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TECHNICAL PAPER

Optimising energy performance of an Eco-Home using Building Information Modelling (BIM)

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Abstract
In a world where sustainability constantly manifests itself as the contemporaneous zeitgeist in practically every facade of our lives, it is imperative to understand the energy performances (EP) of buildings, both old and new, and explore innovative ways to optimise this cardinal aspect of building operation. In this light, we investigate the potential benefits of integrating Building Information Modelling (BIM) into EP analysis of built infrastructures. This research, in the form of a case study, has been designed to uncover equipments of high energy consumption in an Eco-Home, and subsequently to compare BIM-based simulations with the actual data measured on energy consumption. From the analysis, this study also proposes several recommendations on energy optimisation. For the purpose of EP analysis and simulation runs, Autodesk Green Building Studio (GBS) has been deployed, while 3D BIM Model of the Eco-Home was generated using Autodesk Revit. In situ energy audit revealed that the air-conditioner was the most energy-intensive equipment in the Eco-Home. Only a small variation of energy consumption was observed in actual and simulated data. Further analysis on design alternatives illustrated that the EP of the Eco-Home can be vastly improved by adopting a few measures, such as the installation of occupancy sensors to automate lighting, the integration of greywater reclamation system to reduce water consumption, and the addition of photovoltaic panels to increase renewable energy generation. However, from the same analysis, wind energy was found to be inviable due to its low level of energy potential. This paper concludes that integrating BIM and GBS into EP analysis not only improves the overall EP measurements, but also acts as an enabler for designers and building owners to compare design alternatives effectively. The advancement of BIM integration in this study offers an interesting proposition for the architectural, engineering, and construction industry especially when it comes to the enhancement of sustainability of a building.

Keywords Building information modelling (BIM) · Energy performance analysis · Autodesk revit · Green building studio (GBS) · Energy simulation · Energy efficiency

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Introduction

Rolling back history, the United Nations, during its 1992 Conference, mooted the idea of Agenda 21– a loftily ambitious action plan that required a never-before multinational scale of cooperation and commitment to attain sustainable development for the twenty-first century. From this great watershed, Sustainable Development Goal No. 7 envisaged the accessibility of affordable, reliable, sustainable, and modern energy for humanity. The issue of environmental sustainability was first raised by the World Meteorological Organization in 1979, highlighting the urgent concerns on global warming. This malaise has compelled scientists worldwide to dig deep into the solutions of controlling for greenhouse gases. In this continuation, the construction industry was unveiled to be one of the major contributors of carbon emission leading to the pernicious greenhouse effects [1]. Development of new buildings accounts significantly to the construction industry of any country. Additionally, it has been estimated that the buildings sector alone consumes about 76% of the total electricity in United States, as well as an eye-watering 40% of the world's energy resources [2]. Grasping the immensity of this context, it is pellucid that buildings undertake a preponderant role in improving the overall energy performances as compared to other sectors [3].

Besides, the accuracy of energy performance measurement and its associated difficulties in collecting the required data have emerged as concerning issues. To grasp the nettle, Cho and Kim [4] examined the limitations of accurately assessing the EP analysis of an existing building. They found that the actual working conditions of an existing building differed considerably from the as-built documentation, serving as a major concern in EP analysis. To underscore this particular stand further, Burman et al. [5] exhibited that the lack of adequate data for EP analysis contributed significantly to the deterioration issues, compounded by cases where the complete loss of data ultimately handicapped the entire process of EP analysis. Moreover, inadequacies in forecasting energy consumption during the design stage and a lack of proper methodologies in managing building performances during the operation stage were also identified as significant challenges in assessing the EP analysis of buildings. Therefore, to successfully examine the large pool of data acquired from existing buildings and to accomplish the EP analysis, adequate utilisation of highly effective tools is posited to be vital in the whole process. Increasing awareness of energy optimisation, and the challenges posed toward environmental sustainability inevitably led to a rapid emergence of digital technologies to cater to the requirements of analysis for both natural and built environments. Bakar et al. [6] highly recommended the adoption of technological applications, as these computerised tools were found to be user-friendly and cost-effective in performing EP analysis. In the same way, BIM platforms too, were presented as a thoroughly effective tool as it possessed the ability to store an array of information relevant to every design and management process. The success of BIM and its overwhelming positive outcomes have been documented from various BIM applications in construction [7]. Therefore, BIM will be assimilated in the EP analysis of this study, as plenty of studies have attested to its time-saving attribute and its congruent ability to minimise variations and errors. Furthermore, BIM has demonstrated its ability to represent the working conditions of buildings rather precisely as the model was being updated sequentially [8]. Adding on, the latest generations of BIM platforms offer the capability to continuously monitor the energy efficiency of buildings over their entire lifespans.

Circumscribing the hot issues of sustainable developments and the world's energy crisis, this study aims to uncover the EP of an existing building located in University Technology Malaysia (UTM), dubbed as the UTM Eco-Home. Energy Analysis Models (EAM) will be produced during energy simulations, and these models are represented in gbXML (from GBS) file format. The 3D model will be rendered based on actual measurements and conditions to accurately simulate its EP. In addition, input data of various design options will be captured to evaluate the EP of future retrofits for the buildings. This novel hybrid approach in EP analysis which integrates BIM with EAM and GBS has the unique capability of performing analysis and recommending design solutions for optimal energy savings in buildings. This research seeks to contribute to the body of knowledge with regard to the current EP of an eco-building plus several green design alternatives that can facilitate energy optimisation. This integrated modelling approach also seeks to improve current practices with the adoption of state-of-the-art softwares in acquiring better decisions on energy management. Furthermore, the advancement of BIM integration in this study offers an interesting proposition for the architectural, engineering, and construction (AEC) industry especially when it comes to the enhancement of sustainability of a building.

The remaining paper is organized in the following sections. Second section reviews the literature on advantages of BIM application in EP, as well as on EP analysis and measuring tools. Third section elucidates the research methodology, explicating the step-by-step process adopted in this study. Fourth section covers data analysis on energy consumption of various electrical appliances and discusses the variance of results of consumption measured through digital meter and of those simulated via Green Building Studio (GBS). Recommendations to optimise the Eco-Home's EP are proposed in fifth section, and finally, sixth section makes the conclusion.

Literature review

Building information modelling (BIM)

BIM can be defined as an advanced 3D modelling-based method designed to enhance the decision-making processes of building developments and those of other structures [9]. BIM has always been recognised as one of the most significant innovations in the digitalization and visualization of information with regard to natural and built environments. BIM's superior ability to provide essential adaptation plans in addressing climate changes inculcates a higher sustainable approach toward developments. In addition to this, BIM also undertakes a crucial role in analysing and determining the amount of energy consumption in existing structures and buildings. Studies elucidated that BIM application has a significant impact on the accuracy of energy performance estimates [10].

In a BIM-based building design process, architects may adopt BIM technology to explore a wide range of design concepts in a relatively short time frame. A robust attribute of BIM is that the building geometries can be taken from a BIM model to evaluate alternative design concepts. Kuo et al. [11] suggested that by applying this particular feature, specific calculations on rainwater harvesting, accessibility of solar energy, and contents of recyclables can be performed automatically and reliably using high-end computers. Additionally, all the building data in the BIM models can be extracted to facilitate the process of energy simulation and EP analysis. As the conceptual design approaches the finalising stage, architects could then be able to continue to refine the initial BIM model into detailed designs for the subsequent development stage.

It is well understood that BIM comprises sets of interrelated methods, roles, strategies, and technologies, combining every element into a simulated information-based model, storing and managing data in the digital form for the application in the building industry. Also, BIM is a multidimensional (n-D) knowledge and concept source invented to readily provide holistic information about a building through a reliable framework to assist decision-making over the facility's life cycle. BIM encourages the exchange of information on a real-time basis, allowing users to have a mutual understanding of the value of digital information in construction management practices [12]. Bosurgi et al. [13] investigated serval dimensions (See Fig. 1) for the BIM-based study, and found that BIM has the capacity to deal up to n-D (n-dimensions).

Figure 1 illustrates the various dimensions of BIM together with their elements. This study specifically focused on the 6th Dimension – sustainability – evaluating the building's attributes in relation to energy consumption, environmental impact, pollution risks, and others. Simply put, BIM 6D simulates the energy behaviour, allowing the designers to make informed decisions regarding the operation of buildings. When buildings are in use, for instance, BIM 6D allows an exhaustive analysis of the energy behaviour, guiding it towards improvements in electrical and lighting efficiency, which in turn, provides better quality and higher comfort for the occupants, further encouraging them to utilise the building in a sustainable fashion [14].

Energy performance (EP) analysis and measuring tools

Globally, the resurgence of energy consumption has become a worrying trend. It would expand rapidly and may lead to

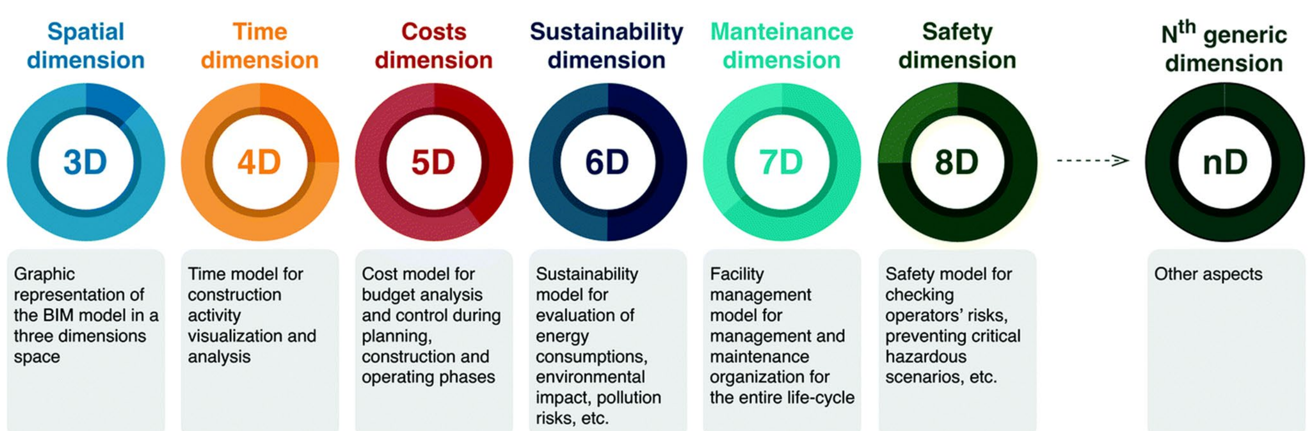

Fig. 1 BIM dimensions adopted from [13]

a catastrophe if a lack of earnestness in addressing this uptick carries on. Further, this unsustainable consumption has also been depleting our natural resources at an alarming pace. This era has witnessed countless natural disasters engendered by global warming, such as depletion of ozone layers and rising sea levels, to name a few. This dismal situation only warrants that the optimisation of building energy management is to be taken seriously. With this in mind, 'performance gap' is the term used to describe the differences between the actual EP and the simulated EP of a building. This 'performance gap' has been garnering stronger and stronger attention in the building and construction industry in recent years [15].

EP analysis can be carried out by adopting the simulation method to assess and compare the EP between different conceptual designs as performed by [16]. Conceptual architecture designs can be configured in terms of energy use. The review of the design process also enables outsourcing to an energy contractor for further detailed analysis. Moreover, the process of energy analysis involves substantial effort in reconstructing the 3D building models from 2D drawings for energy simulation purposes. Therefore, it has often become a huge challenge to integrate this process into the conceptual design stage. Owing to the high cost required to run energy analysis, it is quite typical that the EP analysis is only carried out during the final design stage. If only this energy analysis can be well-integrated with the building design process, the benefits of delivering design information in a highly efficient manner will become significantly more noticeable [11].

In BIM-related software, green building applications' analysis and simulation functions are relatively incomplete, requiring supports from other specialist software packages to accomplish the required energy analysis processes. Scores of energy analysis software packages that can be installed together with Autodesk Revit had been introduced into the market in the past decade, including, but not limited to Autodesk Vasari, Autodesk Insight 360, Green Building Studio, and others, as presented in Table 1.

Table 1 distinguished the functions and features of different energy analysis packages, and based on the analytical comparisons between these applications; it can be deduced that Autodesk Green Building Studio (GBS) provided the most comprehensive list of applications, fulfilling the requirements and expectations for the study, primarily from the users' perspectives. Also, Azhar and Farooqui [17] compared various BIM software and suggested that GBS is one of the highly effective packages for EP analysis in a building. Based on these inferences, it was plausible to adopt GBS as the energy analysis software for this study. The benefits of adopting GBS included complete model viewing capability, analysis results storage in a single file, easy-to-understand results, quick and precise viewing tools, a variety of display mediums, and a flexible zone management system [17].

Raut and Gomez [18] dealt with the BIM grounded energy performance analysis for one building in Johor, Malaysia, optimizing the building energy consumption analysis by utilizing Green Building Studio. The study provided similar input of energy analysis usage for Malaysia, which is the Energy Use Intensity (EUI use as evidence of comparison with the reduced electricity usage from a conventional system to the new proposed method system. In addition, the simple consideration to improve the existing building condition based on energy saving data is seen to be a significant contribution to the study. Another study by Solla et al. [19] stated that the Malaysian Public Work Department had announced the BIM tools to apply in government projects to embark on sustainability. Furthermore, BIM application can also facilitate the assessment process for the Green Building

Table 1 Popular BIM software packages and their functions, adopted from [1]

BIM software	Measuring parameters					
	Energy	Carbon emissions	Natural ventilation	Solar and day lighting	Acoustic	Water
Autodesk® Green Building Studio	×	×	×	×		×
Integrated environmental solutions® virtual environment	×	×	×	×		
Bentley hevacomp	×	×	×			
AECOsim	×	×		×		
EnergyPlus	×	×		×		×
HEED	×	×				
DesignBuilder simulation	×	×	×	×		
eQUEST	×		×	×		
DOE2	×		×	×		
FloVENT			×			
ODEON room acoustics software					×	
TRNSYS	×		×	×		

Index in Malaysia. Thus, GBS is among the recommended analysis tools for sustainability and energy performance analysis in Malaysia buildings.

Research methodology

The design for this study utilises a case study approach to examine the possibilities of optimising EP using BIM related technologies. The process of this research is adopted from [20] as illustrated in Fig. 2.

Step 1: Research questions are formulated in relation to the optimisation of the building's EP. These research questions include:

(1) What is the equipment that consumes the highest amount of energy in a building?
(2) What is the difference between the simulated Energy Use Intensity as compared to the actual Energy Use Intensity?
(3) What are the potential life cycle costs of alternative designs?
(4) What is/are the potential measure(s) to enhance the energy performance of a building?

Step 2: Based on the research questions above, University Technology Malaysia's Eco-Home has been selected as the subject for this case study. The location, building façade, and floor plans are illustrated in Figs. 3 and 4.

Eco-Home is located inside the campus of University Technology Malaysia (UTM) Skudai, Johor Bahru, as depicted in Fig. 3. This building was constructed as a sustainable smart home prototype with a built-up area of approximately 1,450 square feet. A variety of sustainable features can be found in this building, such as solar panels, rainwater harvesting systems, and other high-efficiency equipment, aiming to reduce both its energy consumption and carbon footprint. The building has adopted the Small Office Home Office (SOHO) concept, which has been gaining market popularity in recent years owing to their affordability. Eco-Home consists of one bedroom with an attached bathroom, a common area, a living room, a dining room, and a utility room. Its floor plan is detailed in Fig. 4.

Step 3: Next, a preliminary desktop study was conducted to identify relevant data to be collected. It was found that the required data includes the electrical appliances in the building, energy use intensity, and annual electrical consumption. Besides, to accomplish the aim of this study, a BIM model was designed, and to render this 3D Model, the following processes were conducted:

(1) On-site investigation to physically identify and observe the building up-close.
(2) The information and drawings concerning the building (Eco-Home) were collected from the person in charge of the Eco-Home.
(3) Autodesk Revit-2018 was selected as the 3D modelling software, and the BIM model of the building was sub-

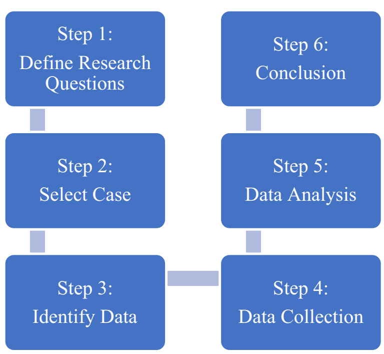

Fig. 2 Adopted case study process

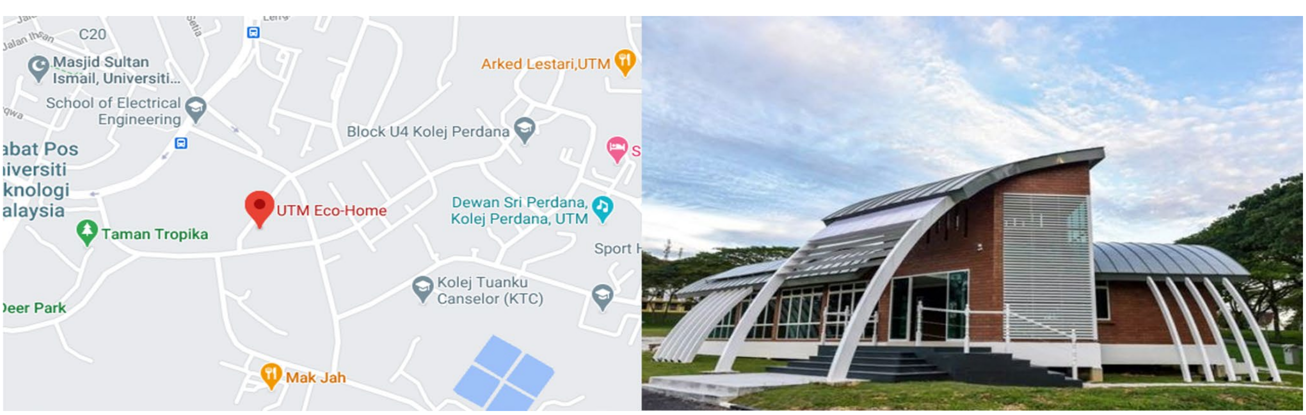

Fig. 3 Location of Eco-Home at UTM

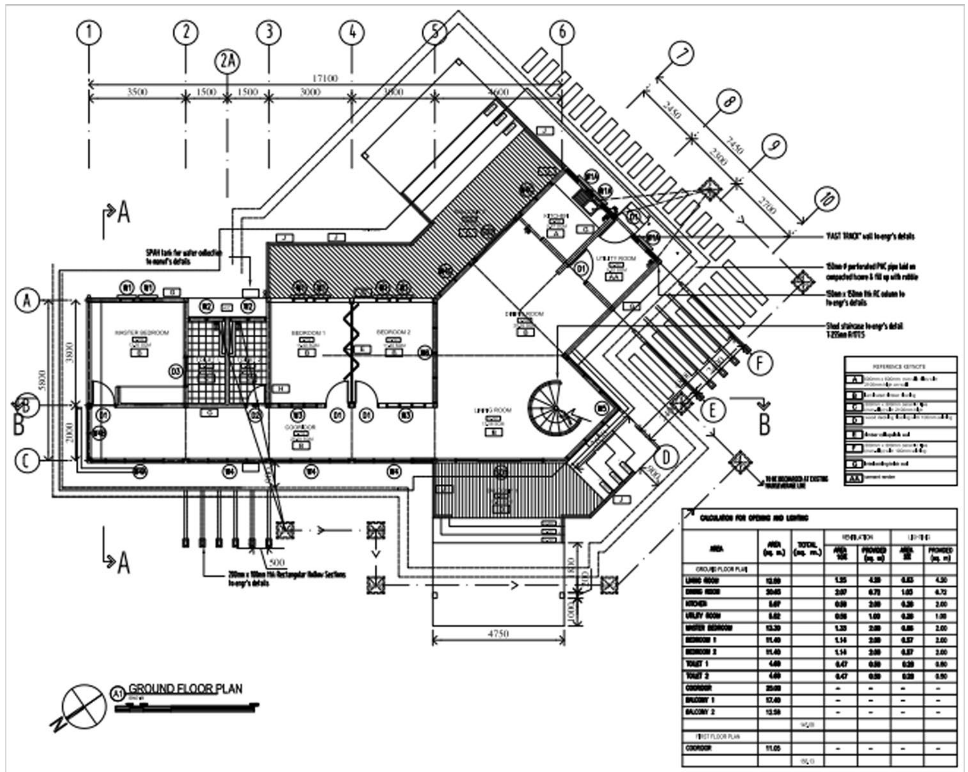

Fig. 4 Ground Floor Plan of Eco-Home in AutoCAD

sequently prepared based on the information obtained on building materials and from the as-built drawings.

The overall workflow of preparing the 3D Revit Model for the Eco-Home can be simplified in the following Fig. 5. By adopting the meticulous processes as described in Fig. 5, a 3D Model of the Eco-Home was successfully rendered, as illustrated in Fig. 6. The remaining steps, i.e. data collection, data analysis, and conclusion, are subsequently addressed in the following sections.

A comprehensive approach was carried out to determine the energy efficiency of the building by collating all details from existing data sources. Subsequently, creation of a 3D model allowed a 360 degrees view of the Eco-Home. To evaluate its energy efficiency, the 3D Autodesk Revit file was imported into Autodesk GBS in gbXML format. An energy analysis model was then deployed in which the building was appropriately assigned as an office with a 12-h daily operation on a 5-day per week cycle using the building's actual location. After completing these initial steps, Autodesk GBS was utilised to evaluate different design alternatives as a method to uncover the optimal energy efficiency of the Eco-Home. Autodesk GBS allowed for the simulation of different building retrofits such as greywater reclamation, rainwater harvesting, solar photovoltaic and wind turbine, which can produce further improvements on EP.

Data analysis and results

Energy consumption measurement through digital meter

Figure 7 shows the energy consumption data recorded by the digital meter for a period of seven days. Digital meters can be set to capture the amount of energy consumption in intervals of one hour or less, mainly for monitoring and billing purposes. Since existing buildings provided limited data for acquisition, the measurement of energy consumption can only be established based on the availability of reliable data. Thus, input data has to be gathered using an in situ energy audit approach, which can result in higher levels of data accuracy. This approach is supported by Cho and Kim [4] who stated that as existing building data can be difficult to obtain, the assessment of building EP is typically conducted based on in situ simplified input. In this study, the amount of energy consumed in a week was measured at 146.1 kWh, and from this, we extrapolated that the yearly energy consumption would average at approximately 7,597 kWh (146.1 kWh × 52 weeks). The variations in energy consumption were observed through recorded data of the Eco-Home, with the highest consumption recorded at 30.5 kWh, while the lowest or most efficient energy consumption was recorded at a mere

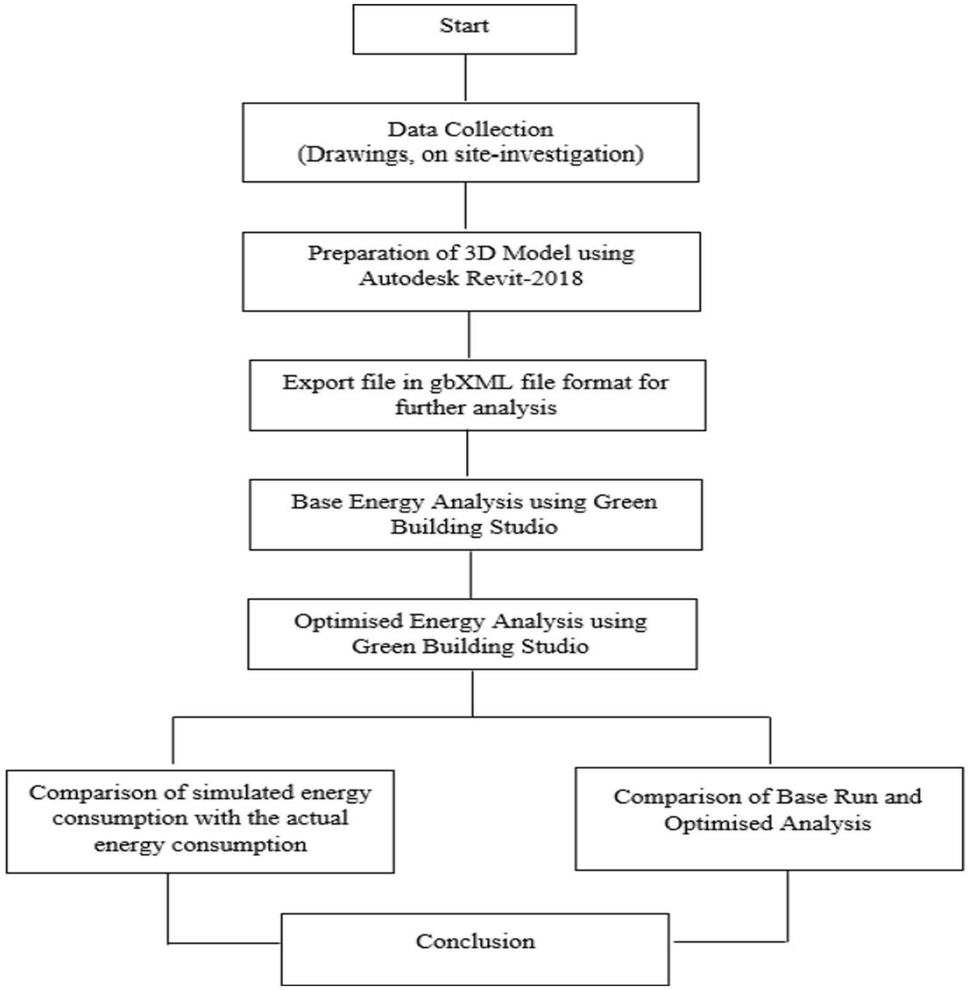

Fig. 5 Workflow of 3D Revit Model Preparation

5.3kWh. This fluctuation could be attributed to the unnecessary utilization of power by the Eco-Home occupants, for instance, the carelessness in not switching off electrical equipment after usage, which then led to additional energy consumption on those particular days. In addition, the distinct ways in which different consumers operated each electrical appliance were also likely to contribute to the variation in energy consumption.

Energy consumption of electrical appliances

The actual energy consumption for Eco-Home was carefully analysed based on each electrical appliance installed in the building, which included the air-conditioners, fans, lightings, and CCTV. A ceiling cassette type split-unit air conditioner could be found in the Master bedroom to optimize the ventilation requirements, as depicted in Fig. 8. This type of air-conditioner allowed cool air to be distributed in four (4) disparate directions instead of the single-direction airflow provided by the more common wall-mounted type. This particular air-conditioner came with a reasonably cooling capacity of 9,500 BTU/h –12,500 BTU/h, deemed sufficient to attain the comfort of building occupants according to the design capacity. The cool air generated by this air-conditioner could be distributed to other building spaces with the assistance of two smart ceiling fans installed along with the corridor spaces, as shown in Fig. 8. Smart ceiling fans can be remotely programmed and controlled using iOS or Android devices when users are away from the building, which also contributed to the optimisation of energy consumption. In addition to the afore-mentioned forced ventilation systems, this building also integrated natural ventilation along various strategic locations to channel fresh air from natural sources into the building to further improve the overall comfort of the occupants.

Meanwhile, the lighting of the Eco-Home was provided by LED lamps, as shown in Fig. 8. Known to be highly energy-efficient, this latest technology in luminaire provided an adequate level of light intensity or lumens for every space, including the kitchen and corridor. The ventilation and lighting systems were typically utilised during working hours from 8 am to 5 pm, on a five-day per week operation

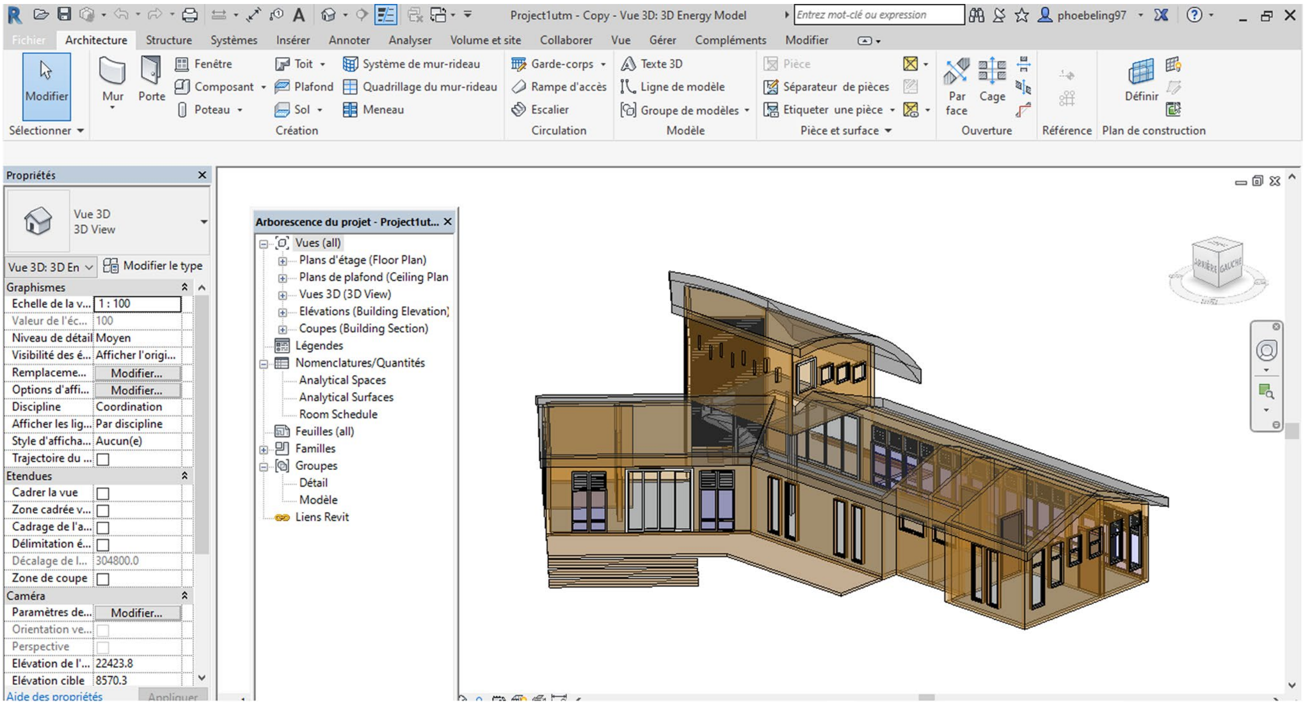

Fig. 6 Eco-Home Building Model developed in Autodesk Revit

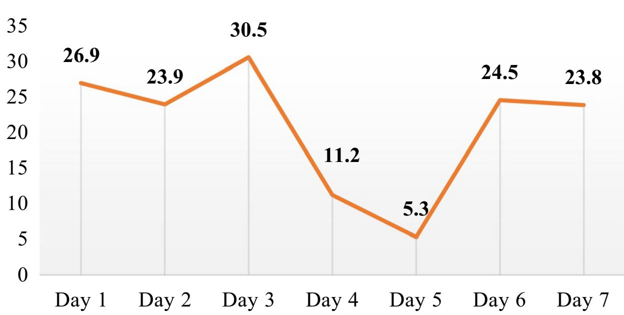

Fig. 7 Energy consumption data from the digital meter (kWh)

schedule. The exception was the CCTV system, which has been installed on both the outside and the inside of the Eco-Home (Fig. 8). Unsurprisingly, this intelligent surveillance and monitoring system needed to be fully functional for 24 h a day and 7 days per week, which suggested energy consumption will always be perennial regardless of occupants being physically present or otherwise. Additionally, from the information gathered, we were apprised of the 'green' status, which accompanied the CCTV system during its procurement process, indicating that the system was designed with environmental friendliness to complement its low operating cost while complying with the stringent reliability standard.

Moreover, an in situ energy audit was conducted at the Eco-Home to obtain data on the actual utilization of electrical appliances. The energy calculation is initially conducted by determining the number of appliances used in the building and the watt usage. Then, the conversion to kWatt is made from the multiplication of Watt/item with the Watt of the appliance. Next, the kWh per week is calculated by multiplying kWatt and the number of hours used per week, 40 h. Finally, the energy used per month is calculated with the weekly energy consumption by four. By referring to Table 2, it is found that the highest amount of energy was consumed by the air-conditioner. This was inevitable as the air conditioner was rated at 1,000 W; further, it was expected to operate 8 h per day on a 5-day weekly schedule. Hence, energy consumption was estimated at 40kWh per week, with a total of 160kWh a month, or almost 40% of the total monthly consumption. The energy needed by the air-conditioning system in Eco-Home, which functioned mainly for cooling purposes, depended on several factors such as the weather condition, whereby ambient temperature can fluctuate between 22 °C and 32 °C in a day. Thus, when the outside temperature is hotter, the air-conditioner operates more to create cool air based on the occupant's demand which has an enormous impact on electricity consumption. Further analysis suggested that the second-highest energy consumption came from 6″ LED lamps installed on the whole of Eco-Home's ground floor, which has been estimated at 88 kWh/month, as indicated by the third item in Table 3.

Similar to the air-conditioner, a total of 54 units of these 6″ LED lamps were expected to operate 40 h weekly, with a rating of 540 W per unit. For other areas such as the

(a) Air conditioning system in Master Bedroom

(b) Ceiling fan at corridor

(c) LED Lighting and sensor system

(d) CCTV System

Fig. 8 Pictorial view of installed electrical appliances

Table 2 Energy consumption estimation by equipment

Room name	Item	No	Watt/Item	Watt	kWatt	Hr/Wk	kWh/Wk	kWh/Mth
Master Bedroom	Air Conditioner	1	1000	1000	1	40	40	**160**
Corridor	Fan	2	75	150	0.15	40	6	24
Whole Ground Floor	6″ LED Lamp	54	10	540	0.54	40	22	88
Corridor	4″ LED Lamp	8	3	24	0.024	40	10	40
Kitchen	LED Lamp	1	12	12	0.012	40	0.5	2
Whole Ground Floor	LED Tube	8	15	120	0.12	40	5	20
Whole Ground Floor	CCTV	4	30	120	0.12	168	20	80
Total							103.5	414

Table 3 Photovoltaic and wind energy potential data

Photovoltaic potential	Annual energy savings	26,552 kWh
	Total installed panel cost	RM 135,780
	Nominal rated power	17 kW
	Total panel area	123 m^2
	Maximum payback period	18 years @ RM 0.24/ kWh
Wind energy potential	Annual electric generation	209 kWh

corridor and the kitchen, the lighting system was estimated to consume 40kWh/month and 2 kWh/month, respectively. Nevertheless, modern LED lamps were designed to consume much lesser electrical energy than their conventional counterparts while providing a far longer service duration. The lighting energy condition also might vary based on the occupancy pattern level on a daily basis and when there are occupants who might differ in function type of the particular space. Besides, the Eco-Home also provided four (4) CCTV, and each CCTV was rated at 120 W, which translated to a gross consumption of 20kWh per week, or a total of 80kWh per month. As explained previously, this CCTV system was always found to be in operation mode at all times, hence contributing quite substantially to the overall energy consumption. Lastly, the two (2) smart ceiling fans were found to be among the lowest energy consumers, with only 24 kWh of energy requirements in a month. Being smart appliances, energy consumption can be optimised in such a way that they will only be switched on whenever required, such as during events or when visitors come, and automatically switched off when the visitors leave. Also, running a fan requires significantly less energy than running an air-conditioner.

Energy consumption measured via green building studio (GBS)

From the energy ratings of equipment and the breakdown of consumption estimated, various total energy consumption patterns were subsequently simulated using state-of-the-art computers. For this, we deployed Autodesk GBS. The advantage of this software is its ability to seamlessly integrate 3D Revit Models into an array of simulation runs without much hassle, owing to the fact that both softwares are developed by the same company, hence their interoperability and user-friendliness are well taken care of. To perform the simulation, the 3D Revit Model in its gbXML file format was exported to GBS, which contained all the information and details of the building. This method has been scientifically justified by several research such as Welle et al. (2011); Pezeshki et al. (2019) and Bonomolo et al. (2021). In the Eco-Home model, the building has been specified as a single-family type and the facility operating time was set as (12/5), which meant the standard operating time was kept as 12 h per day for 5 days in a week. The simulation results are compiled in Figs. 9 and 10. According to Fig. 9, the ventilation of space with fans as well as cooling with air-conditioner accounted for 55.1% of energy consumption, or more than half of the simulated electricity usage. Besides, the lighting and miscellaneous equipment contributed 23% and 22% of total consumption, respectively. This simulation was supported by the building energy audit in which air conditioning and lighting were found to be the top two energy-consuming apparatus in the Eco-Home. Besides, the energy consumption simulation presented an annual energy cost of RM1,953, with an annual peak demand of 3.0 kWh, contributing to an overall energy lifecycle of 239,433 kWh, as empirically tabulated in Fig. 10.

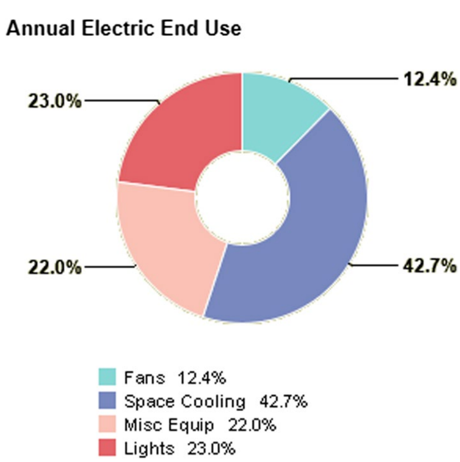

Fig. 9 Energy end-use pie chart (base run)

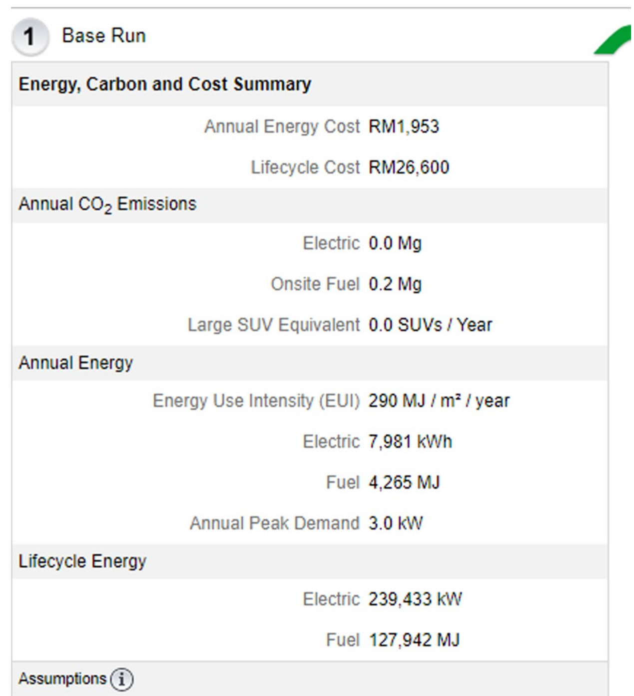

Fig. 10 Base run energy usage results

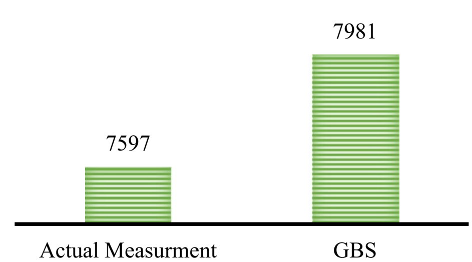

Fig. 11 Comparison between simulated and Actual measurement for Eco-Home in kWh

Comparison of energy consumption between actual measurement and simulation from GBS

Figure 11 depicts the comparison of yearly energy consumption derived from GBS simulation and extrapolation of actual data obtained from the digital meter. GBS simulation estimated the consumption of UTM Eco-Home to be 7981 kWh per year. In contrast, extrapolation from data collected from the digital meter revealed an energy consumption of 7,597 kWh per year, indicating a 4.9% difference. This small variance may due in part to latent factors such as unpredictable human behaviour as well as fluctuations in occupancy rate. For instance, building occupants might not occupy the building throughout the entire working hours as predicted during simulation. This may be due to extraneous commitments such as ad-hoc site visits or attending the external meeting, depending greatly on the occupants' job nature and work schedule, all of which constitute factors that require more thorough investigations. These instances of variability can undoubtedly contribute to differences in the consumption pattern compared to the one simulated using constant factors, such as the 12/5 scenario as previously explained. Other contributing factors may also stem from the differences in work behaviour engendered by diversity in personal, cultural, and even socio-economic preferences.

Recommendations to optimise the building energy performance

This study suggests a few valuable recommendations to enhance the EP of UTM Eco-Home. In this regard, different simulations were undertaken to explore design alternatives for improving the EP. On this front, several alternatives were configured into Autodesk GBS for various simulation runs based on several recommendation of green design solutions. First, the Lighting Power Density (LPD) was set to 20% lesser than the base run. This was kept in view that the Eco-Home adopted passive lighting to maximize natural daylighting, which in turn depended less on artificial lighting. Furthermore, automatic occupancy sensors that can automate lighting were also proposed, which served to differentiate situations and actual surroundings which actually requires lighting, leading to further reduction of wastage. With the introduction of this design alternative, annual electricity end-use can be reduced from 23% to 17.2%, as indicated in Fig. 12.

Figure 13 summarises the overall outcome of the design alternative. In particular, annual energy consumption attained a reduction from 7,981kWh to 7,258kWh per year, a marked difference of 723kWh, or roughly 9% in total reduction. Moreover, the annual energy peak demand was also reduced by 0.2kWh from 3kWh to 2.8kWh, or about 7%

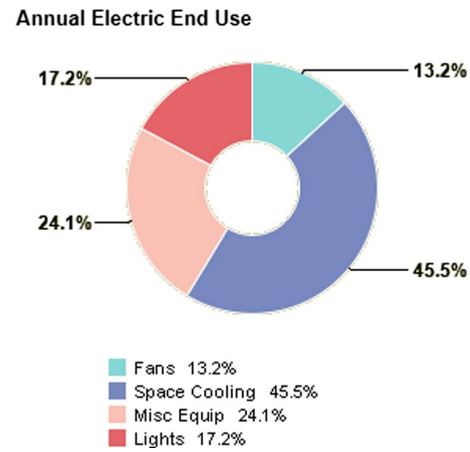

Fig. 12 Energy end use pie chart (design alternative)

2 Design Alternative

Estimated Energy & Cost Summary	
Annual Energy Cost	RM1,777
Lifecycle Cost	RM24,199
Annual CO_2 Emissions	
Electric	0.0 Mg
Onsite Fuel	0.2 Mg
Large SUV Equivalent	0.0 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	290 MJ / m² / year
Electric	7,258 kWh
Fuel	4,265 MJ
Annual Peak Demand	2.8 kW
Lifecycle Energy	
Electric	217,751 kW
Fuel	127,942 MJ
Assumptions	

Fig. 13 Design alternative energy usage results

decrease. On monetary terms, the annual energy cost was reduced from RM 1,953 to RM1,777, indicating a 9% savings from the base run cost to the alternative design cost. Similarly, the lifecycle energy consumption declines from 239,433kWh to 217,751kWh, resulting in the total lifecycle energy cost tumbling from RM26,600 to RM24,199, or a 9% savings. This simulation clearly suggested that the above recommendations were effective at reducing energy consumption, and this ultimately minimises the lifecycle cost.

In the meantime, the existing Eco-Home has been equipped with a rain harvesting system, and to further improve the building's water efficiency, the study

Net-Zero Measures		Annual Rainfall (mm)*	Catchment Area (m²)	Surface Type	Net-Zero Savings Liters per Year	Annual Cost Savings (RM)
Rainwater Harvesting:	Yes	2713	115	Concrete/Asphalt	280,796	562
Native Vegetation Landscaping:	No				0	0
Greywater Reclamation:	Yes				111,014	444
Site Potable Water Sources:	No	Yield:	50	L / day	0	0
*Source: National Climactic Data Center, #CLIM81.				Total Net-Zero Savings:	391,810	RM1,006

Fig. 14 Eco-Home Water Consumption Estimation

recommended a greywater reclamation system. Among others, one of the most common applications of greywater reclamation includes the irrigation of home gardens. Figure 14 illustrates the estimation of water consumption of Eco-Home with net-zero measures. After applying the option of greywater reclamation, it was observed that the net-zero savings of water consumption were projected at 111,014 L annually. This accounted for an annual cost savings of RM444. On this account, the application of greywater reclamation in Eco-Home would be able to complement the current rainwater harvesting system in three likely scenarios; (1) the collection of greywater from the bathroom and reuse for toilet flushing, (2) the collection of greywater from bathroom sinks and reuse in kitchen, and (3) the combination of both for reuse in toilet flushing and other sinks. Greywater, albeit non-potable, is still highly reusable in many other applications that significantly assist in reducing water consumption significantly and serve as a free water supply for the building, especially during unwarranted periods of water disruption, which may occur intermittently.

Building upon the alternative design of lighting and greywater reclamation, this study also highlighted the impact of renewable energy implementations. For this purpose, the installation of photovoltaic (PV) panels is postulated to assume a huge role in the operation of Eco-Home, since its location is well-situated to receive a considerable amount of sunray, owing to minimal blockages in its surroundings. Solar energy, which can easily be converted into electricity for a plethora of applications, has always been one of the most preferred green energy sources. For the Eco-Home, an active PV system can be implemented either on the roof or on the ground, depending on its mounting system. The efficiency of a PV system is assumed to be low (5%), medium (10%), and high (15%). Based on the simulation, the PV has the potential to generate annual energy savings of 26,552 kWh, as suggested in Table 3. The estimated maximum payback period of the PV is only 18 years, which is well within its standard lifespan. Even though the initial cost for implementing solar panels is considerably high, the long-term benefits still outweigh its cost, as it reduces the global carbon footprint significantly, contributing to a sustainable future for the entire citizenry.

Finally, this study also analysed the efficacy of wind as a source of renewable energy. The data for this simulation was acquired from the nearest available weather station in the vicinity of UTM Eco-Home. Simulation results suggested the potential of wind energy at only 209kWh per annum, as shown in Table 3. This is considered trivial when compared to the sterling potential of PV at 26,552kWh per annum. Therefore, wind energy did not appear as an attractive option, mainly because the high initial outlay for a wind turbine will unlikely be recovered by the mediocre amount of energy potential. In addition, the location of the Eco-Home did not seem ideal enough to fully exploit the wind energy potential.

Comparing the findings of this study with those from other regions in Malaysia, the electrical savings model proposed by Sena et al. ranges from 10.4% to 21.3%, which was quite similar to the findings of this study. In that study, monthly income was found to influence the electricity consumption of a household. More interestingly, the characteristics of electrical appliances produced higher impacts on electrical consumption when compared to household characteristics. Therefore, it is important to examine the energy ratings of electrical appliances before their installation, so that a building can achieve a better overall EP.

Conclusion and recommendations

The rigorous in situ building energy audit and the accompanying detailed energy analysis have successfully examined the electrical consumption of appliances found in UTM Eco-Home. From this analysis, it was clear that the appliance that has the highest appetite for electricity was the air-conditioner, accounting for almost 40% of the total monthly energy consumption, followed by the lighting apparatuses. On the other end, the smart ceiling fans were found to be the least energy hungry. Besides, performance analysis was carried out using Autodesk GBS to compute the overall energy consumption of the building. In this respect, the Eco-Home was assumed to operate on a 12/5 basis. The simulated value was then compared with the extrapolation based on actual data collected from the digital meter, and analysis suggested a difference of 4.9% between the two values in favour of the extrapolated result. This is possibly due to latent factors such as unpredictable human behaviour as well as variations in occupancy rate. Next, alternative designs for the building were assessed, with changes applied to the LPD configured at 20% less than the base simulation run, assuming occupancy sensors that can automate lighting were installed. As a result, it was found that this design alternative had the capability to reduce total lifecycle energy cost by 9%. Similarly, water consumption of Eco-Home can also be reduced by installing a greywater reclamation system. From the simulation, 111,014 L of water can potentially be saved, amounting to a RM444 reduction in annual water bills. Likewise, photovoltaic and wind energy potential were explored using Autodesk GBS. Simulation results suggested PV panels were viable to be installed, with a reasonable payback period, as opposed to wind energy harvesting, which yielded very low potential. From this study, Autodesk GBS has demonstrated its ability to perform seamless energy analysis based on 3D BIM Model generated by its sister software, the Autodesk Revit. This interoperability allows the simulation of different design alternatives, a feature that would be immensely useful in assisting the selection process of the most energy-efficient design, particularly during the design stage of a building. In sum, the integration of BIM and GBS into EP analysis greatly improves the energy performance measurements, enabling designers and building owners to compare different designs effectively when forecasting future energy consumption, all in the quest for optimum building energy efficiency.

Recommendations for future research

The current study only shed light on EP analysis for the post construction stage. Hence, future research can be recommended to include a complete construction life cycle, so as to obtain a better EP analysis. Moreover, this study did not consider the parameters of different building materials, which can play an important role in affecting the overall energy consumption. Therefore, it is suggested that future studies should include building material parameters as well as different cooling loads in EP analysis.

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Availability of data and material (data transparency) The required data fill be provided upon request.

Code availability Not applicable.

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

Ethical approval This research does not cover any studies with human participants performed by any author.

Informed consent The authors declare that this study has received consent from the organization where the research was conducted.

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