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Advancing Cost Estimation Through BIM Development: Focus on Energy-Related Data Associated with IFC Elements

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Abstract

Achieving cost-effective energy performance while meeting sustainability goals is a challenge in retrofitting decisions within the construction industry. To enhance the decision-making process, this study introduces an IFC-based approach that integrates cost estimation and energy analysis directly within BIM. This approach supports more structured and data-informed retrofit planning by structuring cost and energy data within a semi-automated IFC-based workflow. The methodology follows a structured approach that includes three phases. The first focuses on developing a BIM model that captures the physical and semantic attributes of an existing building. This is followed by parametric energy simulations to evaluate retrofit scenarios, with cost data integrated and energy analysis reports linked to IFC elements. The final phase involves a post-retrofit cost assessment to identify the optimal scenario based on total cost, with potential for extension to other performance indicators. The framework was applied in a residential case study to evaluate the model's functionality. The results show that IFC-based integration improves transparency, interoperability, and reliability in cost–energy assessments. By structuring data as linked IFC entities, the approach enhances BIM's role as a decision-support tool for sustainable and economically efficient retrofitting.

Keywords: BIM; IFC schema; cost integration; energy retrofitting; semantic data modeling

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1. Introduction

As energy costs continue to rise and sustainability goals become more pressing, building energy retrofitting has emerged as a key strategy for reducing operational energy consumption and improving cost efficiency. Within the Architecture, Engineering, Construction, and Facility Management (AEC/FM) industry, identifying optimal retrofit strategies requires a structured method that integrates energy simulation outputs with detailed cost data, enabling the comparative evaluation of alternative solutions [1,2]. While Building Information Modeling (BIM) has significantly enhanced data management and project coordination across construction workflows, its application in cost estimation for energy retrofitting remains limited. Current BIM models primarily function as geometric representations, often lacking structured integration of cost and energy-related data. Consequently, transparency and consistency in cost assessments for building energy retrofits are limited, which undermines the reliability of decision-making [3].

The Industry Foundation Class (IFC) schema is a standardized data model that enables interoperable exchange of building information across software platforms. It provides a consistent framework for structuring geometric, semantic, and cost-related data within BIM environments [4,5]. However, its application in integrating energy analysis data with cost estimation for retrofitting projects remains limited. Existing cost estimation approaches do not systematically link material, installation, and operational energy costs within BIM, making it challenging to assess total cost trade-offs across retrofit scenarios [6–8]. Moreover, the absence of standardized workflows within IFC limits interdisciplinary data integration and scenario-based comparison [3,9,10]. Addressing these limitations requires an IFC-based methodology capable of structuring cost and energy data for more informed retrofit planning.

This research aims to develop an IFC-integrated cost estimation framework that supports energy and material cost evaluation of energy and materials costs across multiple retrofit scenarios. The framework enhances the reliability of cost estimation and provides stakeholders with a structured approach to minimizing total cost in retrofit selection. The key contributions of this study include:

- Cost Estimation Framework, a structured approach for integrating material, installation, and operational energy costs within IFC, enabling comparative evaluation of retrofit scenarios.
- IFC-Based Cost and Energy Data Integration, a methodology that enhances the structured representation and interoperability of cost estimation and energy analysis within the IFC framework.
- Optimized Retrofit Scenario Selection, a structured decision-support framework for identifying the most cost-effective retrofitting strategy based on total cost considerations.

This research follows a three-phase methodology: (i) BIM Model Development—developing a structured IFC-based representation of an existing building with its geometric, material, and construction properties; (ii) Energy-Cost Data Integration—performing parametric energy simulations to evaluate retrofit scenarios while linking cost estimation data and energy analysis reports to IFC elements; (iii) Optimal Retrofit Scenario Identification—using a structured total cost (i.e., installation material and operational energy) assessment to select the most cost-effective and energy-efficient retrofitting solution.

The novelty of this research lies in the integration of energy and cost data within the BIM-IFC framework, enabling a comprehensive cost estimation and evaluation of retrofit scenarios. The outcome of this study provides industry professionals and policymakers with a structured decision-making tool to maximize energy savings while ensuring cost-effectiveness. Consequently, besides visualizing the physical properties of a building, BIM becomes a multidimensional framework that supports structured decision-making by integrating sustainability, energy performance, and economic analysis.

This paper is structured as follows: Section 2 presents the background and literature review on BIM-based cost estimation and IFC schema integration. Section 3 details the research methodology, including the BIM model development, energy simulation, and cost integration process. Section 4 describes the case study and implementation. Section 5 discusses the results and methodological implications. Finally, Section 6 provides the conclusions and outlines future research directions.

2. Background

Recent advancements in digital construction have enabled BIM to transform traditional cost estimation into a more integrated, data-driven process. In this context, BIM has transformed cost estimation by integrating cost data with geometric and parametric information, enhancing precision in project planning and execution [11,12]. Despite recent progress, BIM-based cost estimation remains primarily focused on quantifying material and installation costs. The integration of operational energy costs into BIM workflows is still underdeveloped and inconsistent, thereby limiting its applicability in comprehensive retrofit decision-making [13,14].

A reliable cost assessment for building energy retrofitting strategies should account for both initial investments and operational energy costs, considering their long-term cost impact to support informed decisions in cost-effective retrofit strategies [15]. Beyond individual cost components, the selection of retrofit strategies also requires the consideration of broader economic implications. Also, given that different retrofit strategies, from partial/standard to deep retrofitting, can considerably impact a building's market value, evaluating a range of alternatives is essential to support informed and value-oriented decision-making [16].

Recent developments have attempted to address these limitations, yet key structural issues remain. The IFC schema provides a standardized framework for structuring cost data within BIM models, improving interoperability between project stakeholders. However, its application in linking energy analysis reports with cost estimation for energy retrofitting projects is still limited [4,17,18].

In current IFC-based models, cost data and energy reports are often stored as basic descriptive properties instead of structured entities, which reduces their effectiveness in supporting efficient data access and scenario-based analysis. As a result, stakeholders face challenges when comparing multiple retrofit strategies. Moreover, there are no consistent methods to embed operational energy costs alongside material and installation costs in IFC models, limiting their role in comprehensive cost estimation workflows [9].

A more structured IFC-based approach is needed to improve consistency and clarity in cost evaluation for energy retrofits. Integrating cost estimation within BIM using the IFC Cost Schedule framework improves cost planning and transparency in retrofitting projects [14]. By embedding cost and energy-related data directly into BIM elements, stakeholders can conduct quantitative assessments of different retrofit scenarios [19,20]. Recent research has shown that BIM-driven cost structuring enhances cost forecasting, better aligning cost estimation assessments with energy-related investment decisions [21].

BIM has the potential to enable the systematic comparison of retrofit scenarios when it is supported by parametric energy simulations. These simulations help estimate the energy demand of each retrofit scenario, forming the basis for evaluating the cost of operational energy [22,23]. For example, studies on envelope retrofitting show that BIM-linked cost and energy assessments help optimize insulation strategies by combining energy data with structured cost data [21].

Furthermore, recent research highlights the benefits of integrating construction and operation phases within a BIM-based framework to reduce life cycle costs, demonstrating how early stage decisions can impact long-term cost performance in commercial building retrofits [24]. In support of this perspective, Life Cycle Cost (LCC) analysis has emerged as a complementary method to BIM-based cost estimation. LCC facilitates early stage decision-making by combining material, installation, and operational energy costs into a unified cost assessment over the building's life cycle. While LCC is typically performed as a separate process, its integration into structured BIM workflows, particularly through IFC-based models, can enhance the evaluation of long-term cost-effectiveness, using metrics, such as payback periods, for retrofit interventions [22,25].

Recent developments in BIM workflows have increasingly emphasized structured and automated approaches to cost estimation. Standardized IFC models are used to define cost items and link them directly to building components, enabling more consistent and scalable evaluations [9]. This structured integration supports scenario-based comparison of retrofit strategies, aligning technical performance with long-term cost efficiency [10].

Despite advancements in BIM-based cost estimation, current workflows still face critical limitations in integrating cost and energy data due to fragmentation, lack of standardization, and limited semantic support for automation. Cost estimations, energy reports, and material specifications are often stored in separate environments, making consistent and scalable evaluations difficult [26,27]. In particular, differences in pricing structures, currency formats, and update mechanisms continue to constrain BIM interoperability [28].

Related work by [29] proposed a BIM-based method to improve IFC interoperability for energy audits using custom property sets, but it did not address cost–energy integration or support scenario-based evaluation. Additionally, a recent study by [29] highlighted persistent interoperability issues in IFC-to-BEM workflows, especially for integrating energy simulation outputs. Furthermore, the authors of [30] highlighted the IFC format's lack of support for time-series data, the challenges associated with geometric data extraction, and the absence of standardized toolchains for converting IFC files into usable formats.

Beyond interoperability and semantic limitations, practical challenges continue to affect the consistency of BIM-based cost estimation. Market dynamics, including fluctuations in material and labor prices, also influence the reliability of cost assessments. Since most BIM models do not support dynamic cost updates, estimation consistency is often affected. While partial automation through scripting is helping address this issue, many workflows still rely on manual data entry, introducing inefficiencies. Linking building objects directly to cost elements remains a challenge in improving BIM-based cost assessments [31–33]. While BIM has supported more advanced cost estimation methodologies in recent years, its integration of energy data for evaluating retrofit costs is still limited. However, IFC provides the potential to represent cost- and energy-related data in a unified model, but its application in retrofit analysis is still developing.

To address these limitations, the integration of parametric energy data into cost-linked IFC workflows remains unexplored. In this study, both energy simulation outputs and cost data are embedded directly into IFC models, enabling semi-automated and interoperable evaluation of multiple retrofit scenarios. Addressing existing gaps in data standardization, cost updating processes, and object–cost associations is important to improve the consistency and applicability of BIM for retrofit cost assessment.

3. Research Methodology

This research follows a structured methodology to integrate cost estimation with sustainability-focused strategies within a BIM environment, using the IFC data schema as shown in Figure 1. The aim is to develop a BIM-based framework that generates cost estimations across multiple retrofit scenarios, providing a structured approach for evaluating energy and cost trade-offs to support the selection of the optimal retrofitting solution.

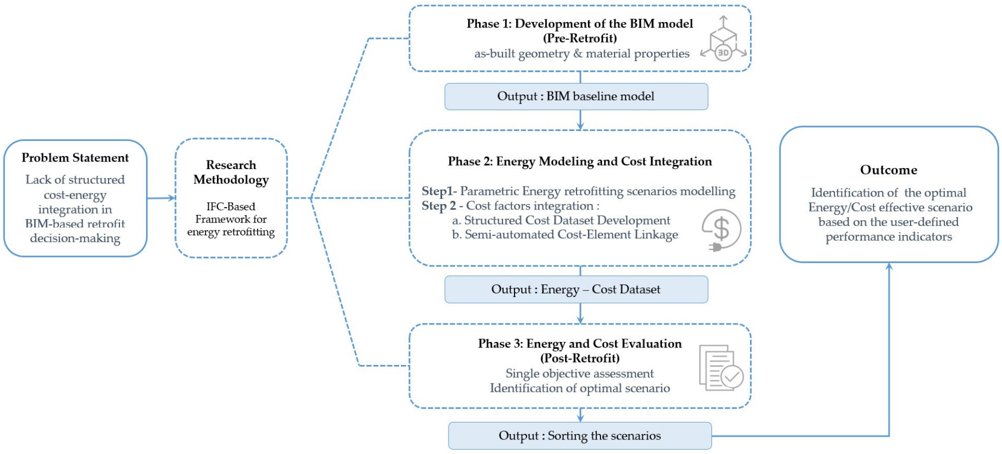

Figure 1. Overview of the research methodology.

The methodology comprises three phases, as outlined below:

(i) **Phase 1—Development of the BIM model**: The first phase focuses on developing a detailed BIM model of the existing building to accurately capture its physical characteristics. The model was created in Autodesk Revit, reflecting the building's as-built condition, including its geometric dimensions, material properties, and construction details. This model was then exported as an IFC file (i.e., IFC4_ADD2_TC1-4.0.2.1), which served as the foundational dataset for subsequent analysis and cost calculations.

(ii) **Phase 2—Energy Modeling and Cost Integration:** The second phase involves two key steps: parametric energy retrofitting scenario modeling and the integration of cost factors. Together, these steps aim to comprehensively evaluate thermal performance and economic implications of various retrofit scenarios.

Step 1—Parametric Energy Retrofitting Scenarios Modeling: This step focuses on the systematic development of multiple retrofit scenarios using parametric simulations in EnergyPlus. The process began with the selection of insulation materials, each characterized by distinct thermal conductivity values while maintaining a uniform material thickness across all scenarios. This standardization ensures the reliability of comparative analysis.

The simulation framework enables a detailed assessment of energy performance, focusing on key metrics, such as annual heating and cooling energy demands. By utilizing parametric simulations, a broad range of retrofitting options can be explored. The modeling process leverages advanced simulation tools to predict the thermal behavior of the building under varying material configurations. This approach facilitates the identification of scenarios with the greatest energy-saving potential, forming a foundation for subsequent economic analysis.

To structure and manage the building envelope components, this research applies the IfcBuildingSystem entity, which allows the grouping of building elements that perform related functions—such as insulation layers and façade components—within the IFC schema. By defining the building envelope as a structured system, individual components, such as insulation layers, façade elements, and HVAC systems, can be systematically categorized. The costs associated with each building component are structured using IfcCostItem entities and linked to their respective thermal properties through an IfcDocumentInformation relationship, enabling a more accurate evaluation of energy-saving potential. This linkage not only improves the clarity and management of retrofit options but also ensures that data are structured in an interoperable and queryable format, enabling a consistent and scalable cost estimation methodology.

Step 2—Cost Factors Integration: This step integrates cost data considerations into the BIM model by associating each evaluated retrofit scenario and its geometric representation with corresponding cost items. The total cost includes material, installation, and operational energy costs for the retrofit scenarios. Maintenance costs are currently excluded due to their relatively negligible impact on the outputs of the proposed methodology; however, they could be integrated into future developments by leveraging the scalable structure of the IFC standard. To ensure interoperability and efficient management of construction data, the research uses the IFC schema not only as a standardized data format but as a structured information model that improves access to both cost and energy-related data. Unlike traditional BIM models that often store cost and sustainability data as static, non-queryable attributes, this research ensures that such information is represented as structured data objects within the IFC schema, enabling efficient search, access, and analysis [34]. By structuring cost and energy information as structured data objects**,** stakeholders can efficiently retrieve, analyze, and compare different retrofit scenarios. This dynamic IFC integration enhances decision-making transparency, allowing users to explore cost–energy trade-offs without relying on external tools or manual data extraction. To implement this integration in practice, the methodology follows two structured processes:

- Structured Cost Dataset Development, A structured cost dataset was developed to represent the 12 retrofit scenarios, where each building object is associated with 12 distinct cost items, each corresponding to a scenario. These cost items are defined using the IfcCostItem entity and are quantitatively derived from the object's geometry. The cost items are grouped into separate cost sheets (one per scenario), representing alternative cost configurations for each retrofitting option. These cost data, sourced from the Regione Lombardia price list, are organized according to a domain-specific ontology previously developed by the research group [34], enabling standardized integration within the IFC schema. The ontology classifies cost items by element type, function, and material properties, enabling consistent BIM integration. Its standardized structure supports reusability across different regional databases and retrofit projects. This structure ensures consistent, interoperable, and queryable cost information within the BIM environment, facilitating comparison across all retrofit scenarios.
- Semi-automated Cost–Element Linkage, To support interoperability and consistency, Python 3.13.4 scripting combined with the IfcOpenShell library is used to partially automate the linkage between IFC elements and cost items [28]. This process extracts structured data from each geometric object—such as classification, dimensions, and material type—and uses it to filter relevant IfcCostItem entries from the dataset. While the script reduces the number of possible matches, the final selection of the appropriate cost item is completed manually by the user. This semi-automated workflow enhances the efficiency and reliability of the cost–assignment process while ensuring that cost data remain linked to the thermal and physical attributes of building components. Although predefined cost values were used in this study, the framework is designed to support dynamic price updates. By extending the existing Python and IfcOpenShell-based workflow, updated prices from structured sources can be programmatically imported and mapped to corresponding IfcCostItem entities. This enhancement would improve the model's responsiveness to market fluctuations while maintaining interoperability within the IFC structure.

(iii) **Phase 3—Identification of Optimal Retrofitting Scenario Through Energy–Cost Integration:** This phase, as part of the post-retrofit analysis, focuses on the comparison of multiple energy retrofitting scenarios by integrating energy performance and associated costs into a unified evaluation framework. Using the total cost as the sole evaluation metric, this phase enables the identification of the optimal retrofitting scenario that balances energy efficiency and economic feasibility.

The cost data integrated with the energy analysis report, embedded into the BIM model during Phase 2, enables the evaluation of trade-offs among material, installation, and operational energy costs. By focusing on the total cost of each scenario, the framework provides a clear and quantitative basis for decision-making. This IFC-based evaluation framework highlights the long-term cost-effectiveness of energy-efficient solutions by enabling stakeholders to compare different energy retrofit scenarios. Structuring cost and energy assessments within IFC enhances transparency and facilitates a detailed evaluation of trade-offs between energy savings and total cost.

The outcome of this phase is the identification of the optimal retrofit strategy, determined through the single-objective assessment of total cost. By embedding energy and economic data within the Industry Foundation Class (IFC) framework, the methodology enhances BIM's application in sustainable construction practices. It offers practical guidance for industry professionals and policymakers, advancing energy and cost management in retrofitting projects while supporting sustainability goals. Figure 2 shows the IFC-based workflow for integrating energy and cost data within the retrofit evaluation process. The diagram highlights the relationships between the pre-retrofit building model, energy analysis, and structured cost estimation, demonstrating how cost items and scenarios are linked through the IFC schema.

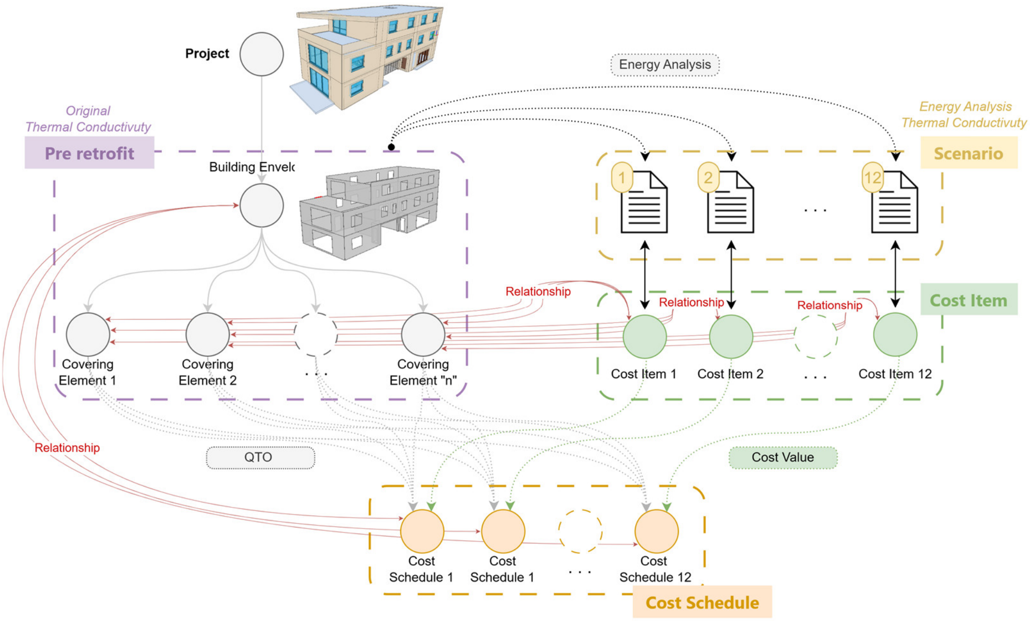

Figure 2. IFC-based workflow for structuring cost and energy data in retrofit analysis.

4. Case Study

The research methodology is applied to a three-story residential building located in Italy, used as a case study to structure cost and energy data within an IFC-based framework for retrofit decision-making. The study evaluates different insulation retrofitting scenarios, focusing on structured cost assessment rather than optimizing energy consumption. The goal is to provide a transparent decision-support system that allows stakeholders to compare retrofit options based on total cost considerations.

To facilitate this evaluation, the BIM model of the building is enriched beyond its conventional geometric representation by embedding cost and linking the energy analysis report within a standardized IFC schema. This approach ensures that the model serves as a searchable and structured information framework rather than just a static digital representation. Cost and energy consumption data are systematically linked to building components, enabling comparative analysis of retrofit scenarios. Twelve parametric insulation retrofit scenarios were developed by applying a consistent insulation thickness but varying the thermal conductivity values (λ ranging from 0.026 to 0.084 W/mK). It should be noted that these form a sample set and can be replaced or extended with other retrofitting scenarios in future applications. These variations represent commercially available insulation materials and support a comparative evaluation of their cost and energy performance characteristics.

The case study utilizes the IfcBuildingSystem to organize the building envelope, ensuring that insulation interventions are clearly classified and their cost implications are systematically integrated. Initially, cost data (i.e., material, installation costs) are defined using IfcCostItem entities, associated with IfcBuildingSystem to organize functional components, and grouped into separate IfcCostSchedules corresponding to each retrofit scenario. This structured flow improves interoperability and accessibility for cost estimation evaluations. By structuring data within an IFC-based model throughout a semi-automated process, this approach reduces data fragmentation and enhances the clarity of cost–energy relationships, demonstrating the advantages of an integrated BIM framework for retrofit planning and decision-making. Due to current limitations in embedding dynamic energy data within standard IFC models, operational energy consumption is simulated externally in EnergyPlus, and corresponding energy costs are subsequently derived and added to the model.

Figure 3 presents the BIM representation of the case study building (left) and the corresponding insulation layer applied for the retrofit analysis (right).

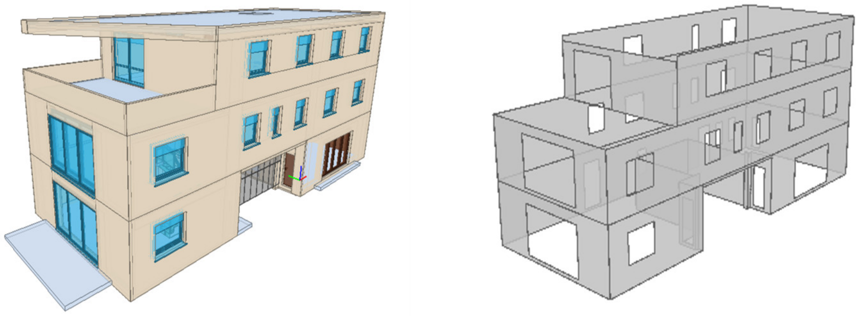

Figure 3. BIM model of the case study building (**left**) and the insulation layer applied for retrofit analysis (**right**).

5. Results and Discussion

The proposed IFC-based methodology produces a structured dataset that integrates energy simulation outputs and cost data across different retrofit scenarios. Each scenario applies an insulation layer with a different thermal conductivity, generating varied cost configurations that can be systematically compared with the pre-retrofit baseline.

The total cost for each scenario was calculated as the sum of Construction and Material Expenditure (CME) and operational energy costs. Operational energy costs were calculated by applying an annual electricity price of 0.109 EUR/kWh, based on the Gestore dei Mercati Energetici (GME) national energy pricing index [35]. The resulting values, obtained externally from the simulation outputs, were incorporated into the IFC model as external references, whereas the CME values are derived from the Regione Lombardia price list. Since the methodology focuses on the digital structuring of retrofit cost information rather than on optimizing energy performance, accordingly, the variation in annual energy consumption across scenarios remains moderate. The evaluated KPI of total cost is employed as a demonstrative output of the proposed IFC-based structuring methodology, illustrating the integration of economic and energy-related data within a BIM environment. However, in future development, additional KPIs, such as payback period, net present cost, and lifecycle cost, can be incorporated into the outputs to enable deeper and more comprehensive scenario comparisons. Table 1 presents a representative overview of the cost breakdown for each scenario, including the construction cost of the insulation system (CME), the annual energy cost derived from the simulated energy consumption, and the resulting total cost.

Table 1. Cost breakdown of insulation retrofit scenarios, including material and installation costs (CME), operational energy costs, and total cost.

Retrofitting Scenarios	**CODE LOM241. OC.EEA. a02.C1515.**	**Annual Energy Consumption**	**Material Unit Price**	**CME**	**Annual Energy Costs**	**Total Cost**
		[kWh]	**[EUR]**	**[EUR]**	**[EUR]**	**[EUR]**
Scenario 1	D0001.0050	3872.2	25.92	22,243.57	422.07	22,665.64
Scenario 2	D0001.0015	3922.6	32.64	28,009.7	427.57	28,437.27
Scenario 3	D0001.0055	3947.5	22.88	19,631.89	430.28	20,062.17
Scenario 4	Od004.0005	3996.2	11.63	9978.77	435.58	10,414.35
Scenario 5	Od004.0510	4020.1	17.79	15,270	438.19	15,708.19
Scenario 6	Od004.0250	4090.1	29.28	25,126.65	445.82	25,572.47
Scenario 7	Od004.0315	4135.4	24.46	20,988.63	450.76	21,439.39
Scenario 8	Od008.0270	4179.7	13.46	11,552.56	455.59	12,008.15
Scenario 9	Od004.0305	4201.5	6.36	5454.08	457.96	5912.04
Scenario 10	D0001.0280	4223.0	9.58	8221.81	460.30	8682.11
Scenario 11	D0001.0295	4244.2	4.81	4124.44	462.62	4587.06
Scenario 12	Od008.0250	4952.2	16.4	14,076.08	539.79	14,615.9

The table demonstrates how the structured cost data enables stakeholders to interpret and compare retrofit alternatives directly within the IFC-integrated BIM model. Scenario 11, for instance, reflects the lowest total cost (EUR 4587.06), indicating a balance between material expenditure and energy performance. In contrast, Scenario 2 and Scenario 6 have significantly higher total costs, mainly due to increased material unit prices. This kind of output dataset enables stakeholders to evaluate cost trade-offs across scenarios, taking into account both initial investment and energy consumption impacts.

The key methodological advantages of this framework are summarized as follows:

- Comparative evaluation for retrofit decisions: Enables systematic comparison of retrofit scenarios by integrating variable cost-efficiency strategies within a structured IFC-based framework;
- Reliable and scalable cost assessment: Enhances consistency and adaptability in cost estimation by structuring retrofit data within the IFC schema, enabling scalable updates and responsiveness to changing material and energy prices;
- Foundation for digital retrofit workflows: Establishes a semi-automated and BIM-based workflow that supports future extension toward fully digital, performance-driven retrofit planning.

While the current framework does not include automated optimization algorithms, it supports informed selection of retrofit strategies by enabling consistent, KPI-based comparison across scenarios. As more detailed or real-time energy consumption data becomes available, the proposed framework can support additional performance metrics without requiring structural modifications.

Despite its contributions, the proposed methodology presents some limitations. First, the current scope is limited to insulation-based retrofitting and does not yet include more complex interventions or deep retrofits, such as HVAC upgrades or renewable energy integration. This limitation is partly due to existing constraints in representing dynamic energy data within the standard IFC schema. The framework also relies on predefined material and installation prices, which may limit responsiveness to real-time market fluctuations. Furthermore, the system does not yet support dynamic cost updates or automated scenario selection, which could further improve its decision-support capabilities.

To support future advancements in digital retrofit planning, the current framework can be extended along several methodological dimensions. Potential developments include the integration of dynamic pricing mechanisms, automated scenario optimization using AI-based approaches, and the incorporation of additional performance indicators such as life cycle cost or payback period. These enhancements would facilitate the evolution of the framework into a fully digital, performance-driven decision-support system, broadening its applicability to a wider range of building systems and retrofit strategies.

6. Conclusions

In parallel to the construction industry's digital transformation, building energy retrofitting requires data-integrated approaches that align sustainability targets with cost-effective planning. This study responds to that need by introducing a structured IFC-based methodology that systematically integrates cost estimation and energy simulation within a BIM environment, aiming to establish a digitalized framework for the comparative evaluation of retrofit strategies. Unlike traditional retrofit approaches that treat cost and energy modeling as separate tasks, this framework uniquely integrates them into an IFC structure, enabling seamless data reuse and scalable application across diverse building contexts. This integration enables transparent, comparative assessments across retrofit options by utilizing structured cost and energy consumption data within a model. The proposed approach is implemented through three phases: (i) generating a detailed BIM model and exporting it to the IFC format; (ii) modeling twelve parametric insulation retrofit scenarios using EnergyPlus, with cost data linked to IFC entities through a semi-automated workflow; and (iii) identifying the most cost-effective solution based on total cost as a key performance indicator.

The results from the case study demonstrate the potential of this approach to enhance consistency and decision-making in retrofit planning. By linking geometric, thermal, and financial attributes within the IFC schema, the methodology transforms BIM from a static design model into a data-rich environment for informed evaluation. The framework facilitated a direct comparison of twelve retrofit scenarios, leading to the selection of the most cost-effective solution based on total cost.

While the current scope is limited to envelope insulation and externally computed operational energy costs, the framework establishes a replicable foundation for broader application. Notably, the methodology is designed to be extensible. Future enhancements could incorporate dynamic pricing, algorithmic scenario optimization, and broader performance metrics, such as payback period, life cycle cost, or environmental impact. These developments would strengthen its applicability to deeper retrofitting measures, including HVAC upgrades or renewable energy integration. Additionally, future developments could address multi-currency handling and diverse pricing structures to enhance interoperability across different regions and cost databases.

This research not only delivers a practical methodology but also contributes to the broader digital transformation of the AEC/FM sector, framing BIM as a foundation for data-driven, performance-based retrofit planning. The structured integration of energy, cost, and geometric data lays the foundation for future alignment with digital twin and smart building initiatives. Future extensions may explore advanced data structuring methods to further enhance semantic querying, interoperability, and scalability across retrofit domains. This aligns with broader industry initiatives focused on improving building stock efficiency and supports policy frameworks advocating data-driven renovation strategies. In doing so, it lays the groundwork for a new generation of performance-oriented, digitally enabled retrofit solutions. Moreover, further validation across different building types, use cases, and geographic contexts would be a valuable next step for assessing the broader applicability of the proposed framework. Validation on a real-life retrofitting project would further support its practical applicability.

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