Budownictwo i Architektura 24(1) 2025, 5-24

DOI: 10.35784/bud-arch.6039
Received: 25.03.2024; Revised: 04.12.2024;
Accepted: 09.12.2024; Available online: 31.03.2025

Orginal Article

Building performance analysis of a digital twin based on paper documentation

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Abstract: This document presents the analysis and optimisation of a digital twin created from paper documentation. It explores the potential applications of the model at various stages of a building's lifecycle and the challenges associated with relying solely on paper documentation. The modelling process is more demanding in such cases; however, it allows for the assessment of beneficial and feasible modifications to reduce energy consumption. To achieve this, a model was developed in Autodesk Revit, and an analysis was conducted using Autodesk Insight in three versions: a design based on the paper documentation, a model reflecting the actual state of the building, and an optimised version derived from the results of the first two models.

Keywords: Building Information Modelling, digital twin, energy performance

1. Introduction

The aim of this study is to verify the feasibility of creating a digital twin model based on paper design, as well as to analyse energy parameters extracted from the model developed in Revit and actual energy consumption. Technology must keep pace with the increasing complexity of building projects, as they become more extensive in architectural, construction, and energy-related aspects [1]. Collaboration among project teams has become even more critical than before to prevent conflicts and optimise buildings as much as possible to meet key requirements, whether related to architectural vision, permissible loads, cost estimates, or thermal properties [2].

Building Information Modelling (BIM) addresses this need for collaboration by allowing users to make changes to the same model, manage it, and oversee its environment. It is a tool that enhances work quality across multiple disciplines and continues to evolve rapidly. With BIM, the graphical representation of a project becomes multidimensional, enabling experts from various fields to integrate their knowledge into a cohesive element [3]. Based on the results of analyses that consider the building as a whole, there is an opportunity to improve designs and correct errors at the earliest stages of the design process [1,4]. By running simulations on the model, designers can accurately assess which solutions have the most significant impact on the building, ensuring greater alignment with real-world scenarios [5].

The use of a BIM model at different stages of the process accelerates the completion of documentation and work on the construction site (Fig. 1). It also reduces the cost of changes that may arise in later stages due to errors or conceptual modifications [5,6]. The assumptions made during the initial design stage shape the final product, the costs involved, and the impact the building will have on its surroundings. As a project develops, knowledge about it increases, but so does the cost of making changes, even those that could potentially minimise the building's future operating costs [7]. The BIM model serves as an integrated database that consolidates architectural and construction knowledge. It automates quantity calculations, improves the accuracy and efficiency of cost estimation, and enhances overall productivity. Most professional engineers, contractors, and architects recognise that structural analysis software saves time. BIM enables recalculations to be checked efficiently, while complex tasks such as load assessments and deflection limits are generated automatically, allowing more time for other design tasks [8,9].

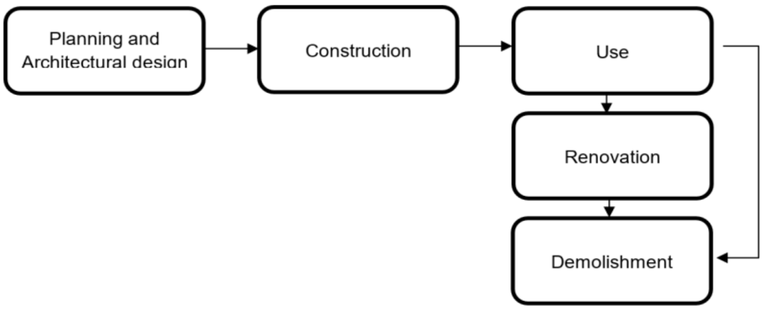

Fig. 1. Life cycle of the building

The stages of building completion overlap, meaning each phase influences the next. The main advantage across all stages of the process is the ease of implementing changes.

BIM technology saves time in creating technical drawings. Accurate data entry enables the automatic generation of drawings and lists. Reducing the time required to prepare technical documentation can allow for an extended design phase, which is crucial for optimising building performance and minimising operating costs.

In Poland, an architect's responsibilities throughout the construction process extend beyond the planning and drawing phase to include inter-disciplinary coordination.

Architectural offices, particularly those working on smaller-scale projects that use BIM technology for technical documentation, often export 2D technical drawings in .dwg format and share them with other project team members from different disciplines. Each discipline then applies its data to the drawings, also in 2D. The architects receive this data and manually enter it into their software. This process is significantly less efficient than having the entire interdisciplinary team work on the same files, inputting data directly into the BIM model.

In Poland, there is no large-scale, reliable survey on the use of BIM technology in architectural studios.

In a survey commissioned by the Ministry of Economic Development and Technology in 2021, only 268 people participated. According to the results, 81 respondents reported using BIM technology in their work, with 39.5% utilising it for collaborative BIM and only 9.9% applying it to the building lifecycle. Just over half of those using BIM technology exchange data with other disciplines in the form of 2D drawings, while 8.6% use BIM software solely for visualisation [10].

The costs of the software itself, along with the necessary staff training, are high, making the implementation of BIM technology from scratch for small-scale projects potentially uneconomical. However, for studios that already possess BIM-enabled software, leveraging its full potential can significantly reduce the time and, consequently, the cost of preparing technical documentation. Additionally, the availability of dedicated plug-ins allows for the efficient preparation of energy and solar analyses, optimising the design for operational cost reductions without requiring additional software.

For complex, large-scale projects, the benefits of BIM technology are even more pronounced. The risk of errors due to the absence of a 3D model that integrates elements designed by various disciplines is significantly high. In such cases, inter-disciplinary coordination can be managed by a BIM manager or an architect qualified to oversee the BIM model and data input throughout all project stages.

A major advantage of using BIM in the next phase, during building design, is collision detection. For buildings with complex and unconventional structures, BIM allows for the identification of overlapping or intersecting elements directly within the model, eliminating the need to infer such issues from 2D drawings (Fig. 1).

Without a model, potential design and construction issues may only become apparent during project execution. However, a created model can also be utilised during the operational phase of the building, particularly for the implementation of systems such as automated lighting or security systems, as seen in intelligent buildings. If a model or digital twin is created for a building that previously lacked one, future renovations can be significantly simplified [11,12]. Most analyses and solutions can be tested virtually without interfering with the physical structure. The final phase of a building's life cycle is demolition. Since all parameters related to materials and construction are known within the model, this data can be used to recover and reuse as many materials as possible [13]. By involving teams responsible for all project stages, a comprehensive life cycle model of the building can be created. The process does not end after the facility is constructed; a complete building model can be used to manage its systems or to simulate optimal solutions for residents, the environment, and the building itself, including potential renovations. Through simulations and virtual analysis, the most economical and ecological solutions can be adapted for each design phase [14]. Fire evacuation simulations, daylighting simulations, safety analyses, and energy performance assessments can be integrated into applications and used for ongoing building management [13,15].

Given that the Architecture, Engineering, Construction, and Operations sectors contribute significantly to pollution, BIM serves as a valuable tool for monitoring and reducing CO_2 emissions at each stage of the building's life cycle [16,17]. According to information from the European Parliament's website, buildings account for 36% of greenhouse gas emissions—more than a third of the total. New legislation aims to enforce emission reductions in the construction sector, with two key milestones: a significant reduction in gas emissions and energy consumption by 2030 and the achievement of climate neutrality by 2050 [13]. Tools that estimate energy consumption and emissions align with BIM technology by integrating models for these analyses. Autodesk Insight, for example, can be used for energy analysis, while One Click supports building life cycle assessments.

2. Materials and methods

As previously mentioned, BIM technology can be used not only for designing new buildings but also for managing existing ones. With a completed model, users can oversee building systems and simulate how proposed changes will affect the structure, which is particularly useful for renovations [5,18]. This type of model is called a digital twin – an exact virtual copy of an existing object that should include five key aspects: the physical component, the virtual component, connections, data, and services [19,20]. The use of digital twins is becoming increasingly popular, with the construction sector being the third most frequent adopter. The most common application is for visualisation, while energy optimisation – used to enhance building performance – is the third most frequent use case [21]. To function effectively, a digital twin should closely replicate the actual state of the physical structure. The benefits of digital twins can be categorised into three groups: economic, safety, and sustainability [22,23]. Simulations and analyses, which support or reject design decisions, help to reduce overall costs by identifying errors at an early stage. This contributes to improved safety by preventing mistakes that could increase construction costs and pose risks to workers on-site. Lastly, digital twins enhance sustainability by optimising building parameters to meet regulatory requirements [20,23].

The biggest challenge in creating a digital twin is accurately mapping the existing condition of a building, as software solutions do not always include predefined elements that match the building's actual features [19]. To maintain fidelity between the digital twin and the physical structure, a well-planned parameter update strategy must be developed. This strategy should ensure high consistency while balancing update frequency, computational load, and real-time responsiveness. Achieving bidirectional interaction between the digital and physical entities is a highly complex and challenging process [24-26]. A smart building can be developed based on the digital twin by integrating technologies that enhance residents' comfort. However, another challenge lies in the application of US-based standards, as buildings constructed according to Polish regulations may produce different results. Depending on the extent of these discrepancies, the model may become inadequate for reflecting the actual state of the building, preventing its use as a reliable digital twin for further development or monitoring.

2.1. Base building

The purpose of this analysis is to evaluate the feasibility of optimising an existing building based on paper documentation, considering the limitations arising from the availability of project information and the capabilities of the software. The paper documentation includes a technical description of both architectural and structural aspects, as well as drawings such as elevations, foundation plans, ground floor plans, first-floor plans, attic plans, roof structure plans, roof plans, two cross-sections, detailed drawings, a carpentry list, and information on sanitary and electrical installations. Based on the traditional paper documentation of a single-family house from 2005, a model has been created using Revit software.

The selected project is a pre-designed single-family house. Such ready-made designs typically require adaptation by another architect to meet specific site conditions and local spatial development plan requirements. Minor modifications to the functional layout or elevations are also frequently made. In this case, the changes were applied manually in red pen, making some dimensions illegible. The original dimensions were crossed out and rewritten without clear alterations to the drawing, making it difficult to determine which elements had been relocated. The ground floor and first-floor plans of the building model were developed in Revit according to the paper documentation (Fig. 2). Any changes made during the adaptation stage have been incorporated into the model. The blue line indicates elements added during adaptation, while the red line represents those that were removed.

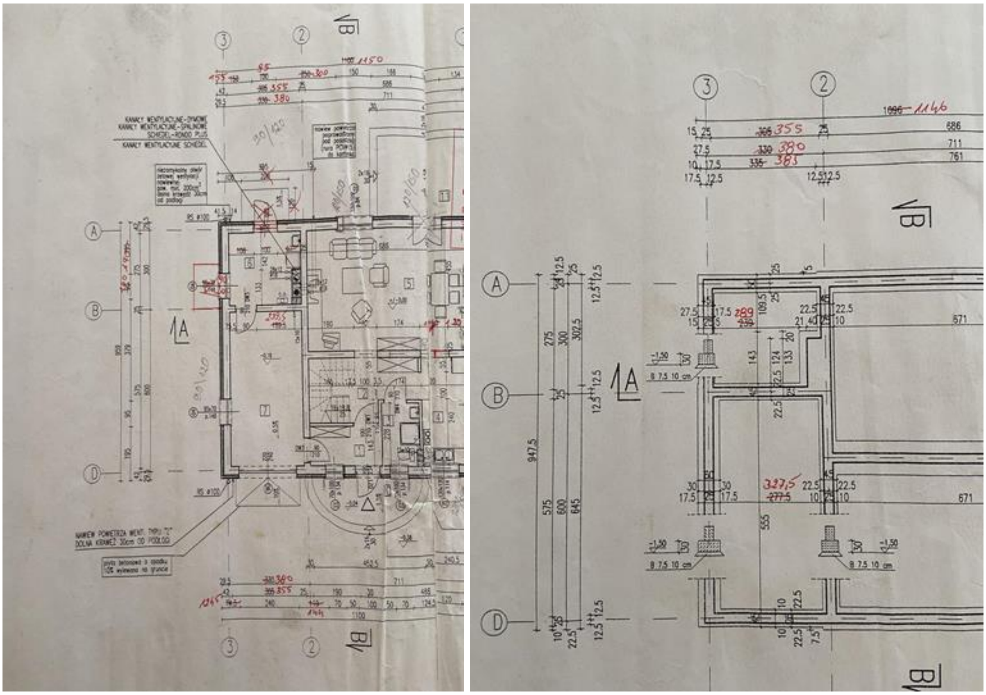

Fig. 2. Photos of the paper documentation. Design: P5 Studio Paweł Piatka, Katarzyna Herba-Janiak

Another issue was the absence of a .dwg version of the project. The building model in Revit was created based on the paper architectural design, incorporating the modifications made during the adaptation stage. These changes involved windows, the balcony slab, and partition walls. Relying solely on a paper version introduces imprecision, making it difficult to measure distances and identify elements whose dimensions are either missing or altered (Fig. 2). The changes applied to windows, doors, and walls were marked on the paper drawings by crossing out the original dimensions and replacing them with new ones. For balconies, the revised outline was drawn on the plans but was not dimensioned. When creating the model in Revit, the dimensions of the balconies were approximated based on their outlines in the plans. However, due to the lack of precise measurements, it is uncertain whether these dimensions were interpreted correctly (Fig. 3, Fig. 4). Additionally, some internal building dimensions were crossed out on the ground floor plan, yet no corresponding changes were indicated for the affected elements. Consequently, these dimension modifications were not incorporated into the Revit model.

Beyond the building's geometry, determining the properties of the materials used was also crucial. A significant challenge arose due to the lack of detailed material information in the documentation. The designer provided only summary heat transfer coefficients for the external walls, roof, and floor. However, in Revit, each material requires specific property definitions to enable accurate analysis. As a result, the model contains material values that approximate the available project data. Since the project dates back to 2005, many of the material properties have improved over time. Searching for precise data on the solutions used further extends the process of creating the digital twin.

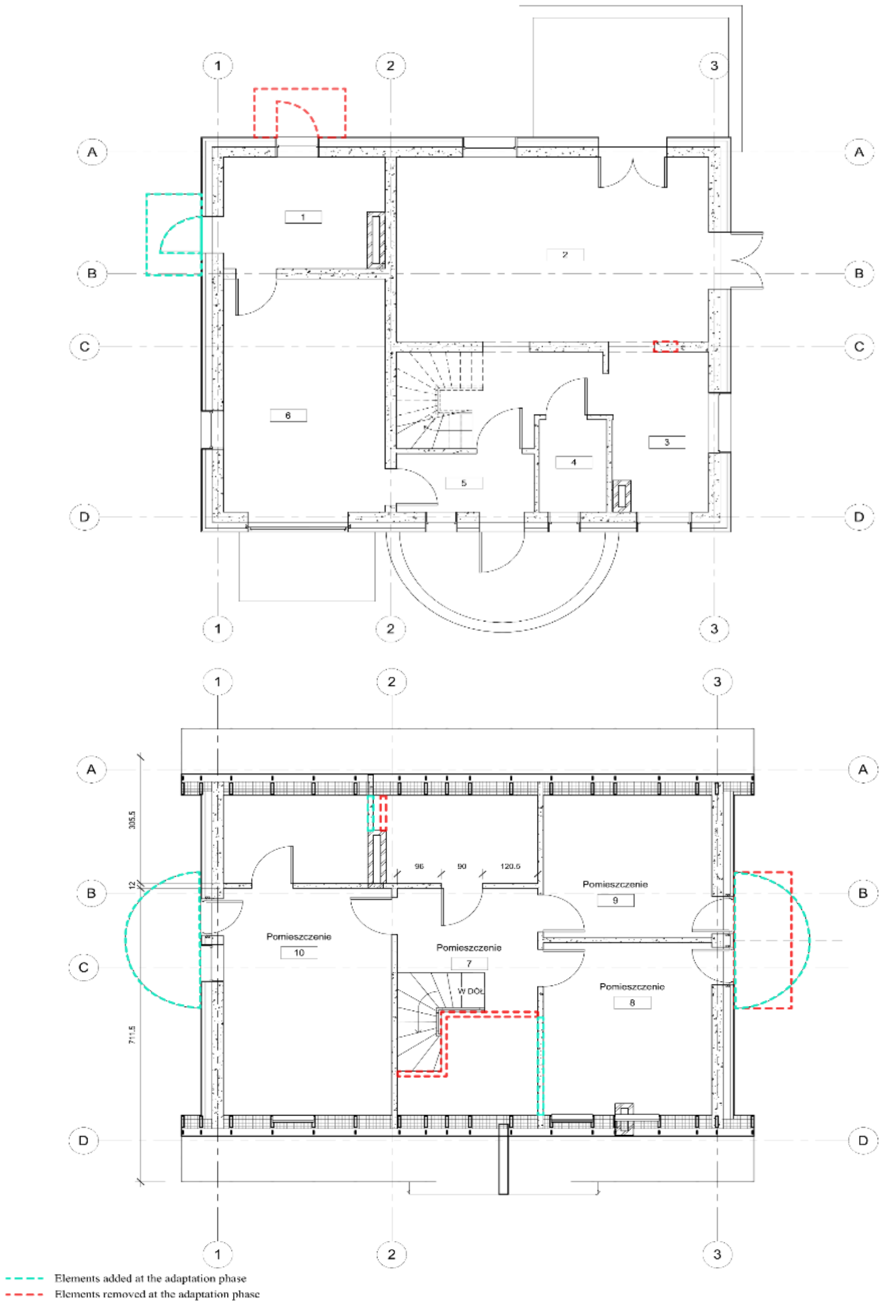

Fig. 3. Changes to the ground floor and first floor

After comparing the traditional project with the existing building, it was found that the construction does not fully align with the original design. Consequently, the paper project serves as the base building, while the existing structure is treated as a variant for comparison in the analysis.

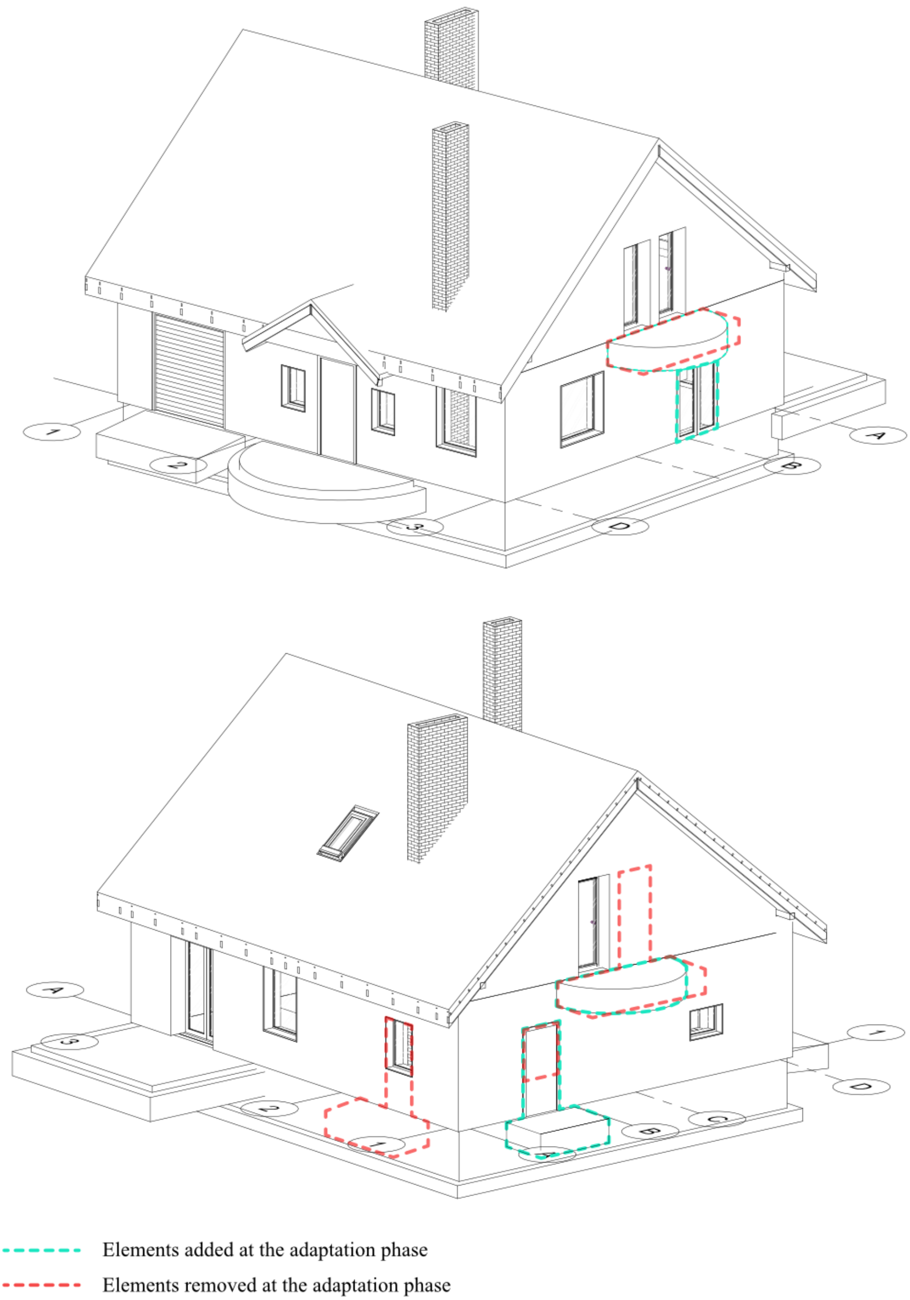

Fig. 4. Changes in the 3D view

The digital twin enabled an energy analysis of the building using Insight software. The results of this analysis compare the traditional project with the existing building and identify the necessary modifications to improve energy efficiency.

The first and most critical parameter analysed is energy consumption in kWh/m²/year, with graphical positioning referenced to ASHRAE 90.1 and Architecture 2030. Revit's thermal analysis capabilities are typically based on standards developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), an organisation founded in 1894 that advances human well-being through sustainable engineering in the built environment. ASHRAE and its members focus on building systems, energy efficiency, indoor air quality, cooling, and sustainability. Through research, standard development, publications, and education, ASHRAE actively shapes the future of the built environment. ASHRAE 90.1 is a standard outlining the minimum requirements for energy-efficient building design and construction. It is the reference standard used in Insight, which is directly integrated with Revit [27]. The Polish equivalents of this standard are PN-EN 15251:2008 and PN-EN 16798. However, ASHRAE 90.1 provides more detailed guidance on HVAC system energy efficiency calculations (e.g., mechanical ventilation and air conditioning), tailored to technologies commonly used in American buildings. This affects energy consumption calculations. In contrast, PN-EN 15251:2008 focuses on occupant health and comfort, while PN-EN 16798 extends ventilation requirements to address indoor air quality. Within Autodesk Revit, the main differences between these standards manifest in the areas of energy consumption analysis (ASHRAE 90.1), occupant comfort (PN-EN 15251), and indoor air quality and ventilation systems (PN-EN 16798) [27-29].

Architecture 2030 is a non-profit, non-partisan, and independent organisation founded in 2002 in response to the ongoing climate crisis. Its mission is to transform the built environment from one of the largest greenhouse gas emitters into a key part of the solution. For nearly two decades, Architecture 2030 has provided leadership and developed strategies to achieve CO_2 emissions reductions, ensuring a high probability of limiting global warming to 1.5°C [30].

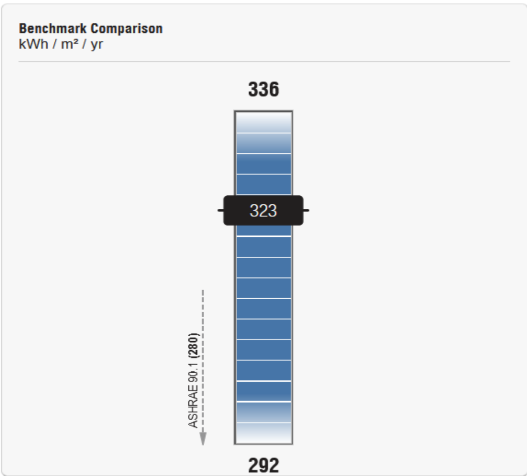

Fig. 5. Energy consumption. *Source*: [29]

After analysing the digital twin, the results were displayed in Insight, where the benchmark energy consumption for the analysed building was 323 kWh/m²/year (Fig. 5).

This value serves as the starting point for modifications and comparisons, which will be presented later in the article. It can be observed that this value is too high for a single-family house – 40 kWh/m²/year higher than the benchmark set by ASHRAE 90.1, the standard used in Revit. Since ASHRAE 90.1 is developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), it is based on American datasets, which may differ from European ones [20,31]. Additionally, the latest version of ASHRAE 90.1 is from 2019, meaning that the 2005 house design is being compared with more recent standards. The Insight analysis includes energy consumption for air conditioning, which is not accounted for in the energy calculations for a typical single-family house in Poland. The analysed building uses gravitational ventilation, which does not require electricity. In Poland, the average energy consumption for houses built after 1996, without air conditioning, is approximately 175 kWh/m²/year – less than half of the value estimated in the digital twin analysis [19].

Based on recent electricity bills, the actual monthly electricity consumption of the house is 221 kWh, which equates to 24 kWh/m²/year. However, several factors significantly reduce electricity consumption compared to the software's predicted value. The heating system is powered primarily by an eco-pea coal boiler, with some reliance on electricity – coal usage reduces electricity consumption. Heat is distributed via radiators and an underfloor heating system. Additionally, the house has no air conditioning, and ventilation is gravitational – these two factors alone substantially impact total energy consumption, as air conditioning can account for up to 60% of a building's total energy usage [32].

In Revit, the single-family house is categorised as "Family 2+1", suggesting a predefined number of occupants. However, the house is currently inhabited by only two people. This highlights a key limitation of Revit's calculations – the software applies highly simplified and generalised assumptions, failing to account for several real-world variables that influence actual energy consumption.

12 SEER/0.9 AFUE Split/Packaged Gas, 5-11 Ton
11.3 EER Packaged VAV, 84.4% boiler heating
Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff
4-Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff
Central VAV, Electric Resistance Heat, Chiller 5.96 COP
12 SEER/7.7 HSPF Split Packaged Heat Pump
2-Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff
12 SEER/8.3 HSPF Packaged Terminal Heat Pump (PTAC)
Residential 17 SEER/9.6 HSPF Split HP <5.5 ton
Underfloor Air Distribution
Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 ton
Residential 14 SEER/8.3 HSPF Split Packaged Heat Pump

Fig. 6. List of available HVAC systems. *Source*: [33]

The first inaccuracy arises primarily with the HVAC system, as Revit offers only a limited selection of solutions, which are adapted to the US market. To complete the data, users must choose the closest available option, but this can distort the results (Fig. 6) [34]. The HVAC systems available in Revit (Fig. 6) are all designed to handle both heating and cooling simultaneously, and the programme does not allow for the selection of individual systems.

- 12 SEER/0.9 AFUE Split/Packaged Gas, 5-11 Ton: Split/packaged gas system, with 12 SEER for cooling and 0.9 AFUE for heating.

- 11.3 EER Packaged VAV, 84.4% Boiler Heating Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff: Volume-controlled airflow system with boilers and chiller.
- 4-Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff Central VAV, Electric Resistance Heat, Chiller 5.96 COP: Four-pipe system, with boilers and chiller, featuring electric resistance heating.
- 12 SEER/7.7 HSPF Split Packaged Heat Pump: Heat pump system for both cooling and heating.
- 2-Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff: System with two pipes, boilers, and chiller.
- 12 SEER/8.3 HSPF Packaged Terminal Heat Pump (PTAC): Terminal heat pump for cooling and heating.
- Residential 17 SEER/9.6 HSPF Split HP <5.5 tonnes: A split heat pump for small residential buildings, providing 17 SEER for cooling and 9.6 HSPF for heating.
- Underfloor Air Distribution: A ventilation system where air is supplied through the floor.
- Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 tonnes: Gas-fired cooling and heating system for small residential buildings – chosen for the existing building as it best matches the specified type.
- Residential 14 SEER/8.3 HSPF Split Packaged Heat Pump: Heat pump system for small residential buildings, for cooling and heating.

These available options allow for an approximation of the actual situation and provide a broader scope for analysis.

2.2. Existing building

The paper documentation and the existing building differ in several respects, as materials and solutions were altered during the construction process. Changes were made to the materials used for the walls, roof, and ground floor, and the positioning and sizes of openings do not always match the actual state. These parameters were adjusted in Revit to reflect the current condition. The HVAC system remained the same as the baseline option, due to the limitations of the software. Despite not being suitable for the existing building in its original configuration, the unfavourable system was chosen for consistency in the comparison between the designed and existing buildings. To show the difference in energy consumption, the most efficient system was used for the upgraded building.

Changes that took place include the following. For the walls, SOLBET cellular concrete blocks were used, replacing the Porotherm blocks originally planned [35,36]. The roof saw a significant change, with the thickness of the mineral wool being increased. The ground floor structure was completely modified due to the installation of underfloor heating, which was not part of the original design. The windows were altered: a 120 x 120 cm window was replaced with a 120 x 150 cm window, a 150 x 150 cm window was changed to a 140 x 220 cm patio door, and another 150 x 150 cm window was replaced with a 140 x 200 cm window. The roof windows in the attic were removed.

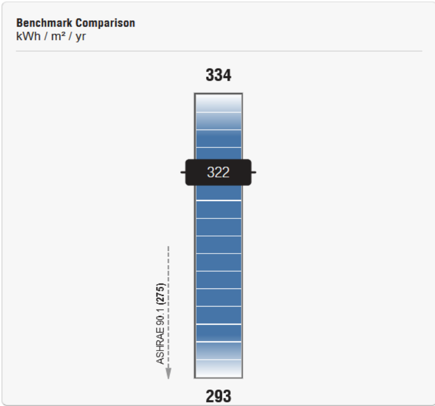

Fig. 7. Energy consumption. *Source*: [30]

After implementing the previously mentioned changes, a re-analysis was conducted, revealing a decrease in energy consumption of 1 kWh/m²/year (Fig. 7). However, these values are quite similar, as the changes were made using materials with similar properties, such as the wall material or improved insulation for the roof.

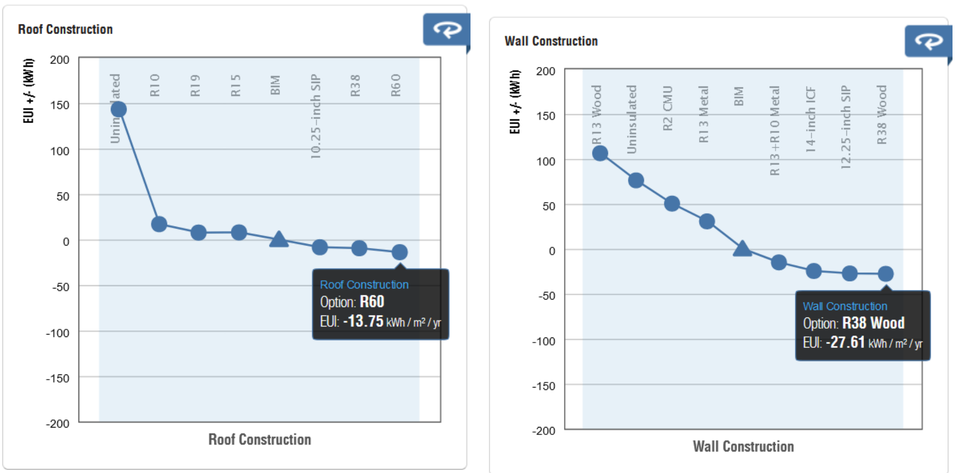

Fig. 8. Variants for roof and wall construction. *Source*: [30]

The model result of the analysed building is presented as a triangle on a graph, allowing the user to determine the building's energy consumption in relation to the proposed alternatives. To significantly reduce energy consumption for the partitions, the solutions proposed by Insight would need to be applied. To reduce consumption by 13.75 kWh/m²/year with only a change in the roof, the R60 variant would have to be used (Fig. 8). As previously mentioned, Insight is a programme developed by the Autodesk Group in the USA and is therefore based on American solutions. For an R60 roof, the R-value is 66.23 hft²°F/BTU, which is approximately 11.92 m²K/W [37]. The roof used in this analysis has an R-value of 5.1384 m²K/W, meaning this value would need to be more than doubled by improving the material properties, increasing insulation thickness, or changing the materials entirely. Similarly, for the walls, the most energy-efficient solution is the R38 Wood wall system (R38

Wood Frame Wall – When this system is insulated with closed-cell spray foam insulation, the R-factor is approximately R-38). The R-value for this solution is 36.75 hft²°F/BTU, or approximately 6.615 m²K/W [38]. For the walls in the model, the R-value is 4.1259 m²K/W, which is not significantly short of the most efficient solution. However, Insight does not provide data related to the floor on the ground.

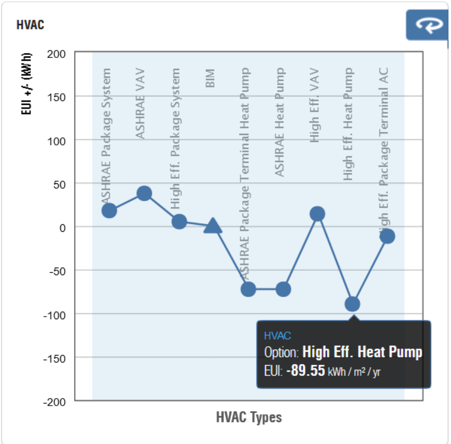

Fig. 9. Variants of HVAC systems. *Source*: [30]

Retrofitting in certain cases can be problematic because, while it is easy to change settings and switch from one material to another in the model, such changes may not be feasible in reality. The optimal solution might be to insulate the building. However, the most significant and beneficial change is related to the HVAC system. A gain of almost 90 kWh/m²/year (Fig. 9) could be achieved by installing a highly effective heat pump, which would reduce energy consumption by 24%, or 1/4 of the total consumption. Replacing the HVAC system is more feasible than replacing materials, especially given the increasing popularity of heat pumps [39].

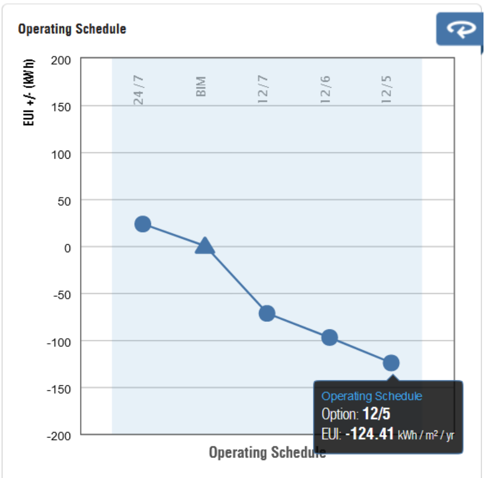

Fig. 10. Variants of operation schedule. *Source*: [30]

Another parameter that reduces energy consumption is the operating schedule. This value is related to the time when the building is in use. Each type of building has its own value that meets the needs of its users. In this case, the building is a single-family house, so the operating schedule must remain 24/7. Even if a change could allow such a significant reduction in energy consumption, it would only have a theoretical impact, as in reality, the building's usage duration will not change (Fig. 10). Consideration could be given, especially after the COVID-19 pandemic, when a large group of people shifted their workplace from office to home [40]. Before the pandemic, they spent approximately 8 hours at work or school, plus additional time commuting, amounting to 8.5-9 hours out of the building each day during the week. This could have been taken into account at that time, but now it is not as influential on consumption [41].

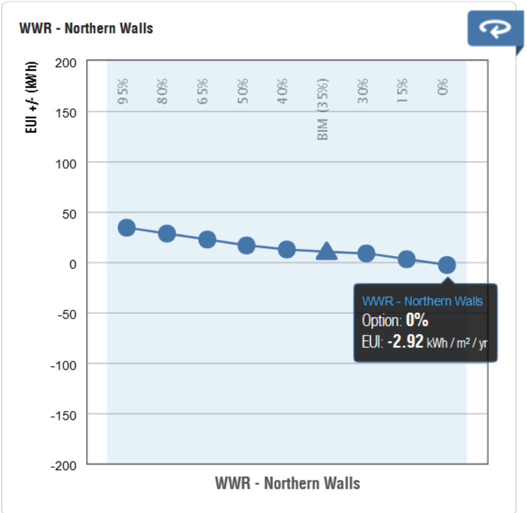

Fig. 11. Variants of wall-window ratio for the northern wall. *Source*: [30]

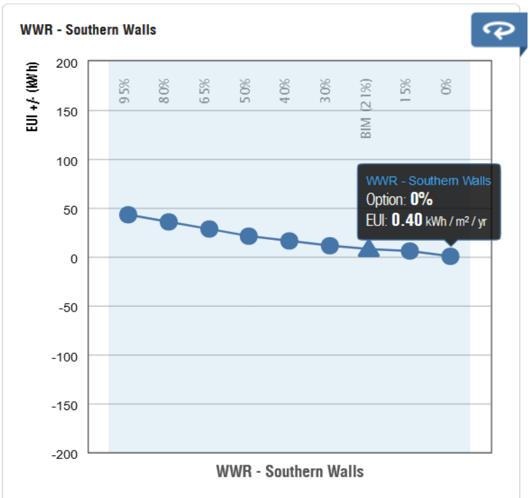

Fig. 12. Variants of wall-window ratio for the southern wall. *Source*: [30]

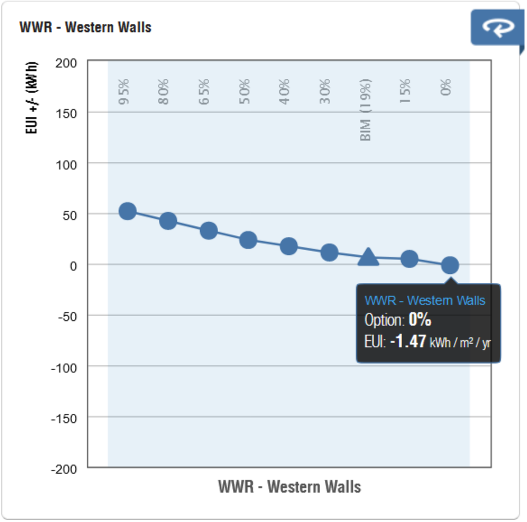

Fig. 13. Variants of wall-window ratio for the western wall. *Source*: [30]

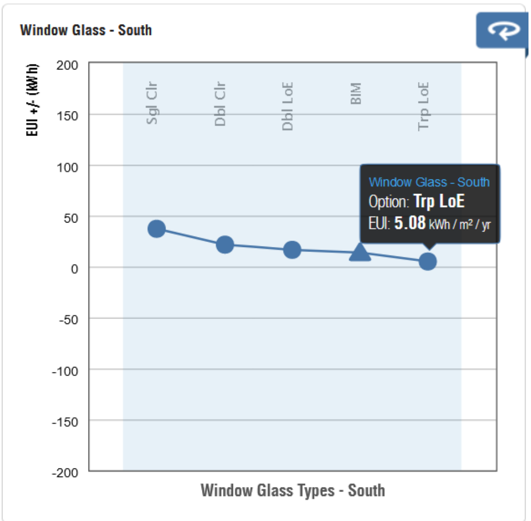

Fig. 14. Variants of window glass for the southern wall. *Source*: [30]

Besides the possible changes in the HVAC system and some additional insulation in the walls and roof, modernization of the windows is also possible. The graphs present the options with the greatest impact. The Window-Wall Ratio (WWR) (glazing area/gross wall area) interacts with window properties to influence daylighting, heating, and cooling [35]. The differences in WWR between the model and the least energy-intensive option are as follows (Figs 11-14):

- Window-Wall Ratio for Northern Walls: 13.22 kWh/m²/year,
- Window-Wall Ratio for Western Walls: 7.75 kWh/m²/year,
- Window-Wall Ratio for Southern Walls: 7.39 kWh/m²/year.

As seen, the lowest energy consumption occurs at 0% WWR, which would mean no windows. However, this is not an acceptable situation according to the Polish Technical Conditions, which state that the ratio of window area (calculated in terms of frame area) to floor area should be 1:8 [38].

The fourth graph, showing a saving of 8.61 kWh/m²/year, is related to the type of glazing. After changing the glazing to Triple Low-E, which has a U-value of 1.55 W/m²K, the savings are realised. However, the Technical Conditions currently stipulate that the permissible R-value should not exceed 0.9 W/m²K [42,43]. Due to the lack of information about the coefficient of the windows used, this value was adopted in the model. Triple Low-E glazing consists of three layers with two low-E coatings, filled with ½” argon gas or ¼” krypton gas between the layers, and low-conductance edge spacers. The middle glazing layer can be either glass or suspended plastic film [44-45]. Changing the glass in the south-facing windows will save 8.61 kWh/m²/year.

2.3. Upgraded building based on previous results

Now, these possible changes, such as the HVAC system and additional insulation, will be implemented in the model to check whether energy consumption has actually been reduced.

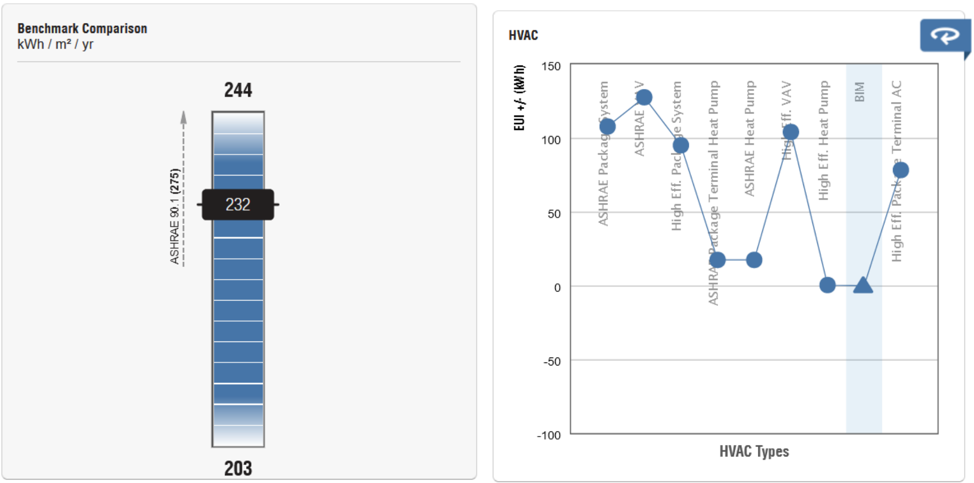

Fig. 15. Energy consumption and HVAC system variants. *Source*: [30]

Initially, only the HVAC system was changed to a heat pump, in accordance with the results of the analysis of the existing building, which allowed consumption to be significantly reduced to 232 kWh/m²/year (Fig. 15).

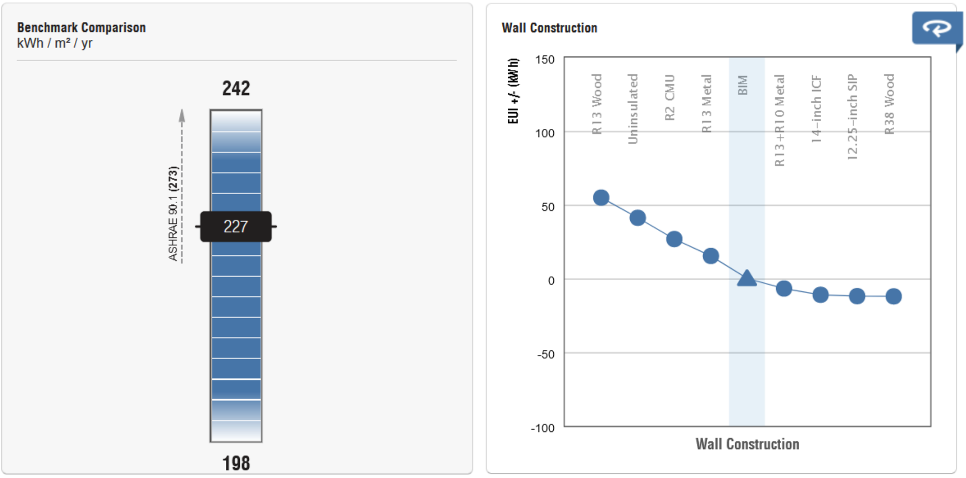

Fig. 16. Energy consumption and wall construction variants. *Source*: [30]

Layers

EXTERIOR SIDE

	Function	Material	Thickness	Wraps	Structural Material	Variable
1	Finish 2 [5]	<By Category>	2.00	☑	☐	☐
2	Thermal/Air Layer [3]	Styropian(1)	7.00	☑	☐	☐
3	Thermal/Air Layer [3]	Styropian	15.00	☑	☐	☐
4	**Core Boundary**	**Layers Above Wrap**	**0.00**			
5	Structure [1]	Concrete, Aerated	25.00	☐	☑	☐
6	**Core Boundary**	**Layers Below Wrap**	**0.00**			

INTERIOR SIDE

Fig. 17. Layers of the external wall. *Source*: [33]

In the next step, the wall parameters were further modified by adding an extra 7 cm of insulation to meet the R-value requirement of R38 Wood. The R-value of the wall in the upgraded model is 6.4593 m²K/W, which is very close to the required 6.615 m²K/W for the specified R38 (Fig. 16). Despite this, it has not been classified as a lower-energy option. This may be due to the wall construction itself. In the model, the wall used is made of cellular blocks, while Revit predicts a timber wall. The R-value is influenced not only by the thickness but also by the type of material used (Fig. 17). In the case of comparative values and solutions presented in Insight Autodesk, those found in the U.S. are used as proxies, which means this does not allow for accurate comparisons or conclusions to be drawn, nor does it help in proposing a solution. The most common construction for a single-family house is a timber-frame construction, and this is reflected in the results [46]. When it came to improving performance, the heat transfer coefficient was the only factor considered, as changing the structure from masonry, used in the existing building, to timber would have meant a completely new building, not a retrofit (Fig. 18).

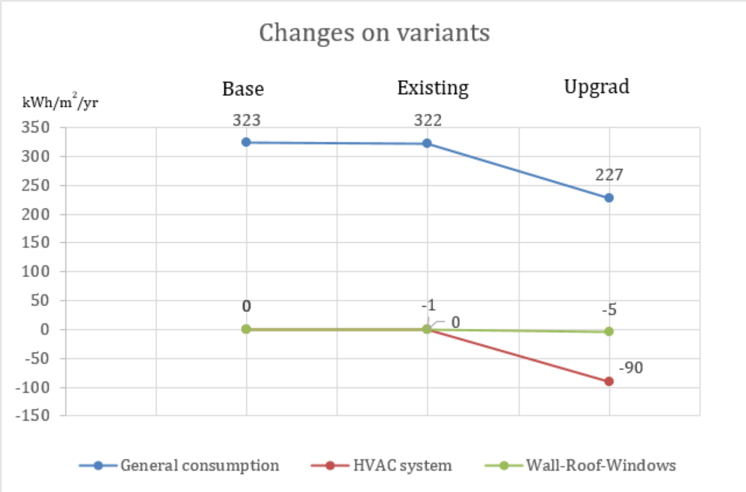

Fig. 18. Energy consumption in variants and energy savings depend on the type of change

3. Conclusions

Creating a digital twin of a building provides many opportunities to analyse the building, such as determining energy consumption and identifying ways to reduce it. While creating a model of a single-family house located in Poland using Autodesk Revit, several advantages and disadvantages were observed regarding the process of transferring the design from paper to the model and optimising the building itself according to the American standard, which differs from those used in Poland. The conclusions will be divided into two parts, focusing on the aspects mentioned.

The design of the single-family house dates from 2005. The transfer from paper design to model can be challenging when dealing with incomplete designs, due to missing data and manually inserted changes that lead to inaccuracies in the individual drawings. Another disadvantage is the availability of tools and software, which sometimes require additional extensions or plug-ins to represent reality as accurately as possible. For Revit, only 12 proposals for HVAC system solutions are available. As Revit is a US-based program, these solutions are tailored to the American market. They do not meet local needs, which formed the basis for this analysis. This leads to the second part of the conclusions.

The essence of the American standard is to reduce energy consumption in new buildings and retrofitted existing buildings by increasing the efficiency of HVAC, lighting, and ventilation systems. The systems used have a significantly greater impact on energy consumption. The options available in Revit are adapted to the technologies used in the USA, which does not align with the Polish context. Using an approximate system significantly distorts the results, particularly when such systems are a key component. As seen in Graph 1, the most significant change is the HVAC system, which decreases consumption by 28% compared to the baseline. However, it is difficult to provide exact values for this building due to the previously mentioned limitations of available systems. In the building used for the analysis, the type of heating does not appear in the list, nor is it possible to account for the absence of a cooling unit, which generates a high level of energy consumption. Polish standards focus heavily on user comfort and building conditions. When analysed, a slight improvement in energy consumption parameters is observed when changing the heat transfer coefficient to a much more favourable value for the walls. This improves the comfort of the building, which could be considered when basing the analysis on Polish standards.

Despite its many weaknesses and obstacles, the use of BIM for existing buildings has great potential, offering a wide range of possibilities. It allows efficiency to be increased through the most favourable solutions for modernisation. This is one of the many opportunities provided by digital twins. Its use can be further enhanced by analyses related to building management, monitoring changes, or assessing the life cycle of a building. However, it would be necessary to adjust the components to the region to account for the separation of different systems, as illustrated in the example above.

Funding

This work was funded by research project no. 0412/SBAD/0081, granted by the Ministry of Science and Higher Education of Poland

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