BIM and EnerPHit-assisted Energy Efficient Refurbishment:
– A case study of a UK Georgian terrace house

SINAN CELAL DADAGILIOGLU[1], HANIYEH MOHAMMADPOURKARBASI[1], STEVE SHARPLES[1]

[1] University of Liverpool, Liverpool, UK

ABSTRACT: The existing UK building stock contributes significantly to high energy consumption and carbon emissions. Accordingly, the UK government proposed net-zero targets by 2050 as a solution for this environmental issue. Although there is a growing interest in the construction industry in meeting low carbon standards for new buildings, there has been a low uptake of building refurbishment due to poor refurbishment strategies, cost overruns and unsatisfactory refurbishment outcomes. This study aims to set a new refurbishment model by implementing Building Information Modelling (BIM) tools and the EnerPHit standard, which is the refurbishment version of the German Passivhaus standard, for energy-efficient housing refurbishment in the UK. The indoor thermal data of a Georgian terrace house in Liverpool has been recorded since November 2021. A semantically enriched BIM model of the selected house was then created in ArchiCAD with a proposed 24-day refurbishment timeline activities. Then, to offer organisational priority for the key refurbishment phases and better coordination in selecting building material, and for energy assessment, DesignBuilder (DB) and Passivhaus Planning Package (PHPP) tools were applied. The final simulation results indicate that the EnerPHit standard is achievable with less than 25 kWh/m2 of heating energy demand annually for the proposed case study.
KEYWORDS: refurbishment, energy efficiency, EnerPHit standard, BIM, UK housing stock

1. INTRODUCTION

The impact of climate change, sustainability challenges, and resource scarcity on the built environment motivate the Architecture, Engineering and Construction (AEC) industry and governmental policies globally to manage resources more efficiently. For example, the UK government committed to achieving net-zero carbon emissions by 2050 (BEIS, 2021). The existing UK building stock is a major consumer of the UK's energy production and contribute to 22% of total carbon emissions (Committee on Climate Change, 2019). If the UK government is to achieve the 2050 net-zero targets then one effective solution is the sustainable refurbishment of buildings, which has enormous potential for improving energy efficiency and mitigating environmental impacts (Juan, Gao, & Wang, 2010).

The conventional building refurbishment process has been examined in recent literature, which identified examples of ambiguous refurbishment strategies, extra costs and effort, and unsatisfactory refurbishment outcomes (Okakpu et al., 2018; Ustinovichius et al., 2018; Wang & Cho, 2015). Due to these issues, homeowners have been quite reluctant to support housing refurbishment projects to meet the 2050 targets in the UK. To deal with this, a novel refurbishment model should be discussed as a holistic approach to sustainable and energy-efficient building refurbishment (Alwan, 2016; Juan et al., 2010; Volk, Stengel, & Schultmann, 2014). This approach can be categorised into three key phases (Ma, Cooper, Daly, & Ledo, 2012):

- Assessment Phase: project setup and data collection
- Method & Strategy Phase: data analysis, strategy formulation, and implementation
- Validation & Verification Phase: post-measurement and post-occupancy survey

The Method & Strategy phase is investigated within the scope of this study.

To cope with the conventional refurbishment-related issues, Building Information Modelling (BIM) has the potential to develop new ways of predicting, managing, and monitoring the impacts of the built environment regarding energy efficiency. Another important approach to energy-efficient refurbishment is EnerPHit, which is the refurbishment version of the German Passivhaus standard. This paper aims to develop a new conceptual framework for implementing BIM tools and the EnerPHit standard to apply to the energy-efficient building refurbishment of the UK residential building sector. With its further dimensions - 4D BIM (time schedule) and 5D BIM (cost estimation) - BIM implementation will be discussed for a real-world case study of a typical 19th century Georgian terrace house in Liverpool.

2. LITERATURE REVIEW

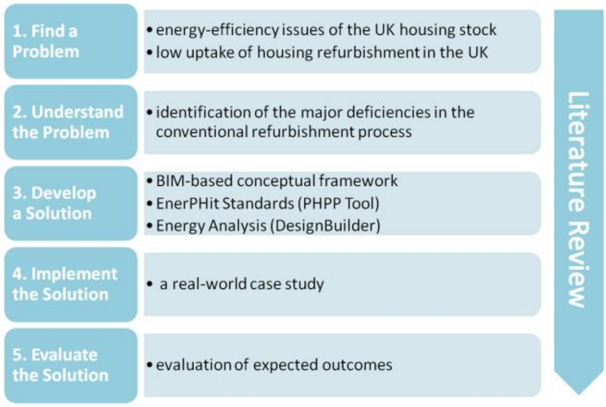
Energy Performance Certificates (EPCs) indicate the energy efficiency of buildings in the UK. They were introduced in 2007 and are based on data about a building's energy features, for example, the building's materials, the heating systems, and insulation. EPCs, measures the energy efficiency on a rating scale from A (most efficient) to G (least efficient). Out of the 27 million homes in the UK, over 19 million have EPC ratings below C (Deasley & Thornhill, 2017). Moreover, approximately 20 per cent of these dwellings were built before 1919 and need to be refurbished for energy efficiency if the UK is to move towards its 2050 net zero target (Piddington, Nicol, Garrett, & Custard, 2020). The Passivhaus EnerPHit standard has been proposed and tested internationally as an energy-efficient refurbishment approach (Bastian et al., 2022). The EnerPHit standard sets performance criteria in terms of fabric U-values, building envelope airtightness, and heating and cooling energy demand. Over 65,000 Passivhaus-certified projects have now been completed all around the world, including 1,300 in the UK (Mitchell & Natarajan, 2020). It is acknowledged that for heritage dwellings, such as this Georgian terrace house, a single retrofit approach, such as EnerPHit, might not always be feasible or acceptable (Wise, Moncaster, & Jones, 2021).

3. METHODOLOGY

The key objective of this study was to evaluate the BIM and EnerPHit-assisted energy-efficient refurbishment of a typical Georgian terrace house within the UK housing context. The approach to the research methodology focussed on solution-oriented research to provide valid knowledge that enables practitioners to solve problems(Saunders, Lewis, & Thornhill, 2016) – see Fig. 1. The purpose of this evaluative methodology was to critically appraise how BIM tools and the EnerPHit standard could develop a novel refurbishment model for the retrofit case study. Models such as this might encourage the housing sector to accelerate demand for an energy-efficient refurbishment programme amongst homeowners in the UK. This study mainly discusses developing and implementing solutions to some of the conventional building refurbishment issues.

A baseline scenario was modelled in a BIM tool, with the geometric and non-geometric features of the real-world case study, a 3-storey Georgian terrace house with a basement located in Liverpool. A potential benefit of the BIM tool for the generated house model was that it provided better coordination with its clash detection feature at the pre-refurbishment stage. Moreover, using 4D BIM offered the virtual environment to simulate 24-day refurbishment project activities with improving time management and avoiding overlapping construction areas. Furthermore, with its cost estimation benefit, 5D BIM had an economically feasible opportunity for the refurbishment project, considering the quantity take-off throughout the refurbishment processes regarding the chosen Passivhaus-certified building components.

Figure 1:
Research Design



As one of the main criteria of the EnerPHit standard, it is important to consider the concept of 'fabric first' approach to defining the refurbishment measures and implementing them step-by-step for heat retention and airtightness regarding building material selection.

To evaluate the proposed BIM-based refurbishment energy performance outcomes, predicted energy demands were compared using the Passive House Planning Package (PHPP) software – an Excel-based Passivhaus tool – and the dynamic thermal simulation modelling software DesignBuilder (DB).

3.1 Case Study Model

This study investigated a 3-storey Georgian terrace house with a basement in Liverpool, built with a brickwork structure and insufficient insulation in terms of energy performance. Liverpool is in a temperate maritime climate of warm, wet summers and cool, wet winters, with temperatures peaking around 20°C in summer and dropping to around 2°C in winter.

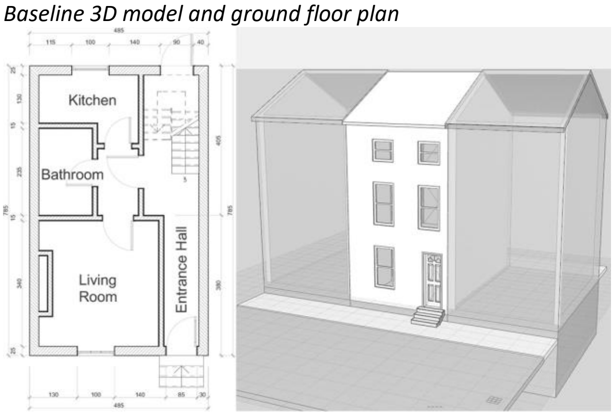
The baseline case study was modelled in ArchiCAD, one of several convenient BIM tools used worldwide. All three floors of the case study are for residential use, each having a similar layout, with a below-ground basement acting as a plant room. The building has 100 m^2 total treated floor area, 2.85 m floor-to-ceiling height, 12.6 m^2 total glazing area, and 221 m^3 net volume (Fig. 2).

Figure 2:
View of the case building in Liverpool

With its geometric and non-geometric details, the baseline model of the property was generated in ArchiCAD (Fig. 3). The potential benefits of BIM in the developed refurbishment model can be categorised as:

- The 3D BIM model can enable the project stakeholders to ensure better coordination to avoid remedial works and clash detection in advance of implementing the proposed refurbishment measures for the building.
- The 4D BIM can offer a virtual environment for simulating and visualising the housing refurbishment process with consideration of construction site coordination and time scheduling throughout the refurbishment project.
- The 5D BIM can provide a cost estimation opportunity to the refurbishment project, performing the quantity take-off from the pre-refurbishment to the post-refurbishment processes related to the selected Passivhaus-certified building components.

Figure 3:
Baseline 3D model and ground floor plan



The EnerPHit standards guide the refurbishment of existing buildings to achieve specified Passivhaus standards. The anticipated energy demand within the context of the Liverpool climate is limited to 25 kWh/m^2 for heating. The EnerPHit criteria demand the same thermal comfort as the Passivhaus criteria i.e. 20°C to 25°C, with no more than 10% of the hours in a year outside of this range (Passive House Institute, 2016).

4. RESULTS AND DISCUSSION

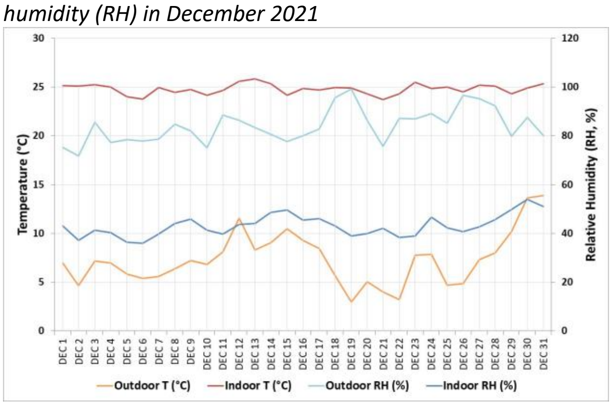
4.1 Field Measurements

The indoor temperature and humidity data have been recorded at 15-minute intervals using HOBO UX100-003 Temperature and Humidity Data Loggers in the house's living room. The outdoor weather data condition was obtained from the University of Liverpool Weather Station (weather.liv.ac.uk). Fig. 4 compares the recorded outdoor and indoor air temperature (T_a) and humidity (RH) data for in December, 2021.

The outdoor temperatures changed from 13.9°C to 3°C. The indoor temperatures changed from 25.8°C to 23.7°C. The occupant's higher preferred temperature due to his Mediterranean background can explain the higher than the UK average indoor temperature.

The outdoor RH levels fluctuated more than the indoor levels, between 71% and 99%. The indoor RH levels changed between 36% and 54%.

Figure 4:
Recorded indoor and outdoor temperature (T_a) and relative humidity (RH) in December 2021

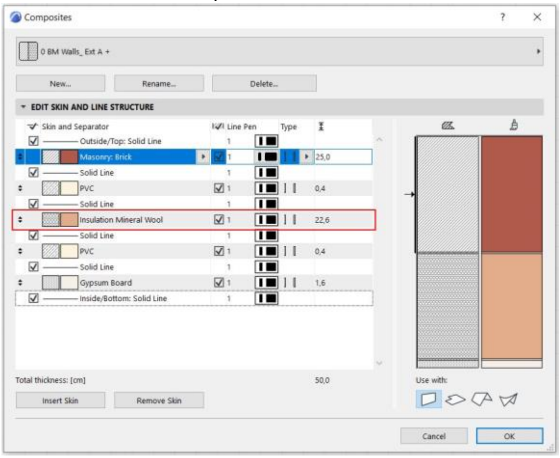


4.2 BIM Model

A semantically enriched BIM model of the selected Georgian terrace house was created in ArchiCAD considering some key criteria: 3D coordination, time schedule and planning, cost estimation, and building refurbishment material selection. Moreover, all relevant building components were defined as different groups and layers in the model: external walls, internal walls, floors, roof, windows, and doors (Fig. 5).

Figure 5:

The external wall components



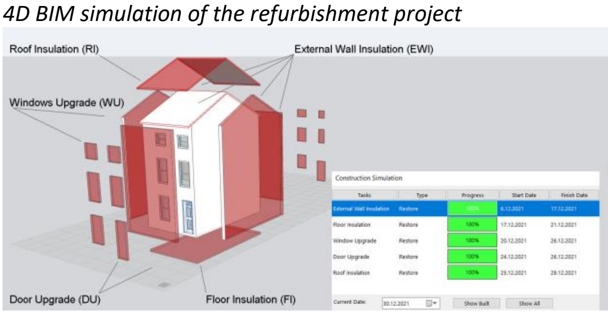
Furthermore, the geometric and non-geometric data were acquired from the BIM model to investigate the property's current condition and improve effective refurbishment strategies. Based on the BIM model calculation, 38 m^2, 238 m^2 and 46 m^2 surface areas of insulation materials were applied to the floor, external walls and roof within the scope of the proposed refurbishment model.

Next, PHPP's material inventory was used to select Passivhaus certified insulation materials. The same materials were modelled in DesignBuilder for energy analysis.

In order to manage the implementation process of the EnerPHit standards, the 4D BIM simulation of the case study was created, including the definition of the refurbishment activities' sequences. The proposed simulation demonstrates 24-day refurbishment project activities, describing the sequences of external wall, floor and roof insulation, as well as windows and doors upgrades (Fig. 6).

Figure 6:

4D BIM simulation of the refurbishment project



4.3 Energy Analysis

After generating the selected case study's BIM model, the EnerPHit-based insulation materials and upgrades were applied step-by-step on the PHPP tool, starting with the exterior walls, floor, and roof to improve the case building's energy performance. Moreover, the double glazed windows were replaced with triple-glazed windows and the doors were upgraded with consideration of energy efficiency too. Table 1 summarises the thermal properties of the existing building and the proposed refurbishment alterations. Table 2 shows the improvements at each stage.

In addition to this, the airtightness assumed at 1.0 ach to meet EnerPHit criteria.

Table 1:

Thermal properties and U-values of the model before and after the refurbishment

	Wall	Floor	Roof	Window
Main material	250 mm brickwork	100 mm concrete	20 mm slate	Double glazing
Insulation material	Mineral wool	Mineral wool	Mineral wool	Triple glazing
Insulation thickness	225mm	150mm	250mm	-
U-value pre-refurbishment	1.69 W/m^2K	1.80 W/m^2K	1.04 W/m^2K	2.90 W/m^2K
U-value post-refurbishment	0.15 W/m^2K	0.15 W/m^2K	0.14 W/m^2K	0.75 W/m^2K

The main focus of the proposed refurbishment was improving the energy performance of the case study. Heating is the primary source of energy consumption in houses in Liverpool, and therefore the aim was to reduce the heating consumption.

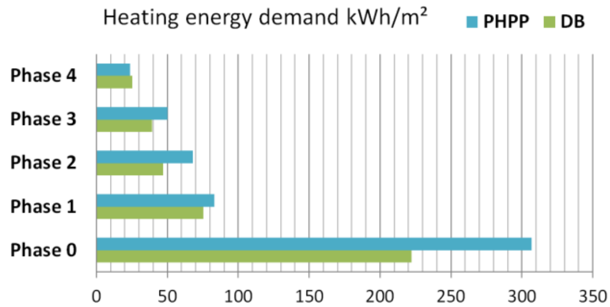
Fig. 7 demonstrates step-by-step heating energy demand reduction and compares the results for the PHPP and DesignBuilder models. With regards to this, Phase 0 represents the baseline heating energy demand of the case study and each of the following phases represents the thermal improvements of the building components phase-by-phase;

- Phase 0 baseline model
- Phase 1 external wall insulation,
- Phase 2 floor insulation
- Phase 3 windows upgrade
- Phase 4 roof insulation

The baseline PHPP model's energy demand was 307 kWh/m^2 for heating, much higher than the EnerPHit standard.

Figure 7:

Comparison of modelled heating energy demand between pre-refurbishment and post-refurbishment



The following alterations (also, see Table 2) were implemented phase-by-phase in DB and PHPP to improve the case study's heating energy performance:

The refurbishment started with external wall insulation and decreased the heating energy demand from 307 kWh/m^2 to 83.2 kWh/m^2. Although Phase 1 was the most effective step of this refurbishment project, it was essential to focus on the whole-house refurbishment approach and to meet EnerPHit standard. In this regard, floor insulation, windows upgrade and roof insulation followed the first phase. The PHPP tool implied how the inadequately insulated baseline model could be refurbished systematically to achieve the EnerPHit heating demand criteria of less than 25 kWh/m^2 annually. As a result of this, the PHPP-based phase-by-phase refurbishment model could achieve 23.7 kWh/m^2 of annual heating energy demand. According to the obtained results, each step of the refurbishment remarkably contributed to high thermal performance.

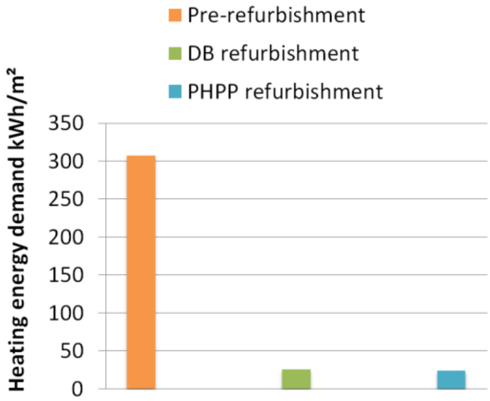
Table 2:
Refurbishment phases, including a summary of U-values (W/m^{2}K), used for each element of the building envelope

Upgrade	External Wall	Floor	Window	Roof
	U-value W/m^{2}K	U-value W/m^{2}K	U-value W/m^{2}K	U-value W/m^{2}K
Phase 0	1.69	1.80	2.90	1.04
Phase 1	**0.15**	1.80	2.90	1.04
Phase 2		**0.15**	2.90	1.04
Phase 3			**0.75**	1.04
Phase 4				**0.14**

After developing the BIM and PHPP models of the case study, the DB model was generated phase-by-phase considering the EnerPHit standard for heating energy demand. The pre-refurbishment energy use results of the baseline model in the DB differed from the heating energy demand in the PHPP simulation results, as shown in Figure 7. The obtained heating energy demands for the first four phases (Phase 0-3) in the PHPP results were greater than that in DB results. This might be due to the different weather profiles as PHPP, Excel-based software, carries out static simulations. DB tool performs dynamic simulations and is more effective in the feasibility studies to evaluate the performance improvements of buildings in terms of energy efficiency. Accordingly, DB uses hourly weather files to run the thermal simulation while PHPP uses the monthly average weather data. However, the same conclusion could be drawn from both tools regarding the effectiveness of the refurbishment phases.

The external wall insulation was the most effective measure in both DB and PHPP results. The following phases, floor and roof insulation and windows upgrade, supported the proposed refurbishment model to meet the EnerPHit heating demand criteria. The correlation between static and dynamic simulations results is noteworthy that the same building components were assessed in the PHPP and DB tools and achieved the targeted heating energy demand score of less than 25 kWh/m^2. The baseline model had 307 kWh/m^2 of heating energy demand. The PHPP and DB refurbishment results had 23.7 kWh/m^2 and 25 kWh/m^2, respectively (Fig. 8). The results had the potential to evaluate the different energy efficiency gains amongst the refurbishment phases regarding various building components.

Figure 8:
Comparison of monthly heating demand (kWh/m^2) of the phase-by-phase refurbishment of the base case model



The proposed refurbishment model of the Georgian terrace house could meet the real needs of the UK housing stock as solution-oriented research to provide useful knowledge that guides practitioners to solve the issues related to the conventional refurbishment process. Utilising a BIM tool for this study provided better coordination in building material selection, organisational priority for the key refurbishment phases, and collective decision making for the project stakeholders with consideration of the EnerPHit standard. Moreover, 4D BIM offered the virtual environment to simulate the 24-day refurbishment project activities, improving time management and avoiding overlapping areas throughout the refurbishment project. The cost estimation benefits of 5D BIM discussed the economic feasibility of the presented refurbishment model as a solution for the conventional refurbishment issues such as cost overruns and unsatisfactory outcomes. Applying static and dynamic energy simulation tools, PHPP and DB, offered a different perspective on the analysis of energy performance of the selected case study. Although some parameters for energy analysis were assessed with slight nuances, both of the results of PHPP and DB energy models achieved 25 kWh/m^2 of heating energy demand for the Passivhaus EnerPHit criteria.

5. CONCLUSION

This paper examines how energy efficiency can be achieved by implementing the BIM and EnerPHit-assisted refurbishment model for the UK housing stock.

A BIM model for a typical Georgian terraced house type was generated and simulated with consideration of the further dimensions of BIM, 4D BIM (time schedule), and 5D BIM (cost estimation). Using PHPP and DB, the energy demand of the baseline model and proposed refurbished model were investigated phase-by-phase. Based on the examined findings, the proposed model shows how the case study building can be refurbished to achieve the EnerPHit criteria by comparatively assessing the PHPP and DB results.

Briefly, the proposed housing refurbishment model has potential as a solution for the conventional refurbishment projects with utilising BIM tools and EnerPHit standards for the energy-efficient housing refurbishment in the UK to meet the UK's 2050 net-zero targets.

ACKNOWLEDGEMENTS

This study was supported by the Republic of Turkey Ministry of National Education, the primary sponsor of my PhD programme.

REFERENCES

Alwan, Z. (2016). BIM performance framework for the maintenance and refurbishment of housing stock. *Structural Survey*, *34*(3), 242–255. https://doi.org/10.1108/SS-03-2015-0018

Bastian, Z., Schnieders, J., Conner, W., Kaufmann, B., Lepp, L., Norwood, Z., … Theoboldt, I. (2022). Retrofit with Passive House components. *Energy Efficiency*, *15*(1), 10. https://doi.org/10.1007/s12053-021-10008-7

BEIS. (2021). *Net Zero Strategy: Build Back Greener*. *Gov.Uk*. Retrieved from https://www.gov.uk/government/publications/net-zero-strategy

Committee on Climate Change. (2019). Reducing UK emissions - 2019 Progress Report to Parliament - Committee on Climate Change. *Reducing UK Emissions: 2019 Progress Report to Parliament*, (July), 1–93. Retrieved from www.theccc.org.uk/publications

Deasley, S., & Thornhill, C. (2017). AFFORDABLE WARMTH, CLEAN GROWTH Action Plan for a comprehensive Buildings Energy Infrastructure Programme. *Eeig*, (September).

Juan, Y. K., Gao, P., & Wang, J. (2010). A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings*, *42*(3), 290–297. https://doi.org/10.1016/j.enbuild.2009.09.006

Ma, Z., Cooper, P., Daly, D., & Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy & Buildings*, *55*, 889–902. https://doi.org/10.1016/j.enbuild.2012.08.018

Mitchell, R., & Natarajan, S. (2020). UK Passivhaus and the energy performance gap. *Energy and Buildings*, *224*, 110240. https://doi.org/10.1016/j.enbuild.2020.110240

Okakpu, A., GhaffarianHoseini, A., Tookey, J., Haar, J., Ghaffarianhoseini, A., & Rehman, A. (2018). A proposed framework to investigate effective BIM adoption for refurbishment of building projects. *Architectural Science Review*, *61*(6), 467–479. https://doi.org/10.1080/00038628.2018.1522585

Passive House Institute. (2016). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard. *Passive House Institute*, 1–27. Retrieved from https://passiv.de/downloads/03_building_criteria_en.pdf

Piddington, J., Nicol, S., Garrett, H., & Custard, M. (2020). *The Housing Stock of The United Kingdom*. Retrieved from https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf

Saunders, M., Lewis, P., & Thornhill, A. (2016). *Research methods for business students*. Pearson Education Limited.

Ustinovichius, L., Popov, V., Cepurnaite, J., Vilutienė, T., Samofalov, M., & Miedziałowski, C. (2018). BIM-based process management model for building design and refurbishment. *Archives of Civil and Mechanical Engineering*, *18*(4), 1136–1149. https://doi.org/10.1016/j.acme.2018.02.004

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Wang, C., & Cho, Y. K. (2015). Application of As-built Data in Building Retrofit Decision Making Process. *Procedia Engineering*, *118*, 902–908. https://doi.org/10.1016/j.proeng.2015.08.529

Wise, F., Moncaster, A., & Jones, D. (2021). Rethinking retrofit of residential heritage buildings. *Buildings and Cities*, *2*(1), 495. https://doi.org/10.5334/bc.94