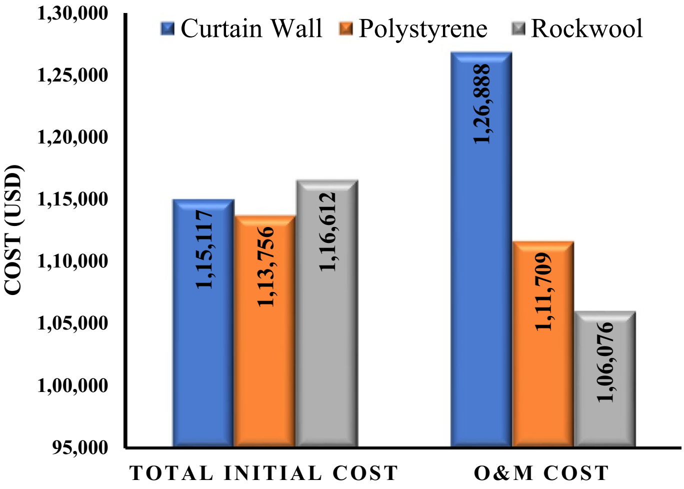


Fig. 13 Total life cycle cost comparison

5 Conclusion

The simplest methodology of integrating economic assessment and BIM simulation for total cost optimization is achived in the current study. Integrating LCCA with the BIM approach in the conceptual planning and design stage supports the decision-makers in optimising the energy and cost in the operation period and reducing total project costs. The BIM approach allows a range of alternative options that give the capacity for sustainability reform and predictive analysis within a single model to improve LCC and building efficiency. A significant factor influencing energy demand and consumption is the envelope of the building. Thus, the current study considered the building envelope to determine energy and cost-saving potential by analysing and comparing the energy needs in a building with various alternate wall systems. The study also shows that walls can reduce the thermal gain and loss of buildings with low U-values. Moreover, implementing the LCCA technique simplified all future costs to the current market value to find the best-optimised alternative. The LCCA determines the rockwool insulation as the best outcome. Although the initial cost could be higher than other options, the cost of O&M for 20 years is low, which optimises the LCCs.

The current research bridges the gap between the integration of BIM technology and economic assessment. While performing the research, data acquisition was a big hurdle to performing LCCA. Moreover, the LCCA is performed manually in the current research, using the data extracted from BIM and external sources. In future, a strategy or a plugin should be developed to directly integrate the project's total life cycle cost by incorporating the simulation results directly within the BIM environment to enhance the results.

Acknowledgements The authors would like to thank Universiti Teknologi PETRONAS (UTP) for the support provided for this research.

Author contributions All the authors contributed equally to this study.

Funding Not applicable.

Data availability My manuscript has no associated data.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

References

ACSON. (2021). Retrieved 28 April from https://www.acson.com.my/

Aditya, L., Mahlia, T. M. I., Rismanchi, B., Ng, H. M., Hasan, M. H., Metselaar, H. S. C., Muraza, O., & Aditiya, H. B. (2017). A review on insulation materials for energy conservation in buildings. *Renewable and Sustainable Energy Reviews, 73*, 1352–1365. https://doi.org/10.1016/j.rser.2017.02.034

Aibinu, A. A., & Venkatesh, S. (2012). The rocky road to BIM adoption: quantity surveyors perspectives.

AlizadehKharazi, B., Alvanchi, A., & Taghaddos, H. (2020). A novel building information modeling-based method for improving cost and energy performance of the building envelope. *International Journal of Engineering, 33*(11), 2162–2173.

Almerino, P. M. (2022). Advancing an automated evaluation in the design of a curtain wall. *Journal of Agriculture and Technology Management, 25*(1), 79–87.

Al-Saggaf, A., Nasir, H., & Taha, M. (2020). Quantitative approach for evaluating the building design features impact on cooling energy consumption in hot climates. *Energy and Buildings, 211*, 109802. https://doi.org/10.1016/j.enbuild.2020.109802

Altaf, M., Alaloul, W. S., Musarat, M. A., & Qureshi, A. H. (2022). Life cycle cost analysis (LCCA) of construction projects: sustainability perspective. *Environment, Development and Sustainability, 30*, 1–48.

Althaus, H.-J., Kellenberger, D., Doka, G., & Künniger, T. (2005). Manufacturing and disposal of building materials and inventorying infrastructure in ecoinvent (8 pp). *The International Journal of Life Cycle Assessment, 10*(1), 35–42.

Amasyali, K., & El-Gohary, N. M. (2018). A review of data-driven building energy consumption predicastion studies. *Renewable and Sustainable Energy Reviews, 81*, 1192–1205. https://doi.org/10.1016/j.rser.2017.04.095

Amirifard, F., Sharif, S. A., & Nasiri, F. (2019). Application of passive measures for energy conservation in buildings–a review. *Advances in Building Energy Research, 13*(2), 282–315. https://doi.org/10.1080/17512549.2018.1488617

Amran, Y. H. M., El-Zeadani, M., Lee, Y. H., Lee, Y. Y., Murali, G., & Feduik, R. (2020). Design innovation, efficiency and applications of structural insulated panels: A review. *Instructure, 27*, 1358.

Andriamamonjy, A., Saelens, D., & Klein, R. (2018). An automated IFC-based workflow for building energy performance simulation with modelica. *Automation in Construction, 91*, 166–181. https://doi.org/10.1016/j.autcon.2018.03.019

Annibaldi, V., Cucchiella, F., De Berardinis, P., Rotilio, M., & Stornelli, V. (2019). Environmental and economic benefits of optimal insulation thickness: A life-cycle cost analysis. *Renewable and Sustainable Energy Reviews, 116*, 109441.

Architecture, F. i. (2007). *A QUICK AND EASY GUIDE TO U-VALUES*. Retrieved 01/08 from https://www.firstinarchitecture.co.uk/a-quick-and-easy-guide-to-u-values/

Ascione, F., Bianco, N., Mauro, G. M., & Napolitano, D. F. (2019). Building envelope design: Multi-objective optimization to minimize energy consumption, global cost and thermal discomfort. Application to different Italian climatic zones. *Energy, 174*, 359–374. https://doi.org/10.1016/j.energy.2019.02.182

Basrawi, F., Ibrahim, H., Taib, M. Y., & Lee, G. C. (2013). Optimum thickness of wall insulations and their thermal performance for buildings in malaysian climate. *International Journal of Automotive and Mechanical Engineering, 8*, 1207.

Bastos Porsani, G., Valle, D., de Lersundi, K., Sánchez-Ostiz Gutiérrez, A., & Fernández Bandera, C. (2021). Interoperability between building information modelling (BIM) and building energy model (BEM). *Applied Sciences, 11*(5), 2167.

Beyhan, F., & Ersan, P. U. (2020). An approach to reduce cooling loads in transparent facades. *Materials Science and Engineering., 960*, 042031.

Biseniece, E., Freimanis, R., Purvins, R., Gravelsins, A., Pumpurs, A., & Blumberga, A. (2018). Study of hygrothermal processes in external walls with internal insulation. *Environmental and Climate Technologies, 22*(1), 22–41. https://doi.org/10.1515/rtuect-2018-0002

Cao, Y., Kamaruzzaman, S. N., & Aziz, N. M. (2022). Building information modeling (BIM) capabilities in the operation and maintenance phase of green buildings: A systematic review. *Buildings, 12*(6), 830.

Carrier. (2021). *Installation cost of the central AC* Retrieved 28 April from https://www.carrier.com/commercial/en/my/services/#tab-2

CEIC. (2018). *Malaysia Discount Rate: Treasury Bills: 12 Months*. CEIC. https://www.ceicdata.com/en/malaysia/discount-rates/discount-rate-treasury-bills-12-months

Chwieduk, D., & Chwieduk, M. (2020). Determination of the energy performance of a solar low energy house with regard to aspects of energy efficiency and smartness of the house. *Energies, 13*(12), 3232. https://doi.org/10.3390/en13123232

CIDB. (2019). National construction cost centre. http://n3c.cidb.gov.my/n3c/output/signup.php

Çomaklı, K., & Yüksel, B. (2003). Optimum insulation thickness of external walls for energy saving. *Applied Thermal Engineering, 23*(4), 473–479. https://doi.org/10.1016/s1359-4311(02)00209-0

DAIKIN. (2021). *Installation cost of the central AC*. Retrieved 28 April from https://www.daikin.com.my/locate-dealer/

Dalla Mora, T., Bolzonello, E., Cavalliere, C., & Peron, F. (2020). Key parameters featuring bim-lca integration in buildings: A practical review of the current trends. *Sustainability, 12*(17), 7182.

Dias, S. M. S. S. (2020). Thermal and mechanical behaviour of sandwich panels for climatic chambers of high performance.

Duraković, B. (2020). Passive solar heating/cooling strategies. In: *PCM-based building envelope systems*. Springer: London. pp 39–62. https://doi.org/10.1007/978-3-030-38335-0_3

Durdyev, S., Dehdasht, G., Mohandes, S. R., & Edwards, D. J. (2021). Review of the building information modelling (BIM) implementation in the context of building energy assessment. *Energies, 14*(24), 8487.

Durdyev, S., Zavadskas, E. K., Thurnell, D., Banaitis, A., & Ihtiyar, A. (2018). Sustainable construction industry in Cambodia: Awareness, drivers and barriers. *Sustainability, 10*(2), 392. https://doi.org/10.3390/su10020392

Elfayoumy, Y. K., ElSaied, M. S., & Elwazeer, M. A. (2020). Sustainable building material technology as an approach to thermal comfort in low income housing in hot regions. *Bulletin of the Faculty of Engineering Mansoura University., 43*(2), 12–21. https://doi.org/10.21608/bfemu.2020.94482

Elkadeem, M. R., Wang, S., Azmy, A. M., Atiya, E. G., Ullah, Z., & Sharshir, S. W. (2020). A systematic decision-making approach for planning and assessment of hybrid renewable energy-based microgrid with techno-economic optimization: A case study on an urban community in Egypt. *Sustainable Cities and Society, 54*, 102013. https://doi.org/10.1016/j.scs.2019.102013

Feehan, A., Nagpal, H., Marvuglia, A., & Gallagher, J. (2021). Adopting an integrated building energy simulation and life cycle assessment framework for the optimisation of facades and fenestration in building envelopes. *Journal of Building Engineering, 43*, 103138.

Fu, Y. (2022). PKPM architectural engineering software system based on architectural bim technology. *Journal of Sensors, 20*, 22.

Gholami, H., Røstvik, H. N., Kumar, N. M., & Chopra, S. S. (2020). Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway. *Solar Energy, 211*, 488–502. https://doi.org/10.1016/j.solener.2020.09.087

Hassan, W. N. H. W., Zakaria, N., & Ismail, M. A. (2014). The Challenges of life cycle costing application of intelligent building in malaysia construction industry. *Journal of Design+Built, 7*, 20.

Hernández, F. F., Suárez, J. M. P., Cantalejo, J. A. B., & Muriano, M. C. G. (2022). Impact of zoning heating and air conditioning control systems in users comfort and energy efficiency in residential buildings. *Energy Conversion and Management, 267*, 115954.

Hollberg, A., Genova, G., & Habert, G. (2020). Evaluation of BIM-based LCA results for building design. *Automation in Construction, 109*, 102972.

Hu, S., Yan, D., Guo, S., Cui, Y., & Dong, B. (2017). A survey on energy consumption and energy usage behavior of households and residential building in urban China. *Energy and Buildings, 148*, 366–378. https://doi.org/10.1016/j.enbuild.2017.03.064

Huang, J., Chen, X., Peng, J., & Yang, H. (2021). Modelling analyses of the thermal property and heat transfer performance of a novel compositive PV vacuum glazing. *Renewable Energy, 163*, 1238–1252. https://doi.org/10.1016/j.renene.2020.09.027

INDiaTHerMOcAre. (2020). *What is Mineral Wool?* Retrieved 29/08 from https://thermocareindia.com/mineral-wool/

Jalaei, F., Zoghi, M., & Khoshand, A. (2021). Life cycle environmental impact assessment to manage and optimize construction waste using building information modeling (BIM). *International Journal of Construction Management, 21*(8), 784–801.

Junker, R. G., Azar, A. G., Lopes, R. A., Lindberg, K. B., Reynders, G., Relan, R., & Madsen, H. (2018). Characterizing the energy flexibility of buildings and districts. *Applied Energy, 225*, 175–182. https://doi.org/10.1016/j.apenergy.2018.05.037

Kabeel, A. E., El-Said, E. M. S., & Dafea, S. A. (2019). Design considerations and their effects on the operation and maintenance cost in solar-powered desalination plants. *Heat Transfer—Asian Research, 48*(5), 1722–1736. https://doi.org/10.1002/htj.21454

Kerzner, H. (2017). *Project management: A systems approach to planning, scheduling, and controlling*. Wiley.

Klarić, S., Samic, D., Duerod, M., & Popovac, M. R. (2016). *Guidelines energy efficiency in buildings as a basis for sustainable social and economic development in bosnia and herzegovina*.

Kumar, D., Zou, P. X. W., Memon, R. A., Alam, M. D. M., Sanjayan, J. G., & Kumar, S. (2020). Lifecycle cost analysis of building wall and insulation materials. *Journal of Building Physics, 43*(5), 428–455.

Levy, S. M. (2018). *Project management in construction*. New York: McGraw-Hill Education.

Li, D., Yang, R., Arıcı, M., Wang, B., Tunçbilek, E., Wu, Y., Liu, C., Ma, Z., & Ma, Y. (2022). Incorporating phase change materials into glazing units for building applications: Current progress and challenges. *Applied Thermal Engineering., 102*, 118374.

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2017). Mapping the knowledge domains of building information modeling (BIM): A bibliometric approach. *Automation in Construction, 84*, 195–206. https://doi.org/10.1016/j.autcon.2017.09.011

Lohtander, T., Herrala, R., Laaksonen, P., Franssila, S., & Österberg, M. (2022). Lightweight lignocellulosic foams for thermal insulation. *Cellulose, 29*(3), 1855–1871.

Lomas, K. J., & Porritt, S. M. (2017). Overheating in buildings: Lessons from research. *Building Research & Information, 45*(1–2), 1–18. https://doi.org/10.1080/09613218.2017.1256136

Lotfabadi, P., & Hançer, P. (2019). A comparative study of traditional and contemporary building envelope construction techniques in terms of thermal comfort and energy efficiency in hot and humid climates. *Sustainability, 11*(13), 3582.

Louanate, A., Otmani, R. E., Kandoussi, K., Boutaous, M. H., & Abdelmajid, D. (2022). Energy saving potential of phase change materials-enhanced building envelope considering the six Moroccan climate zones. *Journal of Building Physics, 45*(4), 482–506.

Luerssen, C., Gandhi, O., Reindl, T., Sekhar, C., & Cheong, D. (2020). Life cycle cost analysis (LCCA) of PV-powered cooling systems with thermal energy and battery storage for off-grid applications. *Applied energy, 273*, 115145. https://doi.org/10.1016/j.apenergy.2020.115145

Meredith, J. R., Shafer, S. M., & Mantel, S. J., Jr. (2017). *Project management: A strategic managerial approach*. John Wiley & Sons.

Monteiro, M. V., Blanuša, T., Verhoef, A., Richardson, M., Hadley, P., & Cameron, R. W. F. (2017). Functional green roofs: Importance of plant choice in maximising summertime environmental cooling and substrate insulation potential. *Energy and Buildings, 141*, 56–68. https://doi.org/10.1016/j.enbuild.2017.02.011

Panteli, C., Kylili, A., & Fokaides, P. A. (2020). Building information modelling applications in smart buildings: From design to commissioning and beyond A critical review. *Journal of Cleaner Production, 265*, 121766.

Pásztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering, 44*, 102604.

RapidTables. (2021). *Refrigeration tons to BTU per hour conversion*. Retrieved 28 April from https://www.rapidtables.com/convert/power/ton-to-btu.html

Read, P., Krygiel, E., & Vandezande, J. (2011). *Autodesk revit architecture 2012 essentials*. John Wiley & Sons.

Robinson, C., Dilkina, B., Hubbs, J., Zhang, W., Guhathakurta, S., Brown, M. A., & Pendyala, R. M. (2017). Machine learning approaches for estimating commercial building energy consumption. *Applied energy, 208*, 889–904. https://doi.org/10.1016/j.apenergy.2017.09.060

Saafi, K., & Daouas, N. (2018). A life-cycle cost analysis for an optimum combination of cool coating and thermal insulation of residential building roofs in Tunisia. *Energy, 152*, 925–938. https://doi.org/10.1016/j.energy.2018.04.010

Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews, 15*(8), 3617–3631. https://doi.org/10.1016/j.rser.2011.07.014

Samanta, K. K., Mustafa, I., Debnath, S., Das, E., Basu, G., & Ghosh, S. K. (2021). Study of thermal insulation performance of layered jute nonwoven: A sustainable material. *Journal of Natural Fibers*. https://doi.org/10.1080/15440478.2020.1856274

Sandberg, M., Mukkavaara, J., Shadram, F., & Olofsson, T. (2019). Multidisciplinary optimization of life-cycle energy and cost using a BIM-based master model. *Sustainability, 11*(1), 286.

Sharif, S. A., & Hammad, A. (2019). Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment. *Journal of Building Engineering, 21*, 429–445. https://doi.org/10.1016/j.jobe.2018.11.006

Singh, P., & Sadhu, A. (2019). Multicomponent energy assessment of buildings using building information modeling. *Sustainable Cities and Society, 49*, 101603.

Solgi, E., Hamedani, Z., Fernando, R., & Kari, B. M. (2019). A parametric study of phase change material characteristics when coupled with thermal insulation for different Australian climatic zones. *Building and Environment, 163*, 106317. https://doi.org/10.1016/j.buildenv.2019.106317

Streicher, K. N., Mennel, S., Chambers, J., Parra, D., & Patel, M. K. (2020). Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. *Energy and Buildings, 215*, 109870. https://doi.org/10.1016/j.enbuild.2020.109870

Tang, L. C. M., Cho, S. Y., & Xia, L. (2013, 2013). Intelligent BVAC information capturing system for smart building information modelling.

Teng, Y., Xu, J., Pan, W., & Zhang, Y. (2022). A systematic review of the integration of building information modeling into life cycle assessment. *Building and Environment, 102*, 109260.

Thabet, W., Lucas, J., & Srinivasan, S. (2022). Linking life cycle BIM data to a facility management system using Revit Dynamo. *Organization, Technology and Management in Construction: An International Journal, 14*(1), 2539–2558.

TNB. (2021). *TNB's pricing and tariffs*. Retrieved 28 April from https://www.tnb.com.my/commercial-industrial/pricing-tariffs1

Tushar, Q., Bhuiyan, M. A., & Zhang, G. (2022). Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing. *Journal of Cleaner Production, 330*, 129936.

Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., & Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews, 41*, 85–98. https://doi.org/10.1016/j.rser.2014.08.039

van Eldik, M. A., Vahdatikhaki, F., dos Santos, J. M. O., Visser, M., & Doree, A. (2020). BIM-based environmental impact assessment for infrastructure design projects. *Automation in Construction, 120*, 103379.

Verbeke, S., & Audenaert, A. (2018). Thermal inertia in buildings: A review of impacts across climate and building use. *Renewable and Sustainable Energy Reviews, 82*, 2300–2318. https://doi.org/10.1016/j.rser.2017.08.083

Wei, Y., Zhang, X., Shi, Y., Xia, L., Pan, S., Wu, J., Han, M., & Zhao, X. (2018). A review of data-driven approaches for prediction and classification of building energy consumption. *Renewable and Sustainable Energy Reviews, 82*, 1027–1047. https://doi.org/10.1016/j.rser.2017.09.108

Wu, S., Wood, G., Ginige, K., & Jong, S. W. (2014). A technical review of BIM based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction, 19*, 534–562.

Xiang, Y., Cai, H., Gu, C., & Shen, X. (2020). Cost-benefit analysis of integrated energy system planning considering demand response. *Energy, 192*, 116632. https://doi.org/10.1016/j.energy.2019.116632

Yao, R., Costanzo, V., Li, X., Zhang, Q., & Li, B. (2018). The effect of passive measures on thermal comfort and energy conservation. A case study of the hot summer and cold winter climate in the Yangtze River region. *Journal of Building Engineering, 15*, 298–310. https://doi.org/10.1016/j.jobe.2017.11.012

Yuan, Z., Zhou, J., Qiao, Y., Zhang, Y., Liu, D., & Zhu, H. (2020). BIM-VE-based optimization of green building envelope from the perspective of both energy saving and life cycle cost. *Sustainability, 12*(19), 7862.

Zhang, L., Hou, C., Hou, J., Wei, D., & Hou, Y. (2019). Optimization analysis of thermal insulation layer attributes of building envelope exterior wall based on DeST and life cycle economic evaluation. *Case Studies in Thermal Engineering, 14*, 100410.

Zhang, L., Huang, F., Lu, L., Ni, X., & Iqbal, S. (2022). Energy financing for energy retrofit in COVID-19: Recommendations for green bond financing. *Environmental Science and Pollution Research, 29*(16), 23105–23116.

Zhivov, A. (2022). Economics of energy master plan implementation. *Energy master planning toward net zero energy resilient public communities guide* (pp. 197–236). London: Springer.