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Classifying the operational energy performance of buildings with the use of digital twins

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ABSTRACT

The classification of the energy efficiency of buildings with the use of the energy performance certificate, constitutes a common practice for the building energy assessment performance community. The main stream in the field is the so-called asset rating, that is the calculation of the energy performance of buildings, whereas another option for the definition of the energy class of a building relies on its measured performance, named operational rating. Despite the fact that significant progress has been achieved in the field of smart sensors and smart buildings, effective solutions related to the employment of Industry 4.0 practices, such as Building Information Modelling (BIM) or digital twins are not employed for the operational rating of buildings energy performance. This study aspires to introduce a comprehensive framework for the operational assessment of buildings energy performance, with the use of advanced tools and practices for building digitization. For the purpose of this study, a relevant set of operational indicators was employed, with the purpose to provide information, both to the landlords and the tenants, related to the actual energy performance of the building. The novelty of this study relies on the fact that for the extraction of the operational rating, a digital twin environment was used, employing smart sensors, real time measurements and a BIM environment. Within this study, the proposed concepts are demonstrated in a case study building of mixed used. This study aims to shed light to the development of practices for the remote and smart real time energy assessment of building units.

1. Introduction

Energy Performance Certificates (EPC) represent one of the core elements of the European Union (EU) policy on the energy efficiency of buildings, as expressed by the Energy Performance of Buildings Directive (EPBD). EPCs mission is to present in a transparent manner building's energy performance as well as to define cost-optimal improvements of the energy efficiency of building units. There are several different types of EPCs; nevertheless, the two main categories of EPCs are the asset and the operational EPCs. The latter class of certificates relies on the measured energy performance of buildings, whereas the asset rating concerns the calculated energy performance. Operational Rating determine a building's energy class by measuring its actual energy consumption, rather than through calculations. Previous studies have shown a significant discrepancy between the results obtained from asset ratings and operational ratings. This disparity can be attributed to various factors, including the assumed usage schedules in asset rating and the standard set of values used in as designed and as built rating schemes. [1].

The distinguishing features of operational rating schemes are twofold. Firstly, they provide more precise information as they classify buildings based on their actual energy consumption rather than relying on standard data sets. Secondly, they necessitate the use of specialized equipment and smart meters, which are currently not available in most existing buildings. The unavailability of specialized equipment and smart meters has been a significant obstacle to the widespread adoption of Operational Ratings for certifying buildings in Europe. Currently, only 11 Member States have implemented an Operational Rating scheme. However, this is expected to change in the near future due to the European Commission's decision to install smart meters in all Union buildings. While this decision was initially made to liberalize the

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Nomenclature

Abbreviation	*Description*
AECO	Architecture Engineering Construction and Operation
BIM	Building Information Modelling
COP	Coefficient of Performance
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LOIN	Level Of Information Needs
IoT	Internet of Things
MSs	Member states
nZEB	Nearly Zero Energy Buildings

electricity market in Europe, it is anticipated to benefit and encourage the use of Operational Ratings as a certification method for buildings.

There is a critical need for improved operational building assessment practices in the construction industry. Despite advances in technology, the current methods used for delivering the operational rating of building energy performance have several deficiencies that limit their effectiveness. To address this research gap, our study aims to introduce the potential of using Building Information Modeling (BIM) files, smart sensors, and digital twin practices as a source of comprehensive static and dynamic data for operational building assessments. In particular, our research seeks to investigate the possibilities of using digital twin technology to address the current limitations of operational building assessment practices. By utilizing BIM data as the initial source of building information, we define a procedure of physical-to-virtual monitored data connection through the use of digital twin technology. This enables us to collect and analyze a vast amount of data in real-time, providing a more accurate assessment of a building's energy performance. Additionally, we propose a set of indicators for operational energy efficiency assessment and present their application through a case study. Our findings will contribute to the advancement of operational building assessment practices and the adaptation of best digital construction practices. This will support the transition to the era of buildings assessment with the use of digital tools and practices, helping to address the current deficiencies in the field. In summary, our research aims to fill the research gap in operational building assessment practices by introducing and investigating the potential of digital twin technology and proposing a set of indicators for operational energy efficiency assessment.

2. Theoretical background

2.1. Asset and operational energy rating of buildings

To enhance the energy efficiency of both new and existing buildings the European Union has introduced the EPBD which aims to achieve a highly energy-efficient and decarbonized building stock by transforming it into nearly zero energy buildings (nZEB) by 2050 [2]. To facilitate transparent information about building energy efficiency, the EPC was introduced by the EPBD in 2002 (Directive 2002/91/EC) [3]. The issuance of an EPC has become a mandatory requirement when constructing, renting, or selling a building or dwelling. The EPC methodology has been continuously revised and supplemented by amendments to the Directives to encourage the conversion of the building stock. Despite the proposed common framework for the evaluation of buildings and the calculation of EPCs, there are methodological differences between EU member states. Therefore, a requirement for the energy performance of a building to be expressed using a numerical primary energy consumption rate in kWh/m^2/year was introduced to standardize the metrics [4].

The ability of MSs to select EPC calculation methodologies leads to varying applications of asset and operational building ratings. The asset rating methodology is based on simulated or modelled energy consumption results, considering physical characteristics of the building such as its envelope characteristics and air leakage, combined with reported measurements from equipment manufacturers [5]. This standardized method of measuring and comparing the energy performance potential of buildings is widely adopted across EU, with the 14 MSs utilizing it as the main procedure for issuing EPC, while 11 MSs applies combination of calculated and measured rating [6].

The methodology of asset rating assesses the primary energy needs without addressing losses during energy production. In contrast, the operational rating considers the energy delivered to buildings, as well as taking into account the impact of user behaviour [5]. The operational rating is based on the measured annual energy consumption of the building and a comparison of the results with a similar building type, which allows to evaluate the impact of user behaviour as well as to encourage building owners and operators to improve energy efficiency [7]. A comparative assessment can also help building owners and managers identify areas for improvement and make informed decisions on energy-saving measures that can reduce energy consumption and greenhouse gas emissions, while also improving the comfort of building occupants.

Over time, the performance of existing buildings can deteriorate, as well as changes in usage, and unexpected malfunctions can lead to a significant efficiency loss in system or building performance, inefficiency in operation, and unsatisfactory living conditions for occupants [8]. This issue can be addressed not only for aged building stock. Despite nZEB are considered as a promising solution to significantly reduce energy consumption in the building sector, neglecting the potential degradation of building components may also result in increased energy consumption [9].

The afore-mentioned considerations and current EPC calculation practices depicts the necessity of a broader application of operational building assessment to boost energy performance of building stock, as well as to reduce the appearance of performance gap.

2.2. Performance gap of the asset versus the operational energy rating

Despite advancements in energy-efficient building design and technology, many buildings are still underperforming their design values, leading to higher energy bills, increased carbon emissions, and decreased comfort levels for building occupants. This phenomenon, where a building's designed energy consumption (asset rating) tends to be lower than its measured operational performance (operational rating), is referred as the performance gap [10].

Buildings consist of multiple subsystems that are influenced by factors that can be grouped into building-related and human-related dimensions [11]. The first dimension encompasses building parameters such as climatic conditions, the building envelope, system parameters, and equipment parameters, while the second dimension relates to user behaviour, indoor environmental parameters set by the user, and operation and maintenance habits that affect building energy consumption. Changes in occupant behaviour can result in increased energy consumption and deviations from the estimated consumption of specific building subsystems, with deviations varying in either direction depending on the building systems [12]. In some cases, the average deviation between calculated and operational energy consumption can reach up to 30% [13], resulting in increased energy consumption and unexploited energy efficiency potential.

The gap in building energy performance can have substantial implications for energy efficiency, sustainability, and economic factors.

The reduction of this gap can be accomplished through the employment of best Industry 4.0 practices such as implementation of real-time monitoring/control systems that provide continuous feedback on building energy performance.

Evaluating and benchmarking the energy performance of buildings with the use of key performance indicators, aligns with the aim of the EPBD to enhance the energy efficiency of the building stock in EU MSs, encompassing both existing and newly constructed buildings. However, current evaluation methods do not sufficiently reflect operational performance at the system level since most commonly developed and adopted indicators depicts building-level performance [14]. These practices result in an insufficient assessment of energy performance at each system level (e.g., lighting, plug-loads, HVAC, service water heating) resulting in incomplete assessment and a lack of data-driven targeting of efficiency improvements. Building service systems are commonly measured only at the aggregate equipment level, such as energy use intensity, or at the individual equipment level, like the coefficient of performance (COP). This approach provides limited information for comparing and diagnosing deviations in the combined technologies that serve a specific function within a building, such as space heating or lighting [15].

The evolving concept of smart buildings and cities [16] has led to the increasing use of building automation systems and remote monitoring capabilities [17], as well as the widespread use of internet of things (IoT) devices [18]. The growth in the accessibility of metering equipment infrastructure facilitates the gathering of energy-related data that can be utilized to evaluate building performance at multiple levels.

2.3. *The use of building information modelling (BIM) for the classification of buildings energy performance*

The aim of performing both an operational building assessment and an energy audit of buildings is to gauge the energy efficiency of a building, taking into consideration the energy use that has been measured. This assessment is compulsory for energy audits at the second and third levels of precision [19]. Although the same input information can be used for both performance evaluation and energy audits, the outcomes of these processes have distinct objectives. However, the data gathering and processing techniques applied do not take advantage of digital construction practices [20]. Additionally, there are a number of factors that may have a negative impact on the quality, detail and effectiveness of the data collected in energy efficiency assessment, including the existing documentation on site, the time frame of the assessment, access to equipment data, etc. [21].

The utilization of Building Information Modelling (BIM) to create digital representations of an asset, which are structured and multidisciplinary in nature, is becoming increasingly popular [22]. This organized information can be used as input data for energy performance evaluation processes. Digital building information technologies can potentially enhance the process of building assessment and energy audits as well as operational rating evaluation procedures. [23].

The BIM model that is created after construction is complete provides adequate information for a detailed energy analysis. This includes data about the building's geometry, floor plans, materials, and technical properties of the elements [24]. The BIM model can also provide reliable information about the building systems, such as equipment, units, and pumps. By adding attributional data to the geometrical asset, machine-readable information is provided that can be used for energy consumption assessment. This comprehensive BIM document can be used to obtain trustworthy and accurate results, and help with informed decision-making [25].

The promotion and integration of BIM technology by public authorities into legislation, design, and construction requirements indicate its widespread adoption and continued improvement in the near future [26]. BIM's use of centralized data repositories could also increase time efficiency. Moreover, the availability of building digital information enables real-time monitoring of building system performance, which can help assess energy usage and operational values. It may even provide opportunities to evaluate environmental conditions, depending on the monitoring equipment [27].

2.4. *Digital twins for the real time energy assessment and classification of buildings*

BIM documents can be a crucial component of a digital twin environment that monitors and controls critical energy-related building operations [28]. This helps to connect static and dynamic building data and address any gaps. Digital twins are virtual representations of an object or system that span their lifecycle, updated from real-time data, and use simulation, machine learning, and reasoning to aid decision-making. Both monitoring and control actions can be implemented using this concept [29]. When it comes to monitoring and assessment of buildings, digital twins can be used for both collecting data and facilitating the transfer of information between physical and virtual assets [30]. Employment of digital twin technology facilitates the visual representation of spatially dispersed energy consumption data [31]. This allows building operators to highlight and focus on specific equipment or occupant practices that may contribute to increased energy usage or exceeding in established consumption benchmarks. By delivering this information in a clear format, incorporating numeric data and supplementary colour palettes [32], digital twin provides a real-time update on energy-related parameters. This method of information delivery allows the ability to promptly identify instances of underperforming building components in a user-friendly manner.

Despite the fact that digital twins is gaining significant interest, its application in the field of buildings energy assessment is still considered to be limited [33]. It is a fact that currently there are no sufficient commercialized tools and services related to buildings energy assessment and digital twins. These circumstances result in various attends to adopt different technologies during the development of digital twins. Digital twins are anticipated to play a significant role in the development of smart buildings and cities. However, to improve building energy efficiency assessments, the physical-to-virtual data bridge should be considered further. This will enable real-time actions and decision-making about a building's energy performance. Although the use of digital twins has the potential to enhance energy assessments' accuracy and efficiency, it is still in its early stages of implementation [34]. Challenges are encountered in the absence of standardized methods for integrating real-time data into a building's BIM model and commercial solutions. Furthermore, software and monitoring vendors' interoperability issues arise as they tend to use proprietary formats and limit data integration access [35].

3. Tools and methods for the operational energy classification of buildings with digital twins

In the context of this research, the methodology concerns the development of operational building assessment framework with the use of digital twins and proposes a novel set of KPIs to evaluate operational building performance. The key elements of this study's methodology are outlined below, as well as presented in Fig. 1.

1. An overview of relevant studies was conducted to evaluate the limitations and opportunities for enhancing existing building energy performance assessments, as well as to assess the feasibility of incorporating digital construction practices in these procedures.
2. The evaluation of a proposed set of indicators related to the operational energy performance of buildings and the assessment of the potential for incorporating these indicators into a digital twin platform was performed. An analysis of the proposed indicators to determine their reliability and validity in measuring energy

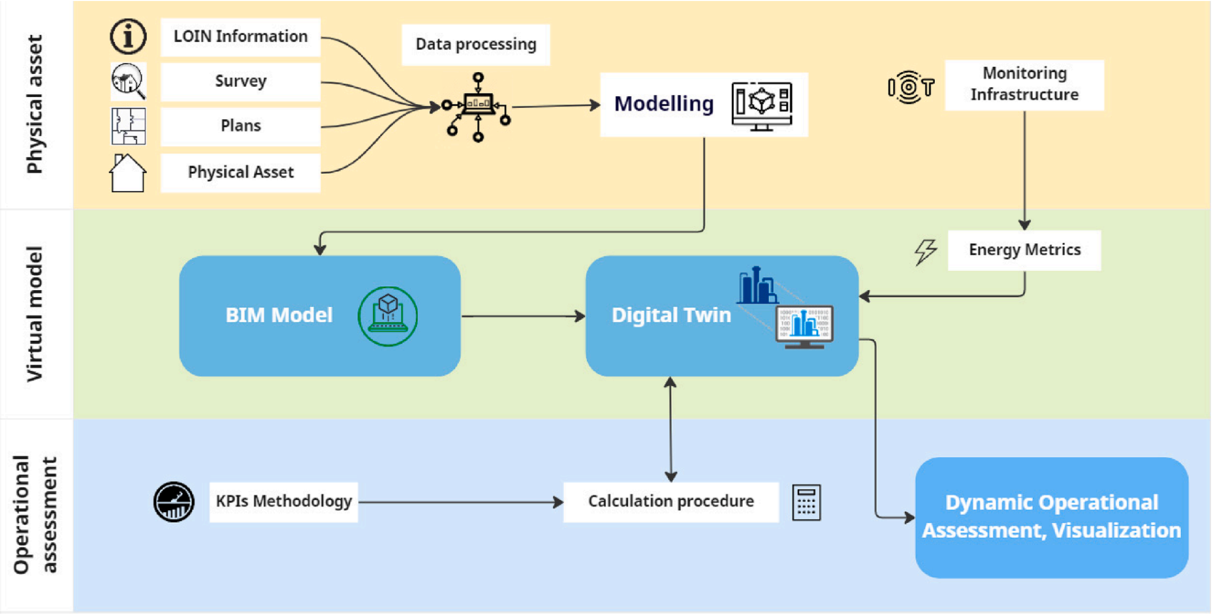

Fig. 1. Operational assessment framework workflow.

performance was implemented. A total of 26 indicators were proposed for the operational building assessment.

3. The development of workflow aiming to convert a physical building asset into a digital one, utilizing BIM technologies and the subsequent conversion into a digital twin by establishing a physical-to-virtual connection for real-time monitoring was delivered.
4. The application of the proposed framework and indicators to a case study building was conducted, in order to carry out an operational assessment, evaluate the feasibility and applicability of the proposed method, and identify any gaps and potential areas for future improvement.

3.1. *Operational assessment indicators*

In terms of this study, a list of novel indicators that covers assessment of energy, smart readiness, human wellbeing, comfort, financial, and sustainability related aspects was introduced [36]. This proposed set of energy-related indicators, delivered within D^2EPC project [37] enabled a comprehensive analysis by complementing the whole-building energy use intensity in performance benchmarking, offering a deeper insight into the performance at system-level compared to similar services in other buildings. The primary metric currently used in the field of building energy consumption is energy consumption per area per year, expressed as kWh/m^2/year, resulting though in some cases in not accurate results [38]. To address this issue, in this study the energy indicators used considered as well the energy usage per occupant, as well as per occupancy hours, as well as per area and per volume of the building. To accurately analyze the energy behaviour of occupants, both end-energy and primary-energy usage were considered. End-energy was particularly important as it reflects the actual energy utilization habits of the inhabitants and provides a consistent correlation with their lifestyle and energy habits. The set of indicators proposed for the comprehensive analysis of the operational performance of a building is presented in Fig. 2. These include the measured energy consumption for power, heating, cooling and air conditioning, lighting, appliances, domestic hot water (DHW), related to the total number of occupants in the building, the time they spend inside, and the building's area and volume.

Total Power/Occupancy	kWh/occupants
Total Power/Occupancy Hours	kWh/h*occupants
Total Power/Area	kWh/m^2
Total Power/Volume	kWh/m^3
Heating Consumption per Energy Carrier/Occupancy	kWh/occupants
Heating Consumption per Energy Carrier/Occupancy-hours	kWh/h*occupants
Heating Consumption per Energy Carrier/Area	kWh/m^2
Heating Consumption per Energy Carrier/Volume	kWh/m^3
Cooling Consumption per Energy Carrier/Occupancy	kWh/occupants
Cooling Consumption per Energy Carrier/Occupancy-hours	kWh/h*occupants
Cooling Consumption per Energy Carrier/Area	kWh/m^2
Cooling Consumption per Energy Carrier/Volume	kWh/m^3
Weather-Normalized Heating & Cooling Energy Cons.	---

Lighting/Occupancy	kWh/occupants
Lighting/Occupancy-Hours	kWh/h*occupants
Lighting/Area	kWh/m^2
Lighting/Volume	kWh/m^3
Electrical Appliances Energy Consumption/Occupancy	kWh/occupants
Electrical Appliances Energy Consumption/Occupancy-hours	kWh/h*occupants
Electrical Appliances Energy Consumption/Area	kWh/m^2
Electrical Appliances Energy Consumption/Volume	kWh/m^3
DHW Consumption per Energy Carrier/Occupancy	kWh/occupants
DHW Consumption per Energy Carrier/Occupancy-hours	kWh/h*occupants
DHW Consumption per Energy Carrier/Area	kWh/m^2
DHW Consumption per Energy Carrier/Volume	kWh/m^3

Fig. 2. Proposed energy related indicators for operational assessment.

3.2. Data collection and integration

3.2.1. Physical to digital conversion – BIM modelling

Within this study the conversion of physical asset into digital representation of building using BIM technologies was implemented. In accordance to the EN 17412–1:2020 standard [39], the quality, quantity, and granularity of the information was communicated, with the aim to ensure that the necessary data for the specific use case was delivered without overloading the recipient as well as the modeler. The level of information needs (LOIN) for the BIM model to serve as a building information data repository for a digital twin, selected in this study, is given in Table 1.

As far as information requirements were defined, the existing building modelling procedure consisted of four main phases which were the following:

1. Site Surveying: While conducting a comprehensive survey of the existing building, accurate data needed to be collected about its physical characteristics, including floor plans, elevations, sections, and details.
2. Data Collection: This phase included the organization and compilation of collected data into a format that could be easily input into the modelling software. This phase concerned the design of drawings, the implementation of measurements, the collection of images, as well as other documentation.
3. Model Creation: Using the collected data, a 3D BIM model of the existing building was developed with a commonly used BIM modelling software in Architecture Engineering Construction and Operation (AECO) sector, Autodesk® Revit [40].
4. Model Refinement: The model was reviewed and refined to ensure that it accurately represented the existing conditions of the building and complied with the LOIN requirements. This phase involved the adjustment of dimensions, the addition or modification of details, and the correction of any errors or inaccuracies.

These steps of physical to digital conversion were employed in this study to develop the investigated model and are considered as good practices for developing as-built BIM models of existing assets, as well in cases when a different modelling software is utilized. The delivered as-built BIM model of the investigated case study is depicted in Fig. 3.

Table 1
LOIN for the development of BIM model selected in this study.

Information	Description	Information used by
General information		
Coordinates	Coordinates were given in the UTM coordinate system	Digital twin
True North	Indicated the orientation of the building in relation to the cardinal directions	Digital twin
Elevation	Building elevation was referred to global system i.e., Orthometric height	Digital twin
Naming	Naming in the model followed naming conventions	Model Operator
Architectural discipline		
Geometry	Building geometry reflected as-built information and building design	Digital twin
Levels	Levels were used, and all of the elements were assigned to building levels	Digital twin
Rooms	Rooms divided a building model into smaller sections, with boundaries determined by elements such as walls, floors, ceilings, etc.	Calculation procedures
Building Technical Systems discipline		
Spaces	Spaces provided information regarding the total volume of room/area, as well as defined boundaries for visualization. Spaces also provided attributional data regarding occupancy	Digital Twin, calculation procedures
Sensors	Sensor's elements enabled information mapping to monitored data stream for data visualization and spatial allocation	Digital twin

3.2.2. Energy-related data monitoring

In order to evaluate the operational performance of the building case study, the data acquisition infrastructure and its importance in the process prior to the installation of any related equipment was considered. The following aspects were implemented during the planning phase of the energy monitoring infrastructure distribution in the building.

1. The identification of the energy systems and the assessment of their monitoring capabilities. Particularly, heating, cooling, lighting, and plug loads were classified and their performance was measured.
2. The definition of the measurement locations within the building. In order to identify the locations for the sensors, aspects of the operational rating, as described in the enhanced set of indicators, were considered. Particularly, multiple sensors were placed in distribution panels, as well as in the building, with the aim to monitor the performance of different building sectors with diverse operational conditions.
3. The decision concerning the types of sensors to be used. Power meters were selected for monitoring parameters such as voltage, current, power, and electricity consumption. The selection of wired monitoring equipment infrastructure was enabled due to practical interior design solutions as well as the accessibility of the building.
4. Connectivity aspects, with the aim to ensure power and connectivity for data collection devices. This aspect is important in order to secure the continuous energy monitoring and assessment. An important feature of the system was the data acquisition system, that could store data in case of connectivity shortages, ensuring continuous energy monitoring and assessment after re-establishment of connection.

In accordance to these criteria and procedures, a network was established to carry out measurements at selected locations within the building. The objective of this monitoring infrastructure and measurement system was to provide energy consumption values for the operational assessment and analysis of the selected set of indicators with the employment of digital twins. Table 2 describes the technical features of the installed sensors used in this work.

3.2.3. BIM to digital twin conversion – Data integration and processing

The workflow used in this study for data integration into the iTwin platform [41], is visually presented in Fig. 4. iTwin platform was primarily designed to be used in the infrastructure domain but was successfully employed for the development of the building digital twin.

The as-built BIM model of the case study building was designed using Autodesk® Revit software and integrated into the iTwin platform using the native file format compatible with Revit project files [42]. However, interoperability issues arose due to the monitoring equipment distributor's failure to provide suitable data integration options for the digital twin platform. As a result, the monitored data file was converted to JSON format and stored in an online database, JSONBin.io [43]. This allowed the data to be integrated into the Grafana application, a multi-platform open-source application that is compatible with the iTwin platform. Grafana was used to link measurements obtained from each sensor to the corresponding elements in the building model and to visualize the collected data in a desired format, such as a table of measurements (Fig. 5). Operational assessment indicators were also visualized using Grafana, providing insightful information on the building's energy performance.

The seasonal operational energy indicators resulting from the assessment of the measurements are presented in Fig. 6.

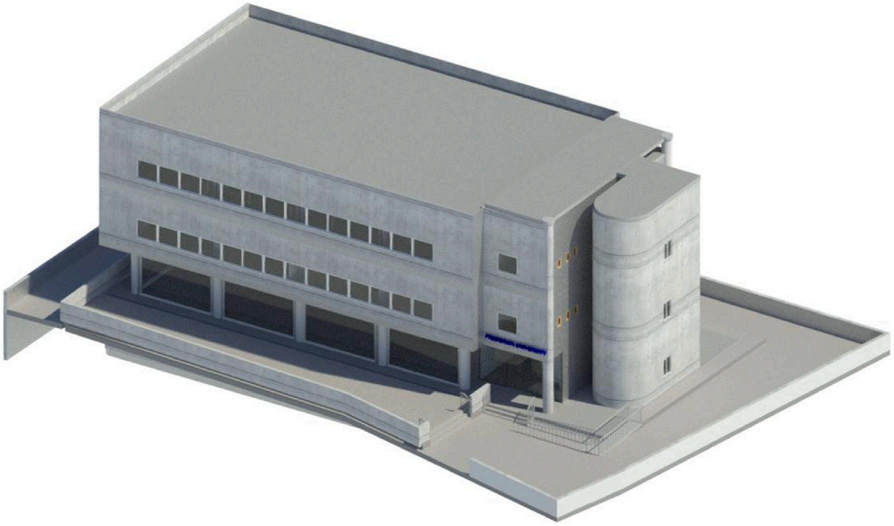

Fig. 3. Delivered as-built BIM model.

Table 2
Monitoring equipment characteristics.

Name	Measured parameter	Accuracy	Qty.
Hobo EG4115 Core Data Logger	AC Voltage: L1: 85–277 Vrms L2: 0–277 Vrms L3: 0–277 Vrms Current: 15 channels 5-6900A per channel Frequency: 50 or 60 Hz	0.5% revenue-grade accuracy compliance	3
Hobo EG4130Pro Data Logger	AC Voltage: L1: 85–277 Vrms L2: 0–277 Vrms L3: 0–277 Vrms Current: 30 channels 5-6900A per channel Frequency: 50 or 60 Hz	0.5% revenue-grade accuracy compliance	1
Hobo T-EG-0630–0100	AC Voltage (V), AC Current 0–100 (A), Kilowatt Hours (kWh), Kilowatts (kW)	Up to +/-1%	21
Hobo T-EG-0940–0100	AC Voltage (V), AC Current 0–100 (A), Kilowatt Hours (kWh), Kilowatts (kW)	Up to +/-1%	3
Hobo T-EG-0940–0200	AC Voltage (V), AC Current 0–200 (A), Kilowatt Hours (kWh), Kilowatts (kW)	Up to +/-1%	3
Hobo T-EG-0390–0050	AC Voltage (V), AC Current 0–50 (A), Kilowatt Hours (kWh), Kilowatts (kW)	Up to +/-1%	30

4. Case study

4.1. Pilot description

The developed framework was utilized to evaluate the operational performance of a University campus building, located in Nicosia, Cyprus. The Frederick University new wing building, which was constructed in 2007, is a contemporary and mixed-use building that occupies surface floor area of 1441 m^2, comprising three above-ground levels an underground floor. The building features a concrete structure with a fair-faced surface finish that confers upon it a refined and modern look.

- The ground floor of the building has a total net surface area of 467 m^2 and contains a canteen facility that caters to the needs of the students and staff of the university. The ground floor's external partitions consist of 175.75 m2 transparent surfaces to allow natural lighting of premises. The estimated average occupancy of the ground floor is 35 occupants.
- The first floor is designed for teaching purposes and is equipped with all the necessary amenities for lectures and training seminars, including three spacious seminar halls. The total net area of the floor is 487 m^2 with estimated average occupancy of 50 occupants.
- The building's second floor has a net floor area of 487 m^2 and is designated as the institutional office area. The office layout is optimized for the provision of a productive and comfortable working environment for the staff, equipped with all required amenities and appliances. The average estimated occupancy for the second floor is 25 occupants.

Table 3 presents a summary of the main floor parameters for the examined building. The underground floor of the building is not included in the energy performance evaluation of the building as it does not contain any energy-consuming devices or equipment.

4.2. Operational energy indicators

Continuous monitoring of the case study building has provided detailed results that were analysed to gain an in-depth understanding of how the building behaves in different seasons over a one-year monitoring period. To calculate the proposed indicators, the monitored information was combined with the static building data obtained from a BIM model. Table 4 presents the calculated performance indicators reflecting the energy consumption of different building systems, such as lighting and appliances, heating and cooling per floor, as well as at the building level. The amount of energy consumed at different system levels is presented per occupant, occupancy hours, area, or volume. This provides the ability to compare the energy consumption of premises with different use-types in various ways.

The analysis of seasonal operational indicators shows that the first and second floors of the case study building, which is located in the area with an average of 326 sunny days [44], consume almost the same amount of electricity for lighting during all seasons. During the summer period, the consumption for lighting on these floors is the lowest at 40.77 kWh/occupant, and the difference from the winter period is only 1.45 kWh/occupant. As for the spring and autumn, consumption for

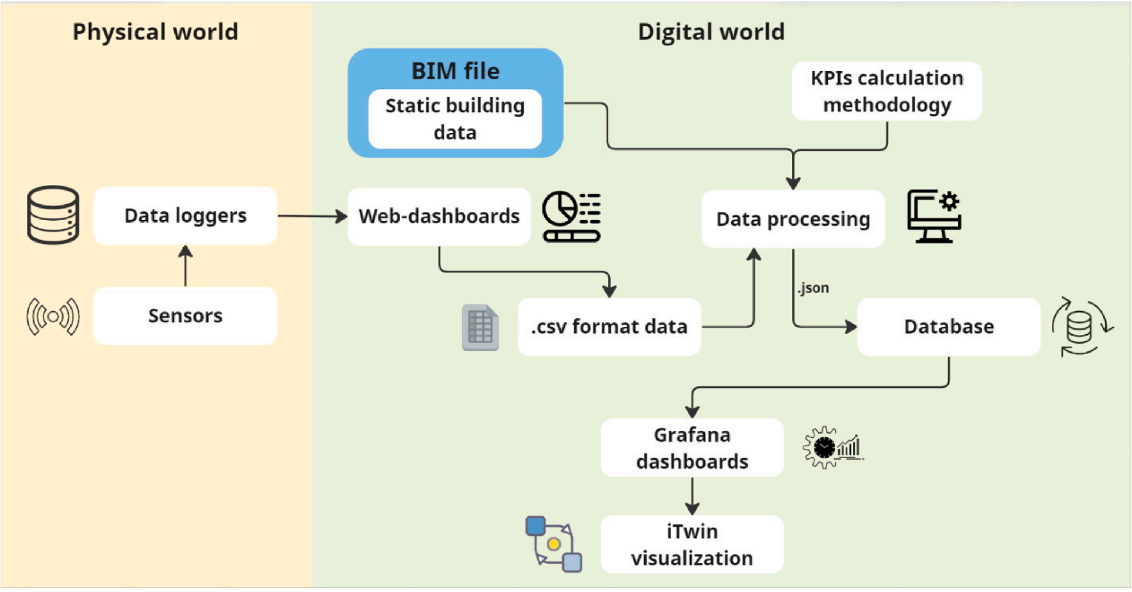

Fig. 4. BIM to Digital Twin workflow.

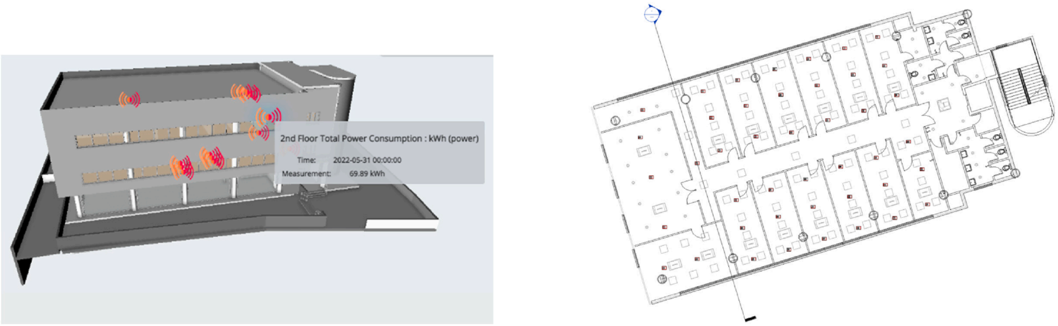

Fig. 5. Monitored data visualization and.

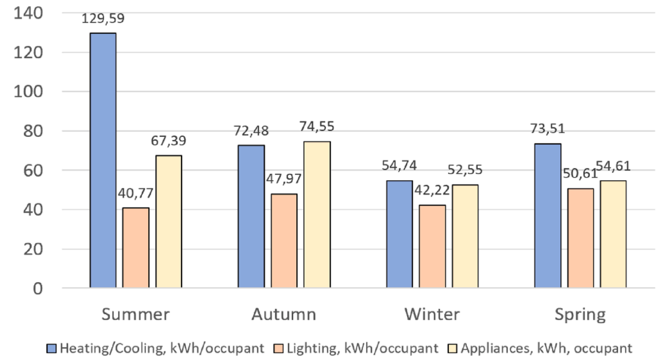

Fig. 6. Seasonal operational rating indicators – comparison.

lighting on the first and second floors requires 50.61 kWh/occupant and 47.97 kWh/occupant, respectively, this could be an area to improve energy efficiency of the building by considering behaviour of the occupants.

Considering energy consumption of appliances in the first and second floors, the lowest consumption can be noticed during winter (52.55 kWh/occupant) and spring (54.61 kWh/occupant) seasons. Seasonal operational assessment of energy consumption per occupant reveals that even the lighting is mostly used during spring, electrical appliances consume less energy compared to other seasons, which may indicate that appliances are not operated in an energy-responsible way.

Table 3
Pilot building floors area, volume and occupancy characteristics.

Floor	Number of people	Floor area (m^2)	Occupancy hours	Volume (m^3)
Ground floor	35	467	8	1450
First floor	50	467	8	1450
Second floor	25	487	8	1450
Total	110	1441	8	4350

As presented in Table 5, energy consumption for the first and second floors for lighting and appliances is 433.67 kWh/occupant, while consumption related to heating and cooling is 330.33 kWh/occupant. These results highlight that occupants of the building consumes more energy than it is required to ensure indoor thermal comfort of the building. While comparing building premises of different use type, it can be concluded that the ground floor where canteen is located, consumes significantly more energy in comparison with first and second floor that are utilized for teaching premises and offices.

With seasonal, annual or other periodic operational results, baseline can be defined for the monitored building's consumption, to continuously monitor and assess performance in real time to ensure the building's efficient energy consumption. This ability provides an opportunity to detect if building is underperforming and to take actions which could

Table 4
Seasonal operational Indicators.

Load	Amount				Unit
	Summer	Autumn	Winter	Spring	
Heating and Cooling/ Occupancy	129.59	72.48	54.74	73.51	kWh/ occupant
Heating and Cooling Consumption per Energy Carrier/ Occupancy-hours	16.19	9.07	6.85	9.19	kWh/ h*occupant
Heating and Cooling/ Area	9.89	5.53	4.18	5.62	kWh/m^2
Heating and Cooling/ Volume	3.28	1.83	1.38	1.85	kWh/m^3
Lighting/Occupancy (1st and 2nd floor)	40.77	47.97	42.22	50.61	kWh/ occupant
Lighting/Occupancy Hours (1st and 2nd floor)	5.09	6.00	5.65	6.33	kWh/ h*occupant
Lighting/Area (1st and 2nd floor)	3.14	3.70	3.48	3.90	kWh/m^2
Lighting/Volume (1st and 2nd floor)	1.05	1.24	1.17	1.30	kWh/m^3
Electrical Appliances Energy Consumption/ Occupancy (1st and 2nd floor)	67.39	74.55	52.55	54.61	kWh/ occupant
Electrical Appliances Energy Consumption/ Occupancy Hours (1st and 2nd floor)	8.43	9.33	6.57	6.83	kWh/ h*occupant
Electrical Appliances Energy Consumption/Area (1st and 2nd floor)	5.19	5.74	4.05	4.20	kWh/m^2
Electrical Appliances Energy Consumption/ Volume (1st and 2nd floor)	1.74	1.93	1.35	1.41	kWh/m^3
Ground floor Power/ Occupancy	–	184.30	324.57	419.89	kWh/ occupant
Ground floor Power/ Occupancy Hours	–	23.04	40.57	52.48	kWh/ h*occupant
Ground floor Power/ Area	–	13.81	24.32	31.47	kWh/m^2
Ground floor Power/ Volume	–	4.45	7.83	10.14	kWh/m^3
Total Power/ Occupancy	237.75	379.3	477.08	598.62	kWh/ occupant
Total Power/ Occupancy Hours	29.71	47.44	59.64	74.83	kWh/ h*occupant
Total Power/Area	18.22	28.78	36.03	45.19	kWh/m^2
Total Power/Volume	6.07	9.45	11.73	14.7	kWh/m^3

be related to occupants' behaviour or performance of building systems.

4.3. Discussion

The integration of data into a virtual building model is a complex process that highlights the lack of standardization and interoperability, resulting in slow digitalization. To improve efficiency, automating data integration processes could be explored, reducing the need for manual intervention. However, limitations in monitoring software can impede the practicality of real-time monitoring. If monitoring equipment manufacturers provide data transfer protocols, direct dynamic data integration with the iTwin platform can be achieved.

Table 5
Annual operational indicators.

Load	Annual Amount	Unit
Total Power/Occupancy	1692.76	kWh/occupant
Total Power/Occupancy Hours	211.62	kWh/ h*occupants
Total Power/Area	128.22	kWh/m^2
Total Power/Volume	41.95	kWh/m^3
Heating Consumption per Energy Carrier/ Occupancy	95.76	kWh/ occupants
Heating Consumption per Energy Carrier/ Occupancy-hours	11.98	kWh/ h*occupant
Heating Consumption per Energy Carrier/Area	7.31	kWh/m^2
Heating Consumption per Energy Carrier/Volume	2.41	kWh/m^3
Cooling Consumption per Energy Carrier/ Occupancy	234.57	kWh/ occupants
Cooling Consumption per Energy Carrier/ Occupancy-hours	29.32	kWh/ h*occupant
Cooling Consumption per Energy Carrier/Area	17.91	kWh/m^2
Cooling Consumption per Energy Carrier/Volume	5.93	kWh/m^3
Lighting/Occupancy (1st and 2nd floor)	184.57	kWh/occupant
Lighting/Occupancy Hours (1st and 2nd floor)	23.07	kWh/ h*occupant
Lighting/Area (1st and 2nd floor)	14.22	kWh/m^2
Lighting/Volume (1st and 2nd floor)	4.76	kWh/m^3
Electrical Appliances Energy Consumption/ Occupancy (1st and 2nd floor)	249.10	kWh/occupant
Electrical Appliances Energy Consumption/ Occupancy Hours (1st and 2nd floor)	31.16	kWh/ h*occupant
Electrical Appliances Energy Consumption/Area (1st and 2nd floor)	19.18	kWh/m^2
Electrical Appliances Energy Consumption/ Volume (1st and 2nd floor)	6.43	kWh/m^3
Ground floor Power/Occupancy (October 2021 – May 2022)	928.76	kWh/occupant
Ground floor Power/Occupancy Hours (October 2021 – May 2022)	116.09	kWh/ h*occupant
Ground floor Power/Area (October 2021 – May 2022)	69.60	kWh/m^2
Ground floor Power/Volume (October 2021 – May 2022)	22.42	kWh/m^3

The case study presented in this research demonstrates that data integration solutions can still be achieved even when monitoring equipment is not compatible with the iTwin platform. This methodology supplements the BIM model with data from installed sensing equipment, which is not compatible with the iTwin platform. This solution could serve as a stepping stone in the digitalization of operational assessment procedures. The monitoring feature of the digital twin enables assessors or building operators to analyse spatially distributed measured values and computed operational indicators, providing a data-driven understanding of the building's temporal behavior. The scale of examination depends on the distribution and amount of sensing equipment installed in the building. Figs. 5-7 illustrate this monitoring feature.

One of the weak points of the proposed approach is the lack of required equipment in most buildings for documenting their performance. Retrofitting existing buildings with sensors and monitoring equipment can be costly, time-consuming, and disruptive. Additionally, some buildings may not have the necessary infrastructure to support the installation of sensors and other monitoring equipment. This can limit the applicability of the proposed approach in some cases. In such scenarios, building operators can consider utilizing manual data collection techniques or investing in retrofits to allow for easier implementation of monitoring solutions.

Another weak point of the proposed approach is the lack of the required digital environment in BIM documents for implementing the assessment. BIM software is becoming increasingly popular in building design and construction, but not all BIM documents are created equal. Some older BIM documents may not include the necessary data fields or parameters required to support the monitoring and analysis of a building's performance. This can limit the effectiveness of the proposed approach, as it relies on accurate and comprehensive data being available within the BIM model. Building operators may need to invest in updating their BIM documents or work with BIM experts to ensure that the necessary data is included for operational assessment procedures to be successful.

In this study, it was attempted to quantify the impact of occupant behaviour on building energy consumption by including occupancy schedules and building usage profiles in our simulations. However, it is recognized that there are limitations to this approach and that there is still a performance gap to quantify this set of indicators. To address this issue, we plan to conduct further research into occupant behaviour and its impact on building energy consumption. Specifically, we aim to investigate how occupant behaviour changes over time and how this affects building energy performance. We also plan to explore the use of smart building technologies, such as occupancy sensors, face recognition techniques and building automation systems, to better understand and manage occupant behaviour.

5. Conclusions and future work

This study demonstrated the application of digital twin principles for the operational energy assessment of buildings, highlighting the significance of adapting the energy assessment of buildings to state-of-the-art practices for digital assessment, such as smart sensors, real-time measurements, IoT, and digital twins. The developed tool, based on real-time monitoring, introduced an enhanced set of indicators for the operational assessment of the energy performance of buildings. These indicators cover not only the total energy consumption of the building but also sectoral consumptions of different energy types, which are adapted to the occupancy, the time, and the volume of the buildings. The findings of this study reveal the importance of integrating Industry 4.0 practices into the operational energy assessment of buildings, indicating that the future of the energy assessment of buildings will include the use of smart sensors. Moreover, the asset information of the building used in this study is BIM based, emphasizing the importance of BIM in this field. The gap between the energy performance observed in asset versus operational rating of buildings, documented in numerous occasions in the scientific literature as well as in everyday practice, motivates studies of this kind. This study emphasizes the concept of conducting buildings' operational energy rating remotely, with the use of smart sensors. The installation of smart meters in all buildings of the EU member states by 2030 underlines the particular significance of this study. The principles developed and tested in this study were employed in a case study building, where the significance of the advanced set of indicators was demonstrated on real-time conditions, with the use of 12 months measurements. The results of this study are expected to lay the path for the future of the operational rating of buildings, highlighting the significance of digital twins for the energy assessment of buildings, and the need for further research in this field. In conclusion, this study underscores the importance of adapting the energy assessment of buildings to state-of-the-art practices for digital assessment, such as smart sensors and digital twins, and demonstrates the potential benefits of such practices. Overall, acknowledging the importance of occupant behaviour in building energy performance is critical, and we will further explore this topic in our future work. The findings of this study are expected to have a significant impact on the future of the energy assessment of buildings and pave the way for further research in this field.

CRediT authorship contribution statement

Paulius Spudys: Investigation. **Nicholas Afxentiou:** Visualization. **Phoebe-Zoe Georgali:** Formal analysis, Project administration. **Egle Klumbyte:** Resources, Validation. **Andrius Jurelionis:** Methodology. **Paris Fokaides:** Conceptualization, Resources, Supervision.

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.

Data availability

Data will be made available on request.

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