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Optimizing office building operations: a framework for continuous dynamic energy simulations in decision-making for efficiency

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Digital twins represent a promising approach for sustainable building operations and management in the context of the carbon neutrality goals of the European Union (EU). Using OpenStudio, an opensource platform for building energy modeling, we demonstrated the creation and editing of building digital twins. OpenStudio provides a user-friendly interface and extensive simulation capabilities, allowing detailed and accurate modeling of building components and systems. Using OpenStudio Measures, users can automate tasks and customize simulation models to optimize the building performance. The process of creating a building digital twin involves collecting historical data and accurately representing the building geometry; materials; schedules; and heating, ventilation, and air conditioning (HVAC) systems. Challenges such as data availability and model accuracy highlight the importance of modeling practices. Editing the digital twin involves modifying the OpenStudio model files and EnergyPlus weather files to simulate different building operation scenarios. Python programming language opportunities were considered for digital twin file modification. The potential of digital twins lies in their ability to simulate future building conditions and optimize building system settings. By integrating digital twins with machine learning algorithms and connecting them directly to building management systems, optimal building control strategies can be automated, thereby reducing energy consumption and improving occupant comfort levels.

KEYWORDS

office building, air exchange, energy simulations, retrofitting, occupancy profile, OpenStudio, HVAC

1 Introduction

As part of the European Green Deal's objective to achieve carbon neutrality by 2050, every sector is required to significantly decrease energy consumption (European Commission, 2019). In the European Union (EU), buildings consume 40% of the total primary energy consumption and generate 36% of greenhouse gas emissions, mainly from construction, use/operation, renovation and demolition (European Commission, 2024). Indeed, the operation of buildings constitutes 30% of global final energy consumption and 27% of greenhouse gas emissions (Buildings, 2024). To diminish energy demand within this sector, building designers have various solutions at their disposal. These include implementing energy-saving technologies to enhance the thermal performance of the building envelopes (Berardi and Naldi, 2017; Huang et al., 2021), optimizing heating, ventilation, and air conditioning (HVAC) equipment efficiency (Conceição et al., 2021; Zhou et al., 2023), and integration renewable energy sources (RES) (Christopher et al., 2023; Lebedeva et al., 2023). Recently, the significance of building automation and control systems (BACS) in decreasing the energy demand of buildings has been increasingly acknowledged (Vandenbogaerde et al., 2023). Consequently, the Energy Performance of Buildings Directive (EPBD), updated in 2018, incorporates regulations on the installation of building automation and control systems as well as on devices responsible for temperature regulation at the room level (European Commission, 2021). The anticipated impact of BACS measures is projected as annual final energy savings of 450 TWh by 2035, as outlined in the EPBD (Waide, 2019).

The majority of buildings in the EU (85%), were constructed prior to 2000, and within this category, 75% exhibited subpar energy performance (European Commission, 2021). Efficient energy management in buildings is crucial for sustainable development. Although the optimization of energy system management has been extensively discussed in the literature (Mariano-Hernández et al., 2021; Çakmak, 2024; Yu et al., 2024; Yelisetti et al., 2022), its practical application remains limited. This underscores the necessity for the full integration of intelligent control into a comprehensive system. To address the limitations of conventional methods, building information modelling (BIM) systems have been increasingly utilized to offer perspective on the modeled assets or systems (Bin Yang and Chou, 2019). BIM is a procedure that entails generating a digital representation of a building or structure for the purposes of planning, designing, constructing, and maintaining it. Nevertheless, BIM faces challenges in handling the life-cycle procurement processes of a building and lacks virtual interactions with actual assets. Consequently, BIM falls short in delivering real-time feedback on asset performance or operational decisions. Typically, for infrastructure inspections, defect identification, and the formulation of maintenance strategies, a universal data model capable of eradicating inconsistencies and inefficiencies does not exist (Zheng et al., 2023). Additionally, decisions regarding infrastructure maintenance must be grounded in a growing volume of collected data, a task beyond the capabilities of current practices. In this context, a digital twin (DT) is a valuable tool for assessing loads and understanding the electrical and thermal behavior of a building (Lu et al., 2020). A DT serves as a virtual representation of a physical object or system, along with the data network connecting them (Qiuchen et al., 2019). It facilitates the management of the entire life cycle of the represented object. In recent years, DTs have proven effective in evaluating decarbonization strategies for buildings, cities, and other sources of carbon emissions (Arsiwala et al., 2023; Arowoiya et al., 2023; Seo and Yun, 2022; Francisco et al., 2020).

In various applications, DTs are utilized during the operational phase of a building, encompassing areas such as facilities and maintenance management, monitoring, and energy simulation (Long et al., 2024). To this end, a DT can include building performance modeling programs (BPMP) to analyze and predict energy consumption, thermal comfort, indoor air quality and other aspects of building operation. These programs help create energy-efficient, sustainable, and comfortable buildings by modelling the complex interactions between building components, systems, occupants, and the surrounding environment.

BPMP typically consider factors such as the following:

- Building geometry and orientation
- Building envelope materials and insulation
- Window and door properties
- HVAC systems
- Lighting systems and controls
- Occupant behaviour and schedules
- Weather and climate data.

1.1 OpenStudio as BPMP

For conducting BPMP analysis, based on simulation experience and studies by other researchers (Wang et al., 2024; Deng et al., 2023; Chen et al., 2023), OpenStudio (OpenStudio, 2024) was used in this study. OpenStudio is an open-source software platform designed to facilitate the energy modeling and analysis of building designs. It was developed by the National Renewable Energy Laboratory (NREL); it is based on EnergyPlus (EnergyPlus, 2024) simulation engine. It offers a comprehensive set of tools that enable to evaluate the energy performance and efficiency of buildings at various stages of the design process. Comparing with EnergyPlus, the program has user-friendly interface and robust simulation capabilities. OpenStudio allows users to create detailed models of building geometry, HVAC systems, lighting, internal loads, and other components, and then simulate their energy usage, thermal comfort, and daylighting characteristics.

OpenStudio is divided into two main parts: the OpenStudio Aplication and OpenStudio OpenStudio Software Development Kit (SDK) with Command Line Interface (CLI). The OpenStudio Aplication is simulation program with a graphical and user-friendly interface. OpenStudio SDK with CLI used to create add-ons for OpenStudio and for complex energy simulations.

The BPMP software plays a crucial role in supporting sustainable building design practices by providing energy consumption patterns, identifying opportunities for optimization, and aiding in the selection of cost-effective energy efficiency measures (Danial et al., 2023; Alzara et al., 2023; Diakaki et al., 2013).

Building modelling in Openstudio is similar to other BPMP programs: the users creates a building geometry and then enters building descriptions and HVAC system parameters. However, building geometry must be performed in third-person programs, such as FloorSpace.Js (open-source program), SketchUp (under Trimble license). The geometry can also be imported as gbXML file. Unlike EnergyPlus, OpenStudio allows to add add-on–OpenStudio Measures.

An OpenStudio Measure is a part of the code written in Ruby programming language that automates specific tasks or modifications within an OpenStudio energy model. Measures can be used to adjust model inputs, create, or modify building

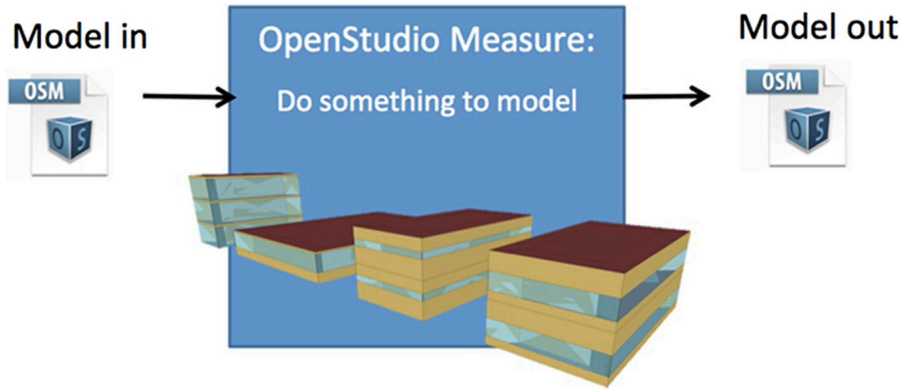


FIGURE 1
OpenStudio Measure simplified working scheme (https://nrel.github.io/OpenStudio-user-documentation/getting_started/about_measures/).

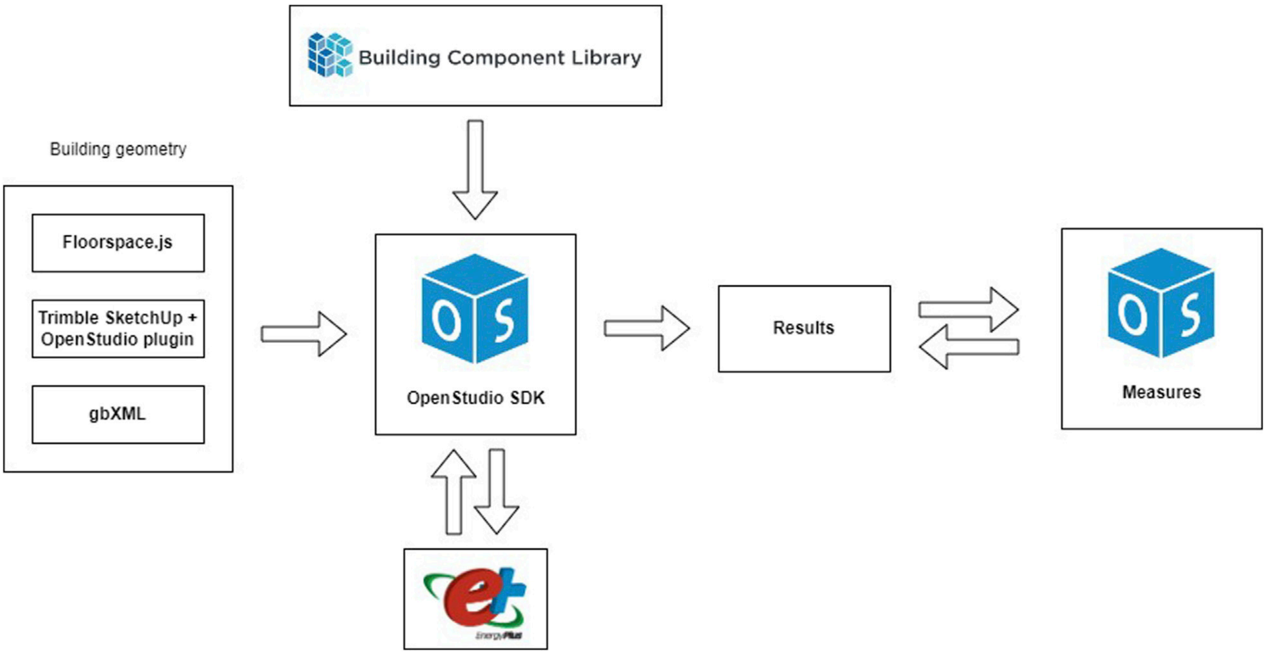


FIGURE 2
Workflow scheme of OpenStudio with additions (Source: own).

components, run simulations, or analyse and report on simulation results. A simplified scheme of programs work is shown below in Figure 1.

OpenStudio Measures can be categorized into three types:

- Model Measures: These measures modify the building geometry, constructions, HVAC systems, and other components directly within the OpenStudio Model.
- EnergyPlus Measures: These measures modify the input data or Input Data File (IDF) for an EnergyPlus simulation generated from the OpenStudio Model.
- Reporting Measures: These measures analyse the simulation results, typically stored in SQL format, and generate reports, visualizations, or other outputs to help users understand and evaluate the performance of their building designs.
- OpenStudio Measures can be created by users, shared within the community, or ac-cessed from the Building Component Library (BCL) that hosts a large collection of prebuilt measures. By utilizing OpenStudio Measures, users can improve the consistency and quality of their models, and easily test various design alternatives to optimize building performance.

OpenStudio Measures can be imported into building simulation model BCL or through OpenStudio Aplication.

Complete workflow scheme of OpenStudio building model creation is shown in Figure 2.

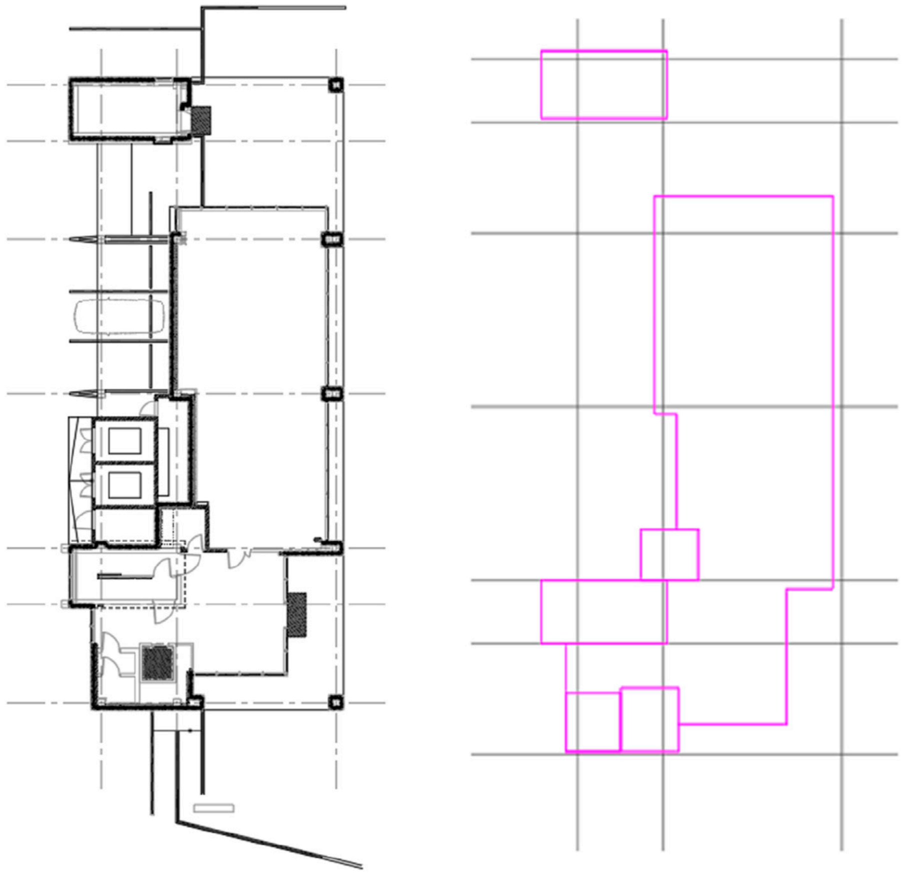


FIGURE 3
Pilot building floor plan: actual (on left side) and used in BPMP (on right side) (Source: own).

2 Materials and methods

2.1 Creating a building digital twin in an OpenStudio environment

To create a DT, the general definition of a DT widely accepted in the research community, given by (Angjeliu et al., 2020; Glaessgen and Stargel, 2012), was applied. DT creation process begins with collecting existing data of building. They must represent all aspects of the building and the processes that occurs therein. Historical data on occupancy and everyday load also must also be collected and used in creating DT. The data can be separated into three groups: building parameters, building schedules, and building loads.

To create a building geometry and its thermal envelope, actual floor plans and building materials must be obtained. OpenStudio, similar to other building performance modelling programs, does not show the actual wall thickness. Therefore, the drawing of the floor plans must be simplified. The boundaries of the internal walls should be in the middle of the actual walls in the plans. The external walls should be on the outer edges of the actual external walls. During the floor plan simplification process, technical shafts in the building can be eliminated, and certain identical rooms can be combined. Figure 3 shows the pilot building floor plan: actual and used in the BPMP.

Building geometry can be craeted in three different ways: exporting geometry from third-person programs as Green Building XML (gbXML) file, creating geometry in SketchUp using the OpenStudio plug-in, or creating geometry in FloorPlan.js (that is integrated in the OpenStudio Application). The simplest and most user-friendly method is SketchUp because of its build-in functions and the ability to edit and supplement the.osm file in subsequent steps.

Schedules play an important role in creating an accurate DT. Schedules can be separated into two groups: schedules connected to occupant and their behaviours, and technical schedules. Schedules connected to occupant and their behaviours will show room occupancy during day and all kinds of process related to occupant, for example, turning on certain devices which can cause significant changes in energy use or indoor environment. Technical schedules describe building system (lightning, HVAC, and water supply system) work. They must represent the equipment parameters that change throughout the day. The main parameters are thermostat setting, lightning, and ventilation schedules. To obtain the most accurate result, schedules for each room in the building must be created.

For thermal envelope creation, construction elements must be created. Each element consists of materials of exact thickness. As mentioned, the construction element thickness will not affect on the

FIGURE 4
The office building complex of the case study (Source: own).

room area but will be used for the thermal transmittance calculation of element.

The building performance model requires entering an internal load such as the emitted heat and consumed energy. Each building equipment consumes energy, and certain energy is converted into heat. In real situation, a large number of these devices can cause room overheating and stress in air conditioning system. Therefore, the actiual building load must be completely repeated in a DT. Electronic devices are not the only internal source of heat influx; occupants also release heat and CO_2. All of these parameters must be entered as loads into OpenStudio model.

The HVAC and water supply equipment must also be added to the DT model. Their integration occurs in three steps. First, HVAC internal equipment, such as ventilation diffusers or heating radiators, must be added to each room. Subsequently, an air handling unit (AHU) or hot water system principial scheme must be created. The scheme consists of elements, each of which has a large number of parameters for maximum representation of the real system. Finally, the building systems schemes must be connected to internal elements in each room. These aspects highlight the importance of collecting existing building data for future DT creation.

The DT challenge discussed herein revolves around the energy efficiency of the office building complex (Figure 4). The pilot building is located in the Riga, Latvia.

It consists of three buildings, and it is an L-shape complex. The complex includes offices and restaurants. The buildings are mainly four-story buildings with underground parking spaces. All buildings have glass facades. In the case study, only one building was considered (the building on the left in Figure 4). It is a four-story building with offices on 1-4 floors and underground parking spaces. The total number of office workers is approximately 20. The total area of the building is 1,806 m^2. The offices and discussion rooms occupy an area of 1,378 m^2. The remining area is distributed between the remaining rooms: staircases and elevators, 117 m^2; auxiliary rooms, 47 m^2; corridors and vestibules, 196 m^2; restrooms, 53 m^2.

The foundation and ceilings of buildings consist of reinforced concrete, walls consist of glass walls and reinforced concrete, and roof consist of flexible sheet materials. The electricity consumption of the building is 327 kWh/m^2 per year; however, the gas consumption during the heating season is 134 kWh/m^2 per year.

The ventilation in the building is provided by two modular AHUs. The ventilation system is separated into two isolated systems: PN1 and PN2. System PN1 ventilates the offices and discussion rooms with a total airflow of 7,130 m^3/h. System PN2 ventilates all the other rooms, and total airflow is 1,595 m^3/h. The elevator and staircases are natural ventilated at a flow of 170 m^3/h.

The air conditioning in the building is provided by five conditioning systems. The CH-1 system provides air conditioning in offices using a cassette fan coil. The outdoor unit of this system is an air-cooled chiller. The SS1 system provides air conditioning in the discussions rooms using cassette fan coils. The outdoor unit of this systems is three-phase heat pump. Systems SS2 un SS4 are used for server room cooling. These systems are used for cooling, and use a heat pump split system as the outdoor unit.

Heating in a building is provides by radiators installed in many rooms. The heat source of the system is gas boiler.

An OpenStudio model was created for the referenced building. A model image with shading surfaces (adjacent parts of the office complex) is shown in Figure 5.

In the pilot building, the DT recreational floor plans and common geometry of building were simplified. Offices and discussions rooms were also merged. The HVAC system was also simplified; the air condition systems CH-1, SS-2 and SS-4 were removed, and their role is performed by PN1 and PN2 system. During process also encountered with the lack of precise information about systems. A description of the PN1 and PN2 AHU systems was provided, but without information on the air exchange in the rooms, working schedules, and thermostat settings. Descriptions of the heating system were also missing. This is because the twin HVAC system does not represent the actual HVAC system. Following the simulation, energy consumption of the building is 296.99 kWh/m^2 annually. However, a framework functionality check does not require creating a highly accurate building energy model.

2.2 Editing a building digital twin created in an OpenStudio and EnergyPlus environment

All information regarding the building model was collected into.osm file that can be considered as text file. The.osm file contains detailed information about the building geometry,

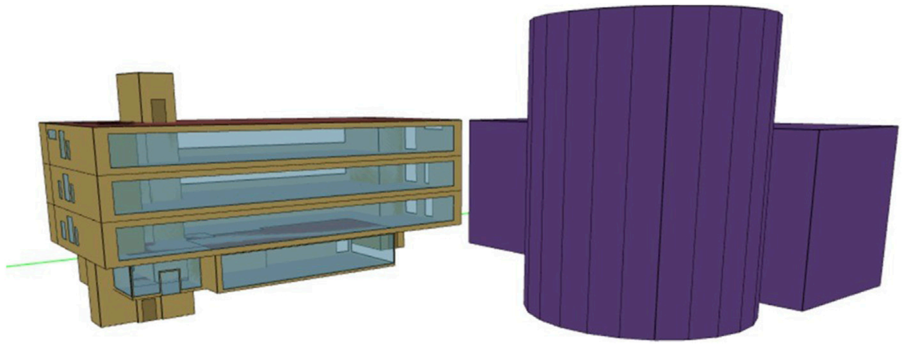
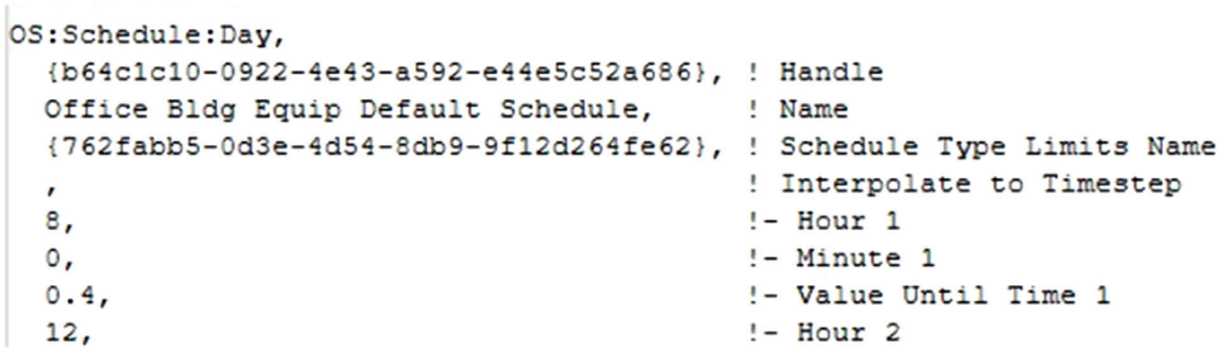


FIGURE 5
The pilot building model (Source: own).



```
OS:Schedule:Day,
  {b64c1c10-0922-4e43-a592-e44e5c52a686}, ! Handle
  Office Bldg Equip Default Schedule,      ! Name
  {762fabb5-0d3e-4d54-8db9-9f12d264fe62}, ! Schedule Type Limits Name
  ,                                        ! Interpolate to Timestep
  8,                                       !- Hour 1
  0,                                       !- Minute 1
  0.4,                                     !- Value Until Time 1
  12,                                      !- Hour 2
```

FIGURE 6
osm file schedule block structure.

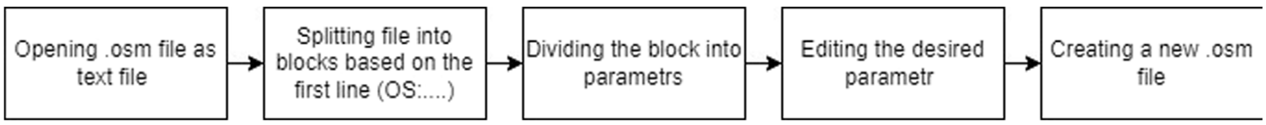


FIGURE 7
osm file editing process (Source: own).

construction materials, internal loads (such as lighting, equipment, and occupants), HVAC systems, schedules, and other parameters necessary for building energy simulation and analysis. The.osm file structure consists of the blocks that describe each parameter of the building energy model–from the building geometry to the simulation setting. Each block has similar structure: each block starts with OS: “Block type”; it has a unique generated Handle and is created by user’s unique Name of the block. The.osm file schedule block structure is illustrated in Figure 6. Almost all moder programming languages can open any file as text file for analysis and editing purposes. The.osm file editing process is illustrated in Figure 7. The Python programming language was used during the pilot project. The.osm file was opened with built-in functionality. The blocks were separated and grouped according to the type. Then, blocks with identical types were grouped according to their unique name. To simplify the work with blocks, nested dictionaries were created. After editing, a new.osm file was created by extracting the data from the dictionaries. OpenStudio simulation can also be launched using Python software. The subprocess Python library was used to run the OpenStudio SDK using command prompt. New simulation result were obtained and analyzed.

The EnergyPlus weather file (.epw), that is used in building energy simulations, can be modified using programming languages. The file structure represents the basic information about climate file as rows and climate data as tables. In pilot project, corrections to outdoor air temperature were performed using Python. The.epw file was converted into data frame, and certain values were changed. After all changes, the.epw file was assembled again.

The results of the OpenStudio simulation are typcally stored in user-friendly tabular formats, such as EnergyPlus.htm report.

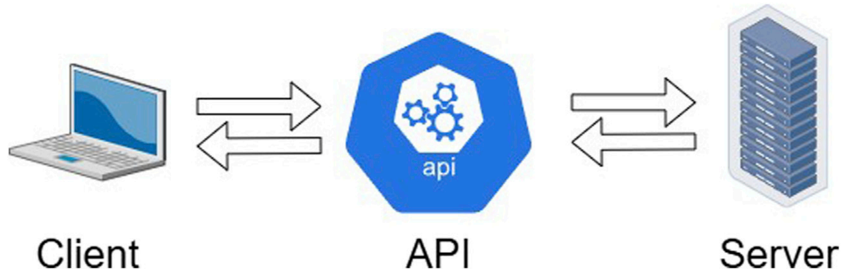


FIGURE 8
API workflow (Source: own).

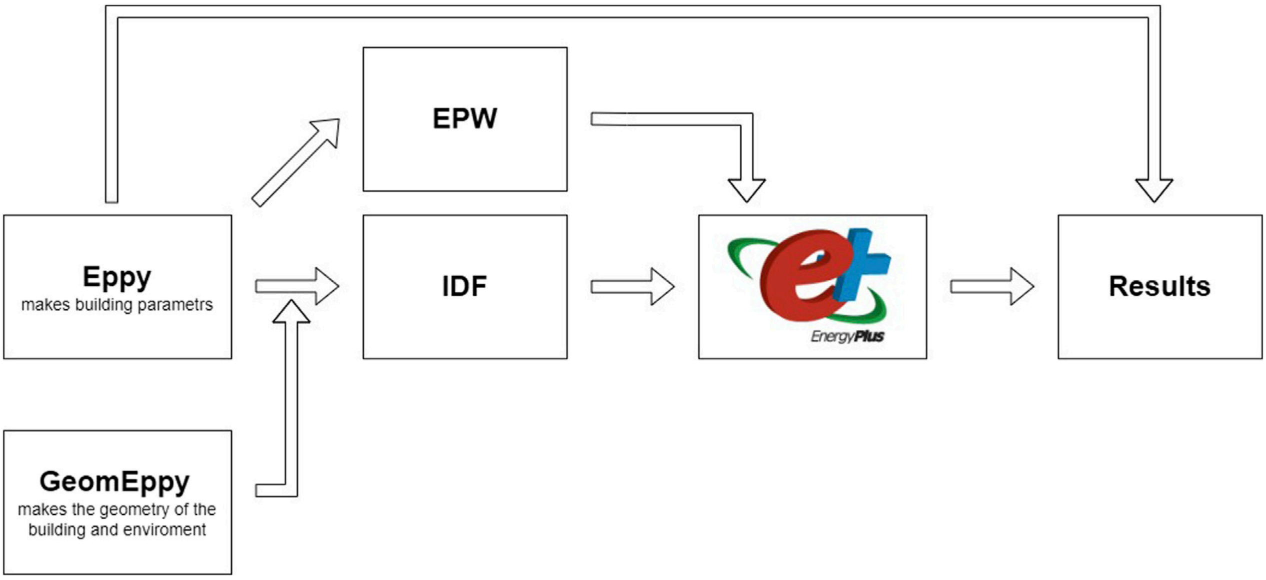


FIGURE 9
Workflow scheme of EnergyPlus with additions (Source: own).

However, hourly matter can be easily obtained as.csv file when using Openstudio Measures. The.csv file can be used for analysis by opening and converting it into a data frame. During the pilot projects, the result was exported from.htm files; hovever, .csv files were also used for several analysis.

Another approach for building simulation model editing that can be used for building energy simulations is to convert an OpenStudio.osm file into an EnergyPlus file format.idf. The EnergyPlus file has a structure similar tothat of the OpenStudio file, and similar to OpenStudio, it can be easily modified using different programming languages. However, EnergyPlus has its Application Programming Interface (API). BPMP with API support allows easier integration with other software tools, automation of workflows, and customization of analysis processes. APIs enable developers and users to programmatically access and interact with the core functionalities of these simulation programs, allowing them to create custom applications or integrate simulation capabilities into existing external software (Figure 8).

The EnergyPlus API, which is passed on C and Python programming languages, enables developers to programmatically interact with EnergyPlus, allowing for the automation of simulation tasks, integration with other software tools, and customization of analyses.

Despite this, certain Python libraries were created for EnergyPlus simulation prepearing and launching. Eppy Python library is used for building model creation and simulation launches, whereas the GeomEppy library is used for building geometry creation. The simulation workflow using the Eppy and GeomEppy library is shown in Figure 9.

3 Results

DTs, which are virtual representations of the physical structures and systems of a building, offer real time information on the energy performance of the building and aid in decarbonization strategies. They are particularly useful for building management and energy simulations. DTs coupled with BPMP offer extensive analyses of building energy consumption, thermal comfort, and indoor air quality.

TABLE 1 Simulation results.

	Turn on	Turn off	CO_2 avg, ppm	CO_2 max, ppm	Energy consumption, kWh	Energy savings, kWh
Pilot building	7:00	21:00	523	873	2,300	
Pilot building	8:00	18:00	631	985	1898	401.3
Pilot building	9:00	16:00	1,253	2,704	1,405	894.8
EN16798	6:00	18:00	547	737	2,904	
EN16798	7:00	17:00	742	982	2,453	451
EN16798	8:00	16:00	1,105	1940	1999	904.3

In this study, OpenStudio was selected as the BPMP owing to its simulation capabilities and user-friendly interfaces. OpenStudio enabled detailed building modeling and energy simulations under various scenarios. Its flexibility allowed the creation of custom simulations using OpenStudio Measures that automated tasks and modified energy models.

The creation of a building DT in an OpenStudio environment involves collecting historical building data and creating accurate representations of buildings geometry, materials, schedules, loads, HVAC and other building systems. Data availability and model accuracy are challenges that highlighted the need for data collection and thoughtful modelling.

Editing a building DT involved modifying the OpenStudio model file (.osm) and EnergyPlus weather files (.epw) to accurately represent building parameters and simulate different building operation scenarios. Python programming was used to automate tasks and optimize the editing process.

The pilot building model was created in the OpenStudio environment (Figure 5), based on the historical data of building energy consumption, as well as HVAC load schedules, the number of employees, the metabolic rate, air flow, etc. and building geometries and materials. Simulations were conducted to compare the energy consumption and CO_2 levels in office rooms under the guidelines of EN 16798 (LVS, 2019) and the pilot building air handling unit (AHU) working schedules. Each schedule was adjusted by modifying the start and end times of operation. The findings are presented in Table 1. Energy consumption data was obtained for 6-months period.

Based on the findings, decreasing the air handling unit's operating time by 1 hour (according to the EN 16798 schedule) proves effective in energy consumption decrease, potentially saving 451 kWh. Moreover, the maximum CO_2 level stays within ASHRAE's (Persily et al., 2022) recommended limit. However, further reducing the operating time by 2 hours in the EN 16798 schedule leads to elevated CO_2 levels in the morning, potentially compromising occupants' comfort. Thus, this level of reduction is not advisable. Similarly, adjusting the operating time by 1 hour in the morning and 3 hours in the evening for the studied building air handling unit schedules yields comparable outcomes. This adjustment maintains occupant comfort while still offering the potential energy savings. Conversely, cutting AHU working hours by 2 hours both in the morning and evening results in suboptimal working conditions.

The results show that by optimizing only the operation of the AHU, it is possible to easily achieve energy savings, maintaining a balance between occupant comfort and efficient energy consumption.

However, a common problem is in building operations, in which traditional and sometimes ineffective methods attempt to adapt to changing conditions. The prospects of using a building DT include future scenario simulation and building system settings optimization. By integrating DTs with machine learning algorithms and with a direct connection to a building management system (BMS), optimal building control strategies can be automated, reducing energy consumption and occupancy and improving comfort level.

4 Discussion

For building operator, the building must be managed as efficiently as possible. For this purpose, a system of sensors and automation is used. Often, these systems are well suited for ideal conditions in which nothing changes. However, in real life, building operator face challenges owing to changes in the life of buildings. The systems that are currently available are either unable or not fully able to assist in building management.

During building operations, only a few building parameters can be changed from those available to operator facilities. Typically, they are HVAC and other building system settings that are controlled using BMS. The operator decides to change the system parameters based on data from indoor sensors or historical data and events. However, in most cases, this corresponds to the use of regular premade schedules in everyday life. In certain cases, this will cause an uncomfortable environment when abnormally large occupancy and excess environment quality occurs when occupancy is insufficient. Weather conditions can also affect the indoor environment. Consequently, traditional operating methods cannot handle the calculation of optimal system settings because of the large number of independent parameters.

DT may be the key to creating an optimal building system setting. If a fairly accurate clone of a building is created, it can serve as a test field for the building system settings. The geometry and components of a building system must remain constant. Accordingly, as in current buildings, building system settings can be changed. However, DT also allow the simulation of future indoor and outdoor conditions. The internal loads and occupancy can be adjusted according to future events. The weather conditions for the following day can be obtained from weather news reports. Consequently, BPMP allow the simulation of the future conditions of a building and predict its consumption under certain building system settings.

The building operator can use DT to select the optimal building control strategies for the next two to 3 days. However, this is an ineffective building management because of the number of possible setting combinations available for the operator's working time. However, DT is a BPMP model that can work in conjunction with other software. This opens opportunities to automate the search process for optimal building system settings for future indoor and outdoor conditions. In this case, complex algorithms and machine learning can be used. In the absence of human intervention, the optimal system parameters can be calculated and immediately applied to a new building operation framework using direct BMS connections. Three components must be included in the framework: DT, indoor occupancy and special loads, and future weather conditions. For this framework, one final accurate DT must be created. All systems and features of a real building must be completely copied. In future, planned occupancy and special internal loads should be provided. Owing to specific loads, atypical equipment can cause changes in indoor environments. For example, additional lighting can result in an additional heat gain. Weather forecasts can be obtained using an API on a weather website.

In conclusion, DT can be a component of a next-generation building operation framework. It can predict the future building conditions and prepare building systems in advance. More detailed building simulations can reduce building energy consumption and increase the level of comfort. Simultaneously, this reduces the load on the building operator.

The main limitation of this study is the availability of real data and the provision of accurate representation of building components and systems, as this is very important for reliable simulation results. Further exploration of strategies for handling data limitations and improving model accuracy would increase the comprehensiveness of the study.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AB: Formal Analysis, Methodology, Project administration, Writing–review and editing. AP: Conceptualization, Investigation, Validation, Writing–original draft. AK: Conceptualization, Funding acquisition, Supervision, Writing–review and editing. KL: Conceptualization, Resources, Visualization, Writing–review and editing.

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Conflict of interest

Author AK was employed by Lafivents Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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