Energy & Buildings 285 (2023) 112884

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Conducting smart energy audits of buildings with the use of building information modelling

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ARTICLE INFO

Article history:
Received 3 January 2023
Revised 6 February 2023
Accepted 8 February 2023
Available online 14 February 2023

Keywords:
Energy audit
Building
Application Programming Interface
Building Information Modelling

ABSTRACT

Energy audits are an integral part of the overall energy savings strategy in the building sector. The significance of energy audits was confirmed both by their adoption by the European Energy Savings Directive (2012/27) as well as by the development and issuance of a large number of European standards (standard series EN16247, EN 15378, EN 16798, EN 16946, EN 16947 etc.), related to the energy audit of buildings and building systems. However, current practices for conducting energy audits in buildings do not adopt the latest developments in the field of Industry 4.0 practices, resulting in the general belief within the engineering community of building physics that energy auditing can be further updated and improved. This work aims to introduce a novel approach for the improvement of existing building energy audit practices with the adaptation of building information models and associated data. The study presents the potential of evaluation process utilizing building information models for constituent energy audit procedure – assessment of building energy consumption related to building envelope. The question of whether there is room for further adoption of digitization practices in carrying out energy audits, as well as the possibilities of developing new tools in this area are addressed. Following this, the main outcome of this study is the overview and analysis of Industry Foundation Classes schema building information model data structure and its interrelationships with the aim of using the extracted information to digitize energy audit procedures. Research approach covers digitization of building energy consumption assessment influenced by building envelope characteristics, as well as evaluation of economic and energy aspects for possible building shell optimization scenarios. The study also presents the results of a case study evaluation carried out with the developed tool using building envelope modification feature for various environment and economic parameters. Additionally, the architecture, and the rationale for the developed tool backed, used to extract necessary information for implementing building energy audits are presented. We finalize with the discussion on upcoming developments in the field and on future work of this study.

1. Introduction

Buildings are one of the major energy consumers in all of the developed countries, thus the research on their energy efficiency is at the forefront of the energy sciences [1]. Efficient use of energy is also one of the main challenges considering the age of European Union building stock. With the European Commission initiative of renovation wave [2] it is aimed to significantly reduce energy usage and emissions. As far as renovations are concerned, energy audit plays significant role in the first phases of building retrofitting process with the aim to identify insufficient energy usage and to propose building upgrades to reduce primary energy consumption [3]. In view of different renovation strategies, it is crucial to outline the importance of complex solutions following building envelope upgrade. Namely, upgrades of heating ventilation and air conditioning (HVAC) systems or at least adjustments of existing systems to achieve the top performance of retrofitted buildings [4]. Therefore, this study delivers the first steps of energy audit procedures concerning building's envelope assessment, as well as briefly evaluates energy source impact for building optimization payback period. A comprehensive analysis of building systems utilizing building information modelling (BIM) documentation is foreseen as continuation of this work.

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https://doi.org/10.1016/j.enbuild.2023.112884
0378-7788/

Nomenclature

Abbreviation	Description
AECO	Architecture Engineering Construction and Operation
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modelling
BMS	Building Management System
CEN	European Committee for Standardization
COP	Coefficient of Performance
DD	Degree Day
HVAC	Heating Ventilation and Air Conditioning
IFC	International Foundation Classes
IRR	Internal Rate of Return
KPI	Key Performance Indicator

BIM model data can be employed for detailed energy consumption calculations, providing reliable and sufficient data of existing building materials and its' properties. BIM-based design processes produce a data-rich digital asset model, consisting of numerous building elements with assigned parameters. Each element of the building model contains sufficient information that can be used for the energy assessment of the building envelope [5], ranging from envelope geometry, and i.e., material layers of a partition, to thermal resistance or thermal conductivity properties of every material layer. The properties assigned to an entity is machine-readable data, that can be interpreted by various algorithms and used in building assessment processes, depending on the purpose of the assessment [6].

With the increasing awareness of BIM technology usage, as well as legislation requirements for the construction sector to introduce BIM for the new projects regarding the investments [7] it is foreseen that in the near future BIM technology will be more widely adopted. In this light, it is envisioned that BIM model can act as a repository of building related information for energy audits. Together with that, building asset data can be enriched with dynamic input, while linking physical and virtual asset through an API. To the authors best knowledge, BIM is currently not employed for conducting energy audits, neither is reflected in recent studies, nor in energy auditing standards and guidelines. In order to enable the use of BIM as an essential information database for buildings energy assessment processes, existing software needs to be upgraded or even new tools should be developed, as there are currently no available solutions in the market for this field. Inevitably, the integration of BIM data into the energy audit procedure, has the potential to increase efficiency and accuracy while reducing time resources.

Utilizing digital twin enabled real-time monitoring, energy auditors can receive reliable building environmental data, linked to particular monitored areas, as well as representation of energy breakdown in the whole building, when energy monitoring is considered. Also, advanced data visualization techniques could be considered for a better identification of monitored abnormalities. In terms of monitoring sensors, the capabilities and reliability of the equipment should also be assessed.

With the work carried out for this study authors aimed to investigate the theoretical background of existing energy audit procedures requirements as well as to identify the processes that can be digitized with the employment of building information model and supplementary technologies. This study also focused on identifying in the literature the main challenges and missing links when digitization aspects of assessment procedures are considered. Aiming to verify potential of BIM data integration to the procedures of energy audits, a comprehensive analysis of Industry Foundation Classes (IFC) schema structure and interrelationships was conducted to outline the targeted data that could be utilized for the assessment of building energy consumption.

With the methodological section of the study authors intended to elaborate the procedure of extracting the required information from IFC documents to be utilized for the energy consumption calculations, as well as to present the architecture of BIM to energy audits application programming interface (API).

To evaluate the developed framework and tool, a case study was selected to assess the energy consumption taking into account the influence of the building envelope and its characteristics.

Within this study, the novel approach of utilizing specific BIM data for building envelope energy consumption assessment is presented, as well as the framework of improved energy audit procedure within the view of digitization. The presented approach also covers unique method that enables to perform energy improvements in building elements indirectly, without affecting native building model, which allows the use of presented application by assessors without specific software knowledge.

2. Theoretical background

2.1. Energy audit for buildings: Current status and need for digitization

According to the EN 16247 standard, an energy audit is a systematic inspection and analysis of energy use and energy consumption of a building, with the objective of identifying energy flows and the potential for energy efficiency improvements [8]. This procedure includes a data collection process, with the aim to understand the characteristics and energy behavior of the building envelope and building systems. The standards EN 16247-2 and ASHRAE 211-2018 [9,10] propose requirements for data collection procedures, depending on the scope and level of detail of the energy audit. To the author's best knowledge, the information collection procedures proposed in the well-established standards of this field, do not cover the increasing use of BIM technologies in the architecture engineering construction and operation (AECO) industry. In particular, this problem can be reported by comparing the information exchange requirements for sufficient BIM-enabled energy modelling with current practices and standard data collection requirements for energy audits [11]. The use of simple or complex energy modelling tools can be challenging due to the software limitations in a specific area of use, modification restrictions or specific software knowledge requirements for the energy auditor [12]. Alongside this, the lack of interoperability of BIM with energy modelling tools, resulting in data loss, the need of manual intervention, as well as different information interpretations by various tools, can be identified as weaknesses that reduce the automation process in the field [13]. As-built BIM models could provide sufficient information for the energy performance assessment as well as reducing the time needed to collect data from various sources, required for the implementation of the required calculations for identifying energy saving opportunities in a building unit. A comprehensive energy analysis requires data input such as the building geometry, floor plans, the thermochemical properties of the building materials used, construction details, as well as information regarding building systems, major appliances, equipment and their operation schedules [14]. In current energy auditing practice, this information is obtained from existing building documentation and surveys, whereas missing information is usually supplemented by standard values. It should be noted that significant uncertainties arise when missing data have to be assumed on the basis of engineering practice or standard values. Afore mentioned BIM features such as sufficient data related to the building envelope and its parameters, building geometry or semantically rich data can be identified and utilized as a promising data base for the building retrofitting, sustainability analysis and optimization [5].

Despite that the use of BIM allows the identification of potential energy efficiency opportunities, the modelling of different renovation scenarios [15] and the coordination of the actions of the different professions and stakeholders involved in the renovation process [16], the scale and application of BIM to existing buildings and renovation strategies is still in its early stages. Nevertheless, EU promotes the use of digital technologies in the construction sector and to support the transition to a more sustainable and energy-efficient building stock by supporting initiatives to develop guidelines and methodologies for the use of BIM in renovation projects [17,18].

2.2. The challenges in the development of BIM for digitizing the assessment of buildings indoor thermal conditions

BIM is described as a digital representation of the building structure and assets, including numerous data that can be processed during the design, construction and operation stages of a building [19]. The use of BIM enables efficient information exchange between various stakeholders, improves decision-making and sustainability, reduces faults during asset assemble, operation and can be described as cost-saving solution [20]. While being a comprehensive repository for all information related to building materials, design and systems, there are still tools and added value services to be developed, in order to enable the exploitation of BIM for all building life-phases [21]. BIM has the potential to enable designers to achieve the most efficient building performance assessment solution, considering the thermophysical properties, as well as the construction details of the building envelope and its materials. This can be achieved in an iterative way during the building design or retrofit process, allowing for the optimization of the building envelope, with regard to its cost-optimal energy performance. It has also been identified that BIM can be used as a basis for building energy performance certification procedures [22].

The integration of real-time indoor environmental data to BIM models could provide a comprehensive understanding of building behavior and potential risks to occupants when indoor environmental conditions are considered. Some elements of this approach were already demonstrated in the study of Desogus et al. [23], which presents a solution that successfully allows real-time and historical data to be accessed and visualized directly within the BIM environment. It enables the association of a room element in the model with the specific sensor data of a physical building, thus reducing the risk of false association between observed values and their associated areas. However, the main downside of the proposed solution is limitation to the specific software. For the development of advanced processes related to spatial data interconnections of elements of a BIM model, Industry Foundation Classes (IFC) were defined as a standard reference [24]. The ISO 16739-1:2018 standard, was developed to be vendor neutral and suitable for wide range of software platforms and interfaces [25]. Vendor neutrality helps to improve interoperability, since despite the differences in vendors' approach, the IFC-based BIM model data structure complies with the described standard.

2.3. Smart sensors and digital twins: the missing link to the digitization chain of energy audits

BIM can provide valuable and reliable information regarding the building assets and elements, it does not though provide operational data related to buildings actual energy performance. This gap may be overcome by exploring the potentials of smart sensors and digital twins.

Field measurements of building energy consumption and indoor environmental parameters with the use of smart sensors, are included in detailed energy audits of Level II and III. A variety of different sensors can be utilized to measure the building energy-related values [26]. Significant evolvements in metering equipment regarding its accuracy, size, robustness, data storage and connectivity have been achieved in the recent past, resulting to a wide range of solutions, leading to a challenging selection of the sensing equipment [27]. Smart sensors used for energy audits should be non-intrusive, transmit wireless data and allow access to data online in real-time, store data internally in case of connection loss, and have long battery life. Compliance with these requirements should be aligned with a reasonable cost [28].

The importance of low-cost sensors constitutes one of the main challenges in the field [29]. Ali et al. [30] discuss the use of Arduino based sensors with a satisfactory result in the accuracy and the level of investments needed, leading to a cost savings of 50–75 %, compared to market alternatives. When the use of multiple sensors is considered, wireless sensors network is especially cost effective, compared to a wired solution due to avoidance of building retrofitting in regard to cabling [31]. Demanega et al. [32] showed that technological advancements in the field of monitoring equipment can be reflected in a performance of low-cost sensors as well. Another significant aspect of wireless sensors concerns their compatibility with Building Management Systems (BMS) [33].

Digital twin concept can be described as a combination of three main components – physical product, its' virtual representation and the continuous data flow that links both physical and virtual products [34]. Connections between these two assets can be described as physical-to-virtual for the monitoring and virtual-to-physical for the control actions [35]. For both cases, the synchronization and data connection are considered as the spine of the concept. Considering digital twin input for the improvement of energy audits, the focus is mainly on a physical-to-virtual connection for monitoring. Digital twin enabled real-time monitoring of various parameters can be employed for prediction, analysis or real-time visualization purposes. The dynamic data bridge between physical and virtual assets allows for simple and clear visualization of the measured data with the use of color palettes that reflect the actual values documented in the BIM model [36]. Visualization could be helpful for indication of limits exceeding values in building environments, as well as for positive impact in regard to energy consumption [37].

3. Materials and methods

In the context of this work, the methodology concerns the design and development of an application programming interface for carrying out the energy evaluation of a building, through its BIM document. The main features of the methodology of this study are described as follows.

1. In terms of the proposed methodology, the IFC data file structure was evaluated, with the aim to describe and identify the targeted data that is mandatory to extract from the IFC-based BIM file for further processing. Building external partitions, its geometrical and thermophysical data as well as consisting materials of the construction were identified in the IFC data file.

2. Within this study, an approach for the relevant data extraction workflow description and detailed implementation definition were also described. The development of the API required a deep understanding of the IFC file structure, the relationships between the elements and the attributes data.
3. An overview of the tool's functions and capabilities was also provided, with the aim to facilitate the energy auditor's assessment of the effectiveness of building envelope improvements and to provide sufficient key performance indicators for proposed upgrades.
4. The developed tool was tested to justify claims and insights and present the benefits that the use of BIM technology can deliver improvements to the field of energy auditing procedures. The case study building was the new wing section of the Frederick University campus in Cyprus. The BIM model of the building was developed with the use of the Autodesk® Revit modeling software, and it was further exported as an IFC data file and introduced to the provided software. The IFC data extraction algorithm, integrated into web-based application, was successfully identified and processed, with 130 external elements that were defined in the BIM file of total 882 elements.
5. Energy efficiency improvement options were analyzed for the case study building. The analysis was performed by considering the potential upgrade of the external construction elements of the building. Simplified management of the material layers, thermophysical properties, dimensions and information of materials allowed to assess a variety of available element upgrades at a building or element level in a time efficiently manner. A parametric assessment conducted, enabled the comparative assessment of different potential upgrade scenarios, quantified in monetary terms, focusing mainly on the cost-optimal aspect of the proposed solutions.

4. BIM to energy audit API

4.1. BIM to energy audit API workflow

The main rationale of the API is to simplify the procedures implemented during an energy audit, as well as to identify the energy upgrade opportunities for a building shell. Concerning the rationale of the tool development, the three key action points can be identified as follows:

- Analysis of BIM documentation and integration possibilities;
- Data extraction from IFC file;
- Calculations and key performance indicators (KPI) methodology.

Fig. 1 presents the general workflow of energy audit procedure utilizing BIM data and the tool developed. Once the IFC file has been uploaded to the application process, the data is extracted according to the algorithm defined below in the section "Data extraction process". The extracted data then is structured and presented to the auditor for further evaluation, validation or, if needed, correction. An assessor shall validate and if necessary, supplement the data acquired from the BIM models IFC document. From the IFC file obtained and validated building envelope characteristics are further utilized for calculation procedures. Calcula-

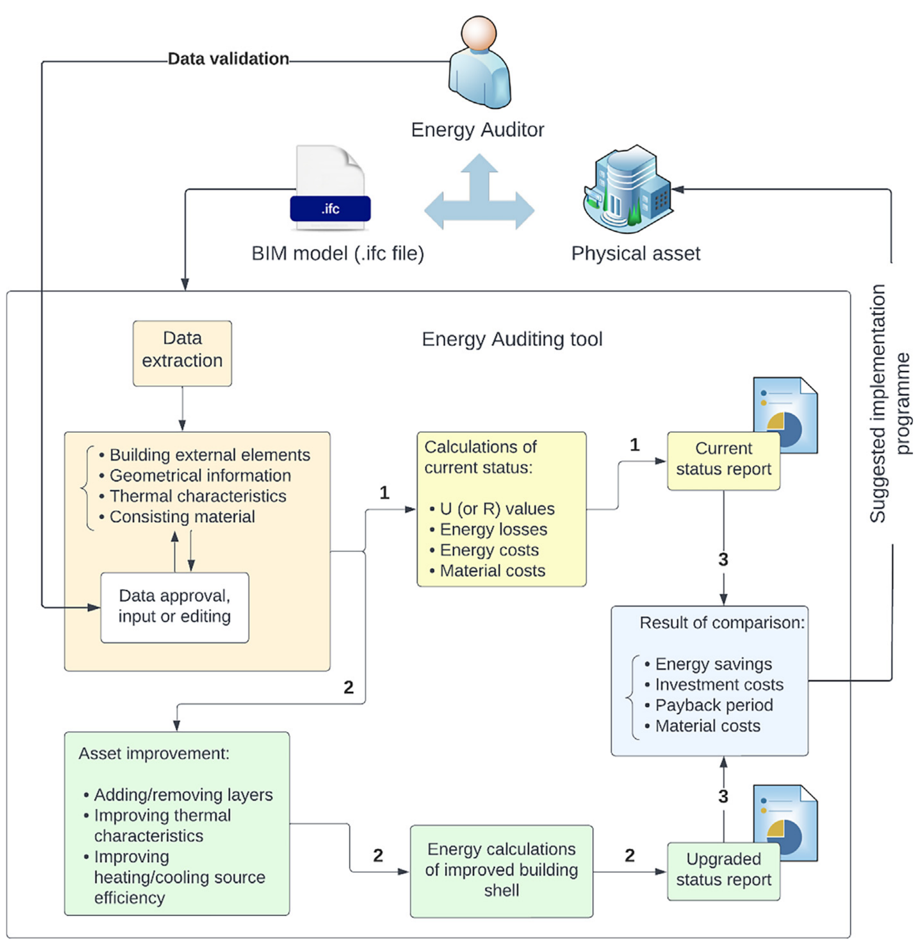

Fig. 1. BIM-based energy audit workflow.

tions performed define the current status of the building envelope, including thermal and financial indicators (1). The revision of the BIM model with the integration or removal of additional construction layers, or the modification of the thermal characteristics, enables time-efficient calculations of the potential energy upgrades, and presents the impact on the asset energy consumption. The ability to modify the characteristics of building elements directly in the application, without affecting the BIM file, enables time-efficient processes and does not require specific software knowledge, making the solution more adaptable. The assessment (2) also considers the required investments for the proposed building envelope upgrade. The tool provides the ability to compare (3) asset performance indicators of the current state of audited building with the indicators calculated considering the building envelope improvements. The ability to modify various parameters, enables to adapt the proposed algorithm for the buildings under different climatic conditions, energy price, energy carriers, increasing in this manner the tool's range of applications, and enabling the implementation of parametric assessments.

Through the comparative assessment of different alternatives, a detailed report is generated, including the considered thermal and financial indicators of the building with and without the implementation of the proposed improvements. It can also be utilized by the auditor to compare the feasibility of the various different alternatives considered for the energy upgrade of the building envelope.

4.2. Interoperability concerns: The use of IFC

One of the main objectives of this study was to provide a vendor-independent solution that can be used and further developed by different users. To this end, the tool was developed based on an open-source format, to facilitate interoperability [38]. Considering the scope and approach of this study, the IFC format was employed as the base information repository. The information of an IFC-based BIM model is stored and defined using the relevant data structure. Based on the BuildingSMART IFC4-ADD2 TC1 [39] schema, a methodology for extracting energy-related data from the IFC file was developed.

The target data structure in an IFC-based BIM model may vary depending on the modelling software used during the modelling stage. The tool developed, utilized some of the parameters that are defined by the IFC standard documentation and are anticipated to be included in an IFC document, regardless of the software provider. Additional information required for the implementation of the required energy assessment calculations, is introduced manually by the user or through the BIM modelling software vendor. As Autodesk® Revit BIM modelling software is identified as the most commonly used software of this type in the AECO sector [21], the data structure of this software was considered in the design of the data mining algorithm. In cases where the BIM model was developed using a software with a different data structure, the use of the BIM to energy audit API may be enabled by pre-processing the IFC file with the open-source code. The required information can be extracted and post-processed in a variety of ways. A commonly used method is the use of a visual programming tool integrated within a BIM application [5]. The main disadvantage of this approach is the lack of interoperability, as the solution is provided and limited to commercial software.

4.3. Data extraction process

BIM models consist of various objects whose descriptive attributes and parameters are aligned with their geometry. Depending on the complexity of the building, the model may contain numerous objects with semantic data that might be irrelevant for the calculation purpose of the energy audit. The scope of the tool at this stage was restricted to the evaluation of the different energy upgrade alternatives of the building shell. Accordingly, the data that defines building envelope geometrical and thermophysical properties was identified and targeted to be extracted from the BIM file.

The relevant data for the building envelope evaluation in regard to the scope of the tool was identified to the building external partitions, their geometry and composition, as well as their thermophysical properties. The IFC-based information extraction algorithm was developed using Python programming language and IfcOpenShell-Python [40] open-source software library, that comes with utility functions and enables data extraction, IFC file query filtering as well as other options.

The workflow of the data extraction algorithm consists of the following steps:

1. querying of building envelope external partitions
2. retrieval of dimensional and analytical properties
3. extraction of object materials and its related data

Building elements that physically exist and have material state, in the IFC schema are defined under *IfcBuildingElement* entity. This entity includes all elements that are part of the building structure or space separating systems. Considering building shell, the following elements that could have an impact on the energy efficiency of the building were identified and selected for further processing: *IfcCovering, IfcCurtainWall, IfcDoor, IfcPlate, IfcRoof, IfcSlab, IfcWall, IfcWindow.*

The distinguishment of the external partitions from the proposed list of elements was performed utilizing the *IfcPropertySet* entity. The *IsExternal* predefined common property was used to identify if the above listed elements faced the outside and were designed as external. By using ifconpenshell.util.selector module for parsing, elements that met defined query requirements were acquired as an output of the first step.

4.3.1. Building external partitions geometry and thermophysical properties

While the previous section describes the workflow of the external building elements extraction from IFC file, this section aims to define the method adopted to retrieve the geometrical and thermophysical information of the external partitions.

Fig. 2 presents the workflow of the targeted data extraction algorithm, which was adopted for both, IFC2x3 and IFC4 versions, as well as the sequence of the dimensional data acquisition. Considering differences in attributes relations, in IFC2x3 an inverse attribute *IsDefinedBy* pointed to list of entities *IfcRelDefinesByProperties and IfcRelDefinesByType*, whereas in IFC4 *IfcRelDefinesByType* an inverse attribute *IsTypedBy* was assigned. The mentioned relationships were defined in the algorithm and utilized for the *IfcPropertySet* selection by the assigned property set *Name* value. For the geometrical information, the *Name* attribute of the *IfcPropertySet* was checked to match "Dimensions" naming. Following that, the targeted area and volume data were retrieved within the *HasProperties* relantionship by selection of the *IfcPropertySingleValue,* based on the *Name* of the attributes.

With regard to thermophysical properties, *IfcPropertySet* was checked to meet the naming requirement as "Analytical properties". This property set was defined and provided by the Autodesk® Revit modeling software. To retrieve thermal properties information, the sequence based on the property selection by *Name* attribute was adopted in the same manner as for dimensional properties.

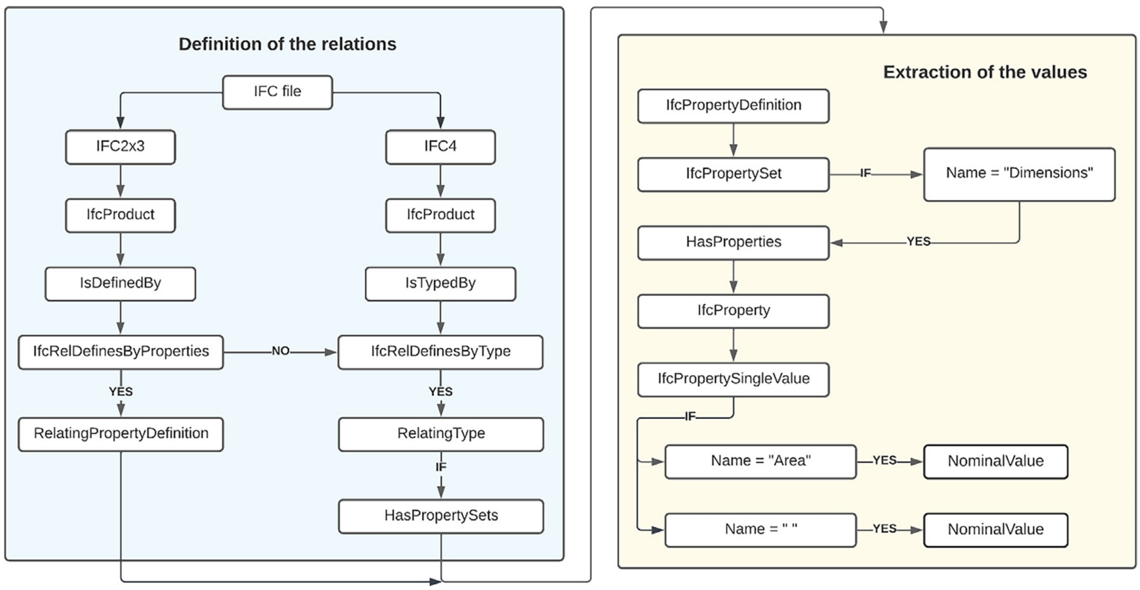

Fig. 2. Flowchart of asset property values extraction.

4.3.2. Building external materials

In order to obtain the external building elements materials, as well as their thickness in accordance to the previously selected building shell partitions, materials and objects relationships were analyzed. The association relationship *IfcRelAssociates* was utilized in the further algorithm development process. Fig. 3 presents the general interconnection schema. Within *IfcRelAssociates*, an objectified connection *IfcRelAssociatedMaterial* between a material definition and elements or elements types to which this material definition applies was chosen. As presented in the Fig. 3, *IfcMaterialSelect* provides an option to select either *IfcMaterialDefinition*, *IfcMaterialUsageDefinition* or *IfcMaterialList* that can be assigned to an entity. Each of them provides specific information as follows:

- *IfcMaterialDefinition* - general supertype for all material related information items in IFC that have common material related properties and that may include association of materials with some shape parameters or assignments to identified parts of a component [41].
- *IfcMaterialUsageDefinition* - general supertype for all material related information items in IFC that have occurrence of a specific assignment parameter, with the purpose to assign a set of materials with shape characteristics [42].

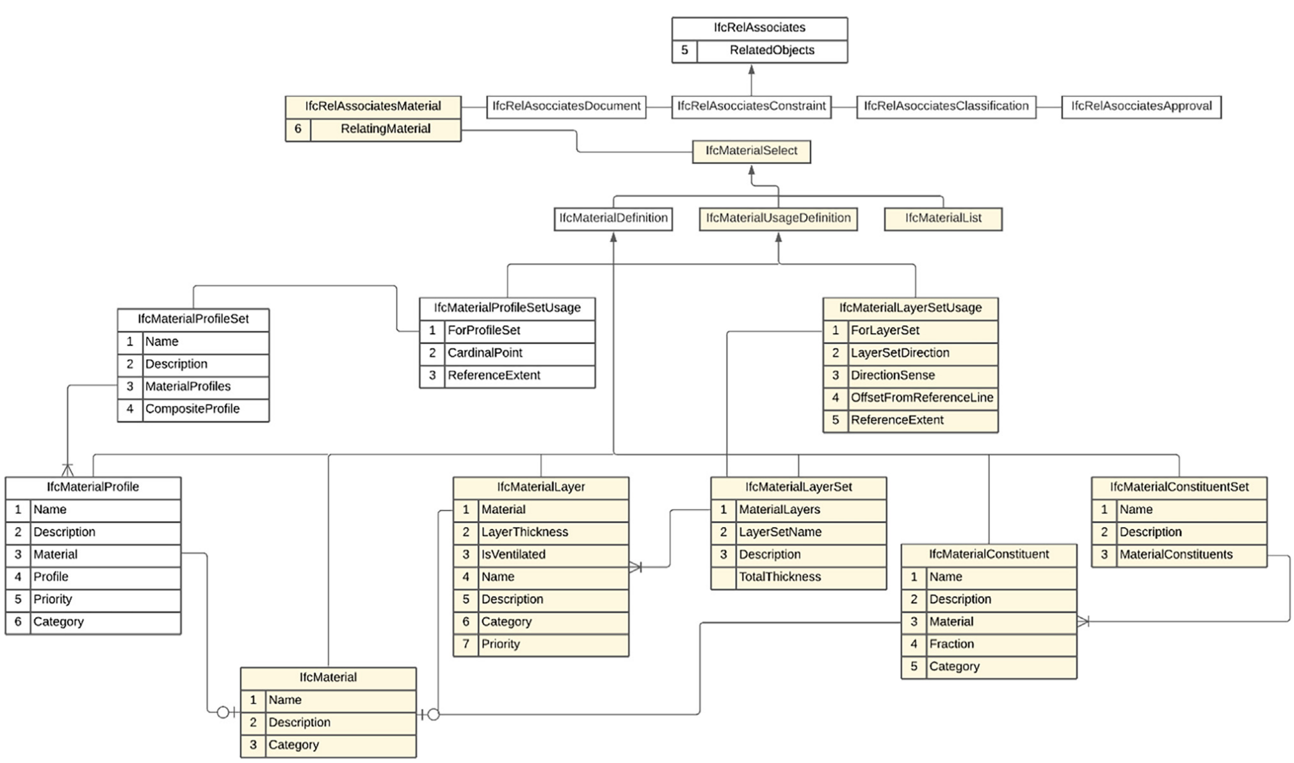

Fig. 3. Material relationship schema.

- *IfcMaterialList* – a list of different materials that are included and used in the element structure.

In the developed API, *IfcMaterialUsageDefinition* and *IfcMaterialList* entities were utilized for the targeted data extraction. *IfcMaterialLayerSetUsage* defined the use of *IfcMaterialLayerSet* considering its location and orientation to assigned element geometry. *IfcMaterialLayer* is a single and identifiable part of an element which is constructed of one or a number of layers. Each *IfcMaterialLayer* has a constant thickness and is located relative to the referencing *IfcMaterialLayerSet*. The mentioned relationships were utilized and enabled to retrieve targeted data considering *IfcMaterialLayer* material name and layer thickness.

The above-mentioned relationships were employed for the layered elements of the building envelope, such as walls, roofs, coverings, slabs. The same sequence could not be adopted for building elements such as windows, doors, curtain walls and plates due to their different material structural. To retrieve the materials data of such elements, *IfcMaterialConstituentSet* and inverse attribute *IfcRelAssociatedMaterial* was adopted. The provided data consisted of a group of individual material elements, where each material was assigned to a part of a whole element. Parts of elements were only identified by a keyword. In this case, each part did not have a shape parameter i.e., layer thickness, but represented an association to an element.

5. Case study

5.1. Audited building unit

The tool developed was applied and tested on a mixed-use real-life building of Frederick's University Campus in Cyprus Fig. 4. The New Wing building, built in 2007, consists of an underground floor, designed for parking and three floors above ground, with a total floor area of 2000 m^2. The structure and external partitions of the building consist of a concrete fair faced finish surface, whereas the ground floor external partitions consist of 175,75 m^2 transparent surfaces. The ground floor of the mixed-use building contains canteen facilities, whereas the first floor is used for teaching purposes, including training seminar rooms. The second floor hosts the administration offices of the institution.

The BIM model of the case study has been developed utilizing Autodesk® Revit modelling software. Initial validation was performed for the model to match the requirements. The validation was mainly required to ensure that all of the external building elements functions were set up as exterior and that sufficient data for the extraction algorithm was provided. The validation procedure consists of automatically generated lists cross-check utilizing Autodesk® Revit Dynamo visual programming plugin. During the procedure, element name value is compared with its function, as well as thermal properties values are revised to be set. Where potential discrepancies in element information are noted, visual inspection can be carried out for the exact element and its properties. Considering the case study model, all elements were set correctly, and no further adjustments had to be made or implemented.

Following the validation procedure, the model was exported as an IFC data model based on IFC 4 Design Transfer View version and deployed for further energy audit processing with the use of the API.

To reduce energy losses through the external partitions of the studied building, an individual and complex solutions were considered for the building envelope improvement, which are the followings:

- External walls insulation installation
- Roof insulation installation
- Windows replacement
- Complexed wall, roof insulation installation and windows replacement.

All of the above-mentioned options were assessed considering the feasibility aspect to increase the thermal characteristics of such partitions.

5.2. Energy audit results

The thicknesses of the construction layers, as well as the heat transfer coefficients were introduced to the calculations by the data extraction algorithm and if needed supplemented by the energy auditor. Utilizing these characteristics, the thermal transmittance of the building envelope elements was calculated in accordance with the calculation methods provided by the standard ISO 6946:2017 [43]. The thermal building envelope evaluation and the energy cost calculations were based on the energy losses and heat gains of the building with the use of degree-days methodology [44].

Table 1 presents the total volume and area of the extracted building elements of the analyzed geometry. The calculation of the energy cost from each element, was calculated based on the

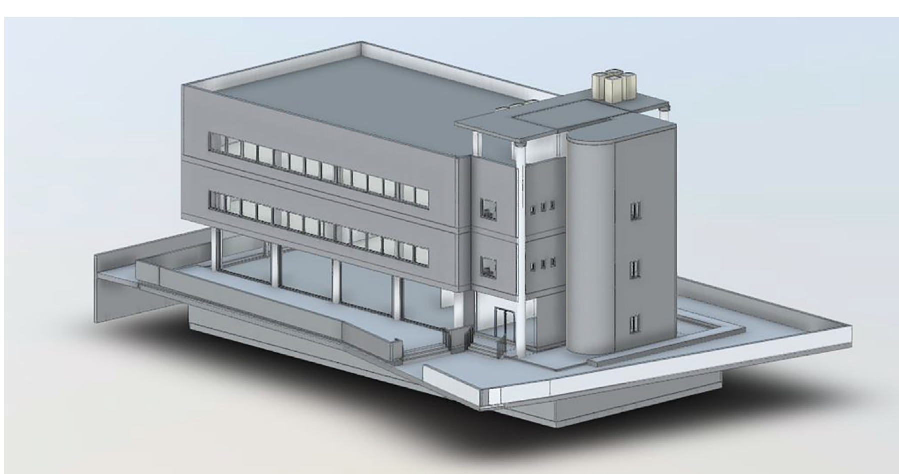

Fig. 4. BIM model view of the Frederick University New Wing Building, Cyprus.

Table 1
Analysis of different building element, their volume and area, as well as monetization of heat losses through the elements, using the degree day method.

Element Type	Total Volume, m^3	Total Area, m^2	Energy Cost, €
Basic Wall: Exterior wall – mk	299.09	1142.93	3019.72
Windows_Sgl_Plain:910 × 1330 mm 1stfloor	5.13	206.29	1601.16
Floor:Roof 352 mm	181.61	515.93	1298.32
Windows_Sgl_Plain:Windows ground floor	3.52	143.72	1115.54
Windows_Sgl_Plain:400 × 600	0.19	7.42	57.58

Fig. 5. Graphical and numerical comparison report.

degree day method, for a given energy cost, based on the energy carrier considered.

The tool developed provides an opportunity to the user to propose construction suggestions for the energy upgrade of the building shell. Simplified procedures allow the user to make changes to the structure of the building's external elements directly in the application, to add or remove component layers, and to assess the improvement of the thermal performance of various elements. The changes made can be quantified in monetary terms, including energy savings and investment required for the improvements.

In addition, the user is given the possibility to make comparisons between different packages of energy efficiency improvement solutions, visualizing the results in graphical or detailed numerical form (Fig. 5). In this context, the user can identify the optimal renovation option for the building shell and the payback period of adapted energy saving packages.

5.3. Parametric assessment of the energy audit results

The energy costs for the heating and cooling needs of the analyzed building were evaluated under various scenarios, while the tool enabled modification of the environmental, energy source efficiency parameters, as well as of the energy prices. The data retrieved from the tool were supplemented with an additional evaluation criterion, namely the Internal Rate of Return (IRR) which defined the feasibility of the energy upgrade potential investments [45]. Investment's IRR was utilized for the comparison of various building upgrade propositions.

The parameters calculated were the payback period (in years) of the energy upgrade of the walls, the windows and the roof of the building, as well as the IRR of the investment for the same elements. The costs of the elements were retrieved by the report of the Republic of Cyprus in regards to the calculation of the cost optimal levels with regard to the minimum legislative requirements for buildings thermal insulation, in compliance with the Regulation 244/2012/EC [46]. The cost considered for the energy upgrade of the different elements are provided in Table 2. The parameters assessed, were defined based on the work of Fokaides and Papadopoulos [47] and were the following:

- The climatic conditions, expressed in degree days (DDs). Particularly values from 1000 to 6000 DD were considered, covering the climatic conditions within the European Union member

Table 2
Thermal insulating cost of building elements used for the audited building.

Building Element	Cost
Thermal insulation of roof	40 €/m^2 + 2 €/(cm*m^2)
Thermal insulation of wall or beams and columns	55 €/m^2 + 2 €/(cm*m^2)
Double glazing window – low e	240 €/m^2
Triple glazing window	300 €/m^2

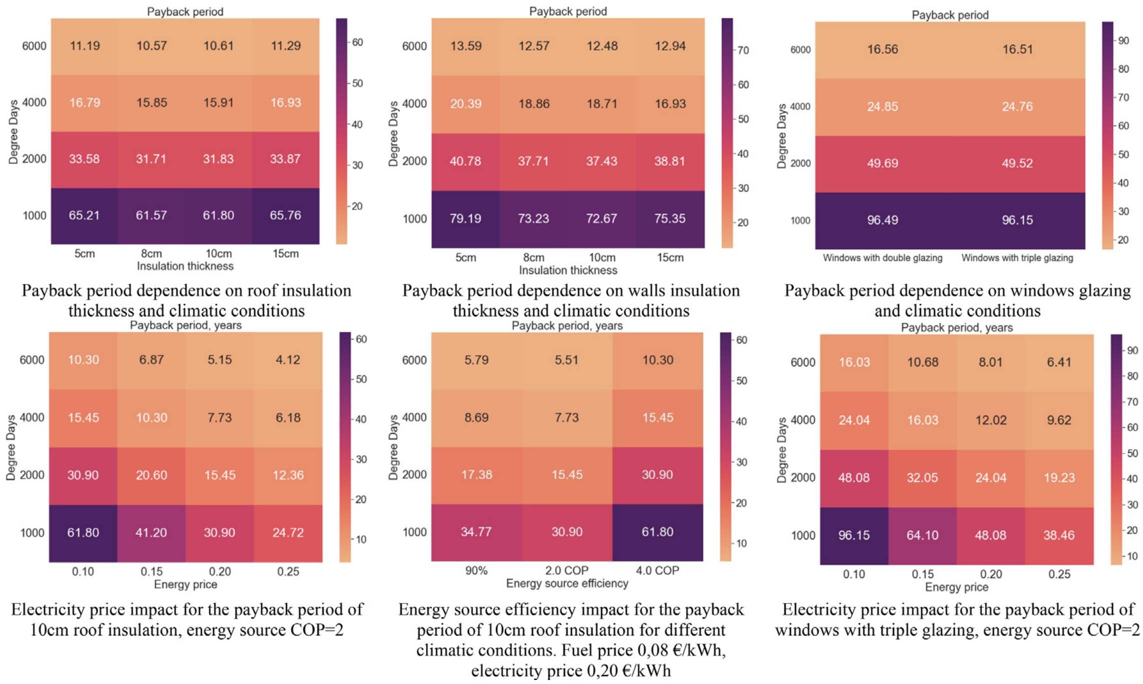

Fig. 6. Parametric assessment of different parameters on the payback period of potential energy upgrade of walls, roofs and windows.

states (1000 DD for the southern member states of Cyprus and Malta, and 6000 DD for the northern member state of Finland),

- Different insulation thickness, namely 5, 8,10 and 15 mm for walls and roofs and double low-e or triple glazing for windows,
- The discount rate for the life cycle costing calculation of the IRR, which varied from 2 % to 5 % with a step of 1 %,
- The efficiency of the building systems used for heating and cooling of the building, ranging from 90 % for heating boilers to 2.0 and 4.0 of coefficients of performance (COP) for heat pumps used for both heating and cooling purposes.

The lifetime of the scenarios was implemented in compliance with the guidelines provided in the EN 15459–1:2017 [48], to avoid economically non-beneficial solutions, since the payback period exceeds the building life cycle range, and it was considered to be 30 years. The graphs were created utilizing Python programming language, with the use of data analysis modules such as Pandas [49], Seaborn [50], Numpy [51], Matplotlib [52].

Fig. 6 and Fig. 7 presents the analysis carried out for different environmental and building envelope improvement options using a heat map format. The results presented confirm the logical con-

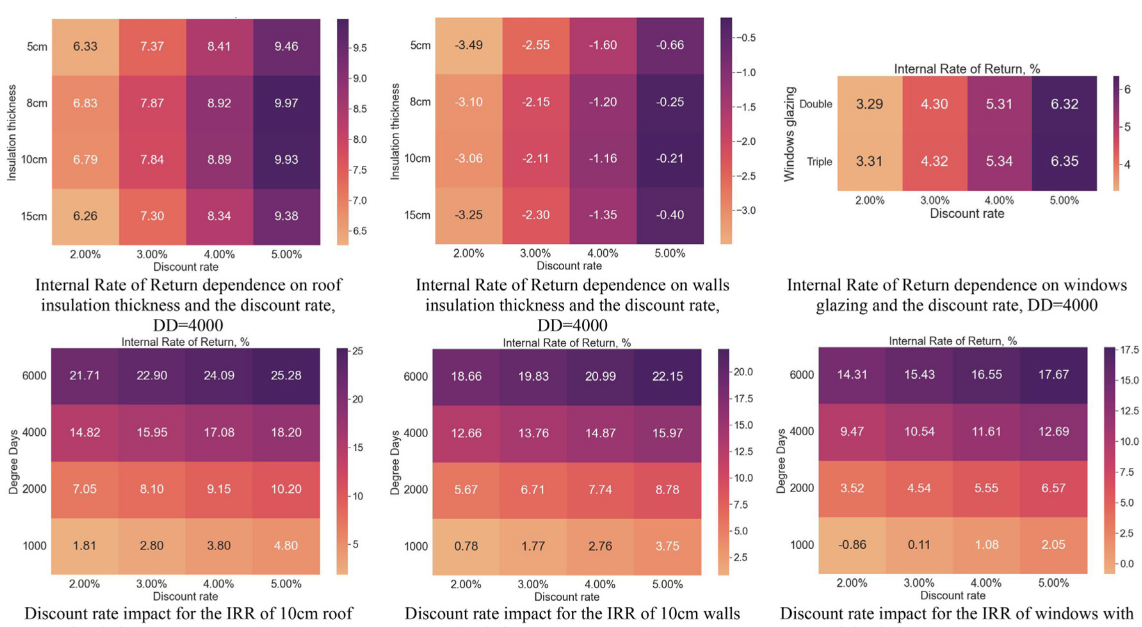

Fig. 7. Parametric assessment of different parameters on the IRR of potential energy upgrade of walls, roofs and windows.

nection that a better payback period is found in those areas with higher DDs. In comparison, the payback period for 15 cm of roof insulation is 5.82 times longer in the southern EU areas (1000 DDs) compared to the northern areas (6000 DDs). However, a thicker layer of insulation will not necessarily be more cost-effective, as shown by the payback period when comparing different thicknesses. The analysis shows that an insulation layer of 8–10 cm will give a higher economic benefit compared to a 5 cm and 15 cm insulation layer on roofs and walls. The results also show that an increase or decrease in energy prices will have the same impact on the payback period in both southern and northern EU countries. The case study analysis also took into account the effect of the discount rate on the IRR calculations, suggesting that a higher discount rate leads to a higher IRR, an increase in which makes the investment more attractive. As discussed above, the analysis of the external insulation options showed that an insulation thickness of 8–10 cm is the most cost-effective solution, and the IRR calculations also reached the same conclusion.

6. Conclusions and future work

This study discussed on the necessity and potential of improving the procedures of conducting energy audits in buildings with the employment of building information models. Through state of the art analysis, it was revealed that at present energy auditing practices do not take advantage of obtained knowledge in digitization of the built environment assessment. As far as BIM documentation adaptation is concerned, this study delivered a comprehensive analysis of building data and its relationships regarding IFC schema that can be utilized for the building envelope assessment. This study proposed a novel BIM-based framework ant a tool to serve as a starting point for future building envelope assessment procedures by applying best practices using BIM documentation. Proposed workflow defines the procedure of targeted data extraction as well as its processing without affecting native BIM model which results to easily applicable end-user-oriented solution that could be utilized by the assessors and personnel without specific BIM modelling software knowledge. The use of the developed tool and proposed novel workflow resulted in significantly less effort to conduct the assessment of the impact of potential building upgrades on the life cycle costing performance of the building energy uses. As BIM methodologies are increasingly used and promoted by public authorities, it is expected that it will become common practice for property owners and stakeholders to own and maintain building BIM data, which can be used as an essential source of information for building assessment. In the light of this, the study is expected to be a steppingstone for the employment of digital construction practices in the field of energy audits. Insights were also provided related to the enhancement of the energy auditing processes, with the purpose of considering the integration of dynamic building system data as well to enable real-time operational energy audit procedures. The ability to assess the virtual reflection of the building extends the applicability and accessibility of energy audits.

Considering applicability and critical points of the framework delivered within this study, it can be argued that the main risks are related to insufficient design and completeness of the digital building model, which may lead to inaccurate calculation procedures. In order to reduce the appearance of inaccurate data in the calculation procedures, the proposed workflow includes a data verification and validation phase already at the beginning of the evaluation. Even if validation procedures are considered, human error during validation cannot be reduced to zero. Since the workflow and tool developed is based on IFC schema, most of the parameters utilized for calculation procedures are already defined, but for a better applicability of the solution, minimum modelling and export requirements can be defined and addressed in the future work. The following actions should also consider standardization of digital energy audit procedures, as well as comprehensive analysis and suggestions to improve already existing data modelling and data transfer standards.

As far as the future research in the field is concerned, the enhancement of the developed methodology should focus on the integration of monitored data, enabling the energy assessment of the building on an operational basis. Initial analysis of the monitoring equipment abilities and its features was conducted, revealing that flexible, non-intrusive and reliable solutions for the monitoring of indoor environmental conditions and energy consumptions can be employed. Monitored data linked to the digital building model could enrich an auditors' understanding of the building behavior, enabling comprehensive real-time energy consumption and distribution analysis. One of the main requirements for this development, is the identification of a data connection approach for BIM as a contextual information repository and time-series data that records continuous sensors readings.

7. Data accessibility

https://zenodo.org/badge/latestdoi/487601986

CRediT authorship contribution statement

Paulius Spudys: Formal analysis, Investigation, Writing - original draft , Writing - review & editing. **Andrius Jurelionis:** Methodology, Validation, Visualization, Writing - review & editing. **Paris Fokaides:** Conceptualization, Resources, Supervision, Project administration, Writing - review & editing.

Data availability

The BIM parser used in this work is accessible under https://zenodo.org/badge/latestdoi/487601986

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge financial support from the research project "Development of Utilities Management Platform for the case of Quarantine and Lockdown" (Grant agreement ID: 101007641), funded by the European Commission.

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