Journal of Engineering, Project, and Production Management
2023, 13(3), 0024

Condition-based Maintenance Using BIM: A Case Study of Energy Modeling for a Residential Building

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Project Management
Received November 6, 2022; received revisions March 2, 2023; May 6, 2023; accepted May 9, 2023

Abstract: Efficient management of the built environment is a top priority globally. In light of climate change and funding deficits, and considering the huge stock of buildings and infrastructure, especially in urban centers, the needs and demands induced can be successfully met through effective and efficient maintenance of existing built assets, rather than building new ones. This is the reason behind the continuous refinement and update of operation and maintenance policies and programs in a process of addressing technological advances in the construction industry to render maintenance as the primary approach to achieving the upgrade of the built environment. Yet, a fast transition to modern maintenance management systems requires an understanding by the construction industry of their mode of implementation and of the benefits involved. This paper contributes to this goal by presenting clear and easy to replicate examples of applying Building Information Modeling (BIM) in the context of the condition-based maintenance strategy. First, the dominant maintenance strategies in the construction industry, including preventive, predictive, reliability-centered, corrective, etc. are presented and explored in relation to their efficiency for construction projects. Then BIM technology is applied to showcase the implementation of condition-based maintenance for improving the energy profile of a building. A BIM model of a simple residential building generated in the context of this research is used as a basis for respective energy models addressing three different scenarios of interventions in thermal insulation and door and window frames. The scenarios are evaluated in terms of energy cost reductions and building's useful life prolongation concerning the energy efficiency aspect. The paper presents to practitioners in the construction industry – mainly designers and operators – a clear, straightforward, and replicable method of designing BIM-based maintenance for buildings that highlight issues of concern and facilitates understanding of the mode of implementation, thus enhancing in real terms the industry's efficiency in applying technological advancements in every day's practice.

Keywords: Building information modeling, computerized maintenance management system, maintenance management, energy modeling.

DOI 10.32738/JEPPM-2023-0024

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1. Introduction

The global economic crisis of 2007-2008 has significantly affected the construction industry and resulted to the reduction of the industry's activity (Sudheer Babu and Ceo, 2016). At the same time, the growth of cities and the demand for an increased standard of living under the conditions met during a climate change era impose – maybe now, more than ever – the efficient maintenance of numerous structures (Yin et al., 2020). Such efficient Operation & Maintenance (O&M) programs can be successfully implemented with the use of Building Information Modeling (BIM), which constitutes a very promising tool for Building Maintenance Management (BMM) (Yin et al., 2020; Falorca, 2019; Carbonari et al., 2016; Wang et al., 2014). Nevertheless, even though BIM's potential for O&M is acknowledged for many years by facility operators, there is strong evidence that is it still unexploited due to several limitations, and challenges (Falorca, 2019; Gao and Pishdad-Bozorgi, 2019; Ismail, 2019; Liu and Issa, 2014). Durdyev et al. (2022) examine such issues met in New Zealand's construction industry, while Gao and Pishdad-Bozorgi (2019) refer to a similar survey that indicates the marginal added value of BIM in facility operation in the Netherlands. In both these cases, as in many others cited in several recent research efforts (e.g., Durdyev et al., 2022; Ensafi et al., 2022), the findings, collectively, indicate a current situation where mainly industry professionals, while they increasingly implement BIM in the design and construction phases to benefit in multiple ways (Ensafi et al., 2022), they still hesitate to extend its application to O&M phase as they lack evidence and understanding of the respective earnings from such exploitation of BIM (Gao and Pishdad-Bozorgi, 2019).

This paper aims at contributing to the goal of enhancing the research and industry community's understanding of both the potential and benefits, as well as the mode of application of BIM for O&M in construction. As a proof of concept, it adopts a case study approach, similar to respective previous research efforts (e.g., Ensafi et al., 2022), to present a comprehensive, easy to replicate example of applying BIM for condition-based maintenance of ordinary buildings. The produced results allow also for a clear identification of the earned benefits from a rapid and accurate investigation of many scenarios when it comes to interventions for improving an ordinary building's energy performance with the use of BIM. Hence, this paper provides a practical and useful insight to designers and operators that could enhance in real terms their understanding and efficiency in applying BIM for O&M in their every day's practice. The following sections first present and analyze the context (i.e., maintenance strategies) and then provide an application of BIM-based building maintenance for energy requirements.

2. Methodology

The applied methodology is graphically presented in Fig. 1. As shown there, the first step is the study of the various maintenance strategies that allow the understanding of the goals and requirements existing in different contexts. This step is a two-stage process comprising: (a) literature sources identification and study, and (b) selection of the appropriate maintenance strategy for the case in hand.

The second step which can run simultaneously to the first one is the creation of the building's model with the use of some appropriate BIM software. Then the last, step is to apply the required analysis (in this paper, it is an energy efficiency analysis) and examine (i.e., run and evaluate) several scenarios of maintenance plans to decide the most efficient one.

The proposed methodology was applied in the presented case as described in the following:

- The literature review on BMM confirmed the grouping of maintenance strategies and allowed for the identification and understanding of their determinants and main features. The reference in a previous research effort of a comparative scheme that allows for the selection of the appropriate maintenance strategy in a specific case was drawn from the literature and exploited in this paper.
- The digital model of a two-story, 8,0m tall residential building with a tiled roof was created with the use of Autodesk's Revit. Revit was selected based on the criteria of: (a) direct and unhindered availability, (b) convenience of application due to the researchers' previous familiarization to other Autodesk's CAD software, and (c) popularity in the construction industry (Aladağ et al., 2016; Ismail, 2019; Kaewunruen & Lian, 2019), which could increase the impact of the presented work.
- The energy efficiency analysis based on different building's maintenance scenarios was performed with the use of Autodesk's Insight. Insight is a software that provides the ability to designers to test various scenarios towards improving the energy performance of their models. Insight can process all relative data from a BIM model and perform calculations according to specific standards (e.g., ASHRAE 90.1). Being an Autodesk's product, Insight collaborates perfectly with Revit, thus creating (the two of them together) an effective and reliable platform for designers (AutoDesk, Inc., 2021).

The detailed application of the methodology is presented along with the results in Section 3.

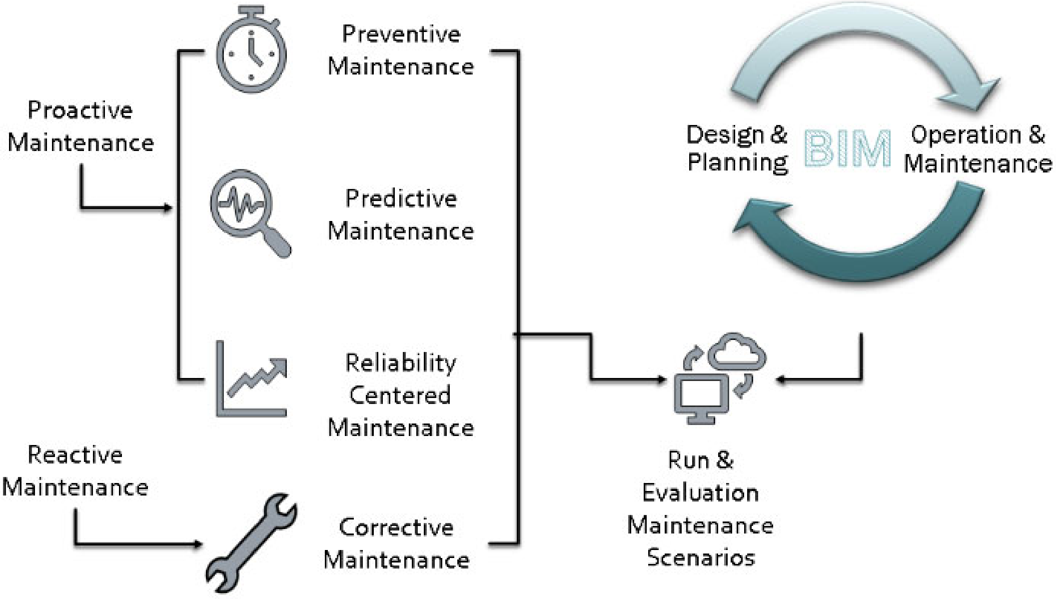


Fig. 1. Graphical illustration of the applied methodology

3. Results

The results from the application of each step of the described methodology are presented in Sections 3.1-3.3.

3.1. Maintenance Strategies

Maintenance can be proactive or reactive depending on whether it is applied, respectively, before or after a failure occurs. Proactive maintenance aims at preventing a failure and/or minimizing the failure's risk, i.e., minimizing the probability of occurrence or the consequences' impact upon occurrence. On the other hand, reactive maintenance aims at restoring operation at acceptable levels after the event of a failure. While reactive maintenance can be – by nature – only corrective, proactive maintenance can take the form of several approaches, namely preventive, predictive, and reliability-centered as shown in Fig.1. The study of the respective literature helps to identify the main characteristics and the differences between the distinct approaches. Selcuk (2017) highlights the following characteristics of each one of the mentioned approaches:

- Preventive (PM) or time-based maintenance (TBM), is performed on a periodical basis to prevent from the occurrence of a potential failure. The periods of application may be determined either based on the calendar time or on the operational time of the system or equipment that needs to be maintained.

- Predictive or condition-based maintenance (PdM) is based on information that indicates wear and tear, which may lead to more energy consumption and/or is likely to result in failure. Thus, PdM aims at preventing failure, but also at providing efficient operation for the system.

- Reliability-based maintenance (RCM) is the most recent maintenance strategy and could be characterized even as an analysis and decision making method extending from the context of a typical maintenance strategy. In fact, it resembles a more comprehensive predictive maintenance approach (PdM), which is mostly based on the reliability of a system or component.

According to the literature, proactive maintenance has the following specific advantages (Basri et al., 2017; Kim et al., 2016; Selcuk, 2017): (a) it improves health and safety, environmental conditions, as well as product's quality and reliability, (b) it leads to less cost requirements for spare parts and corrective tasks and reduced amounts of waste of raw materials and consumables, (c) it increases return on investment (ROI) and reduces maintenance costs up to 10 times, (d) it drastically reduces repairs, which significantly increase costs, (e) it drastically reduces system failures by 70% to 75%, and downtime of a failed system by 35% to 45%, and (f) it increases productivity by 20% to 25%.

Basri et al. (2017) have compared the discussed maintenance strategies in terms of various features, thus producing a quite fair guide on the selection of the appropriate one for a case in hand. This comparison is presented in Table 1.

Table 1. Maintenance strategies according to Basri et al. (2017)

Features	Corrective maintenance	Preventive maintenance	Predictive maintenance	Reliability-centered maintenance
Maintenance approach	Reactive	Proactive	Proactive	Proactive
Maintenance category	Fixing after failure	Time-based maintenance (periodic)	Diagnostic-based maintenance (condition monitoring)	Prognostic-based maintenance
Downtime	Highest	Less	Close to minimum	Least
Good for failures	Random age-based	Age-based	Prevents to occur (near-optimal)	Prevents to occur
Expensive (manpower)	Maximum	Little less	Moderate	Minimum
Initial deployment cost	None	Slightly higher	Higher	Most expensive
Computational cost	Least	Little higher	Based on current conditions	Highest
Schedule required	Not applicable	Based on the standard useful life of component or history of failures	Inspect, repair, or replace based on need	Based on forecast of remaining equipment life
Action	Inspect, repair, or replace after failure	Inspect, repair, or replace at predetermined intervals, forecasted by design, and updated through experience	Continuous collection of condition-monitoring data	Forecasting of remaining equipment life based on actual stress loading
Prediction type	None	None	On and off system, near real-time trend analysis	On and off system, real-time trend analysis

3.2. Building's Information Model

In the context of this work, the digital model that was developed is presented in Fig.2. The two views (Fig.2a, Fig.2b) and the plans of the basement (Fig.2c) and the first floor (Fig.2d) depict a typical and simple residential building. To conduct the building's energy-efficiency analysis, the typical profiles of the windows and doors frames, the exterior walls, the tiled roof, and the ground floor need to be considered and the thermal resistance (R) of each one of them needs to be assessed. Both the drawings of the structural details and the calculations of the thermal resistance are feasible using Revit. The respective results are summarized in tables 2-4.

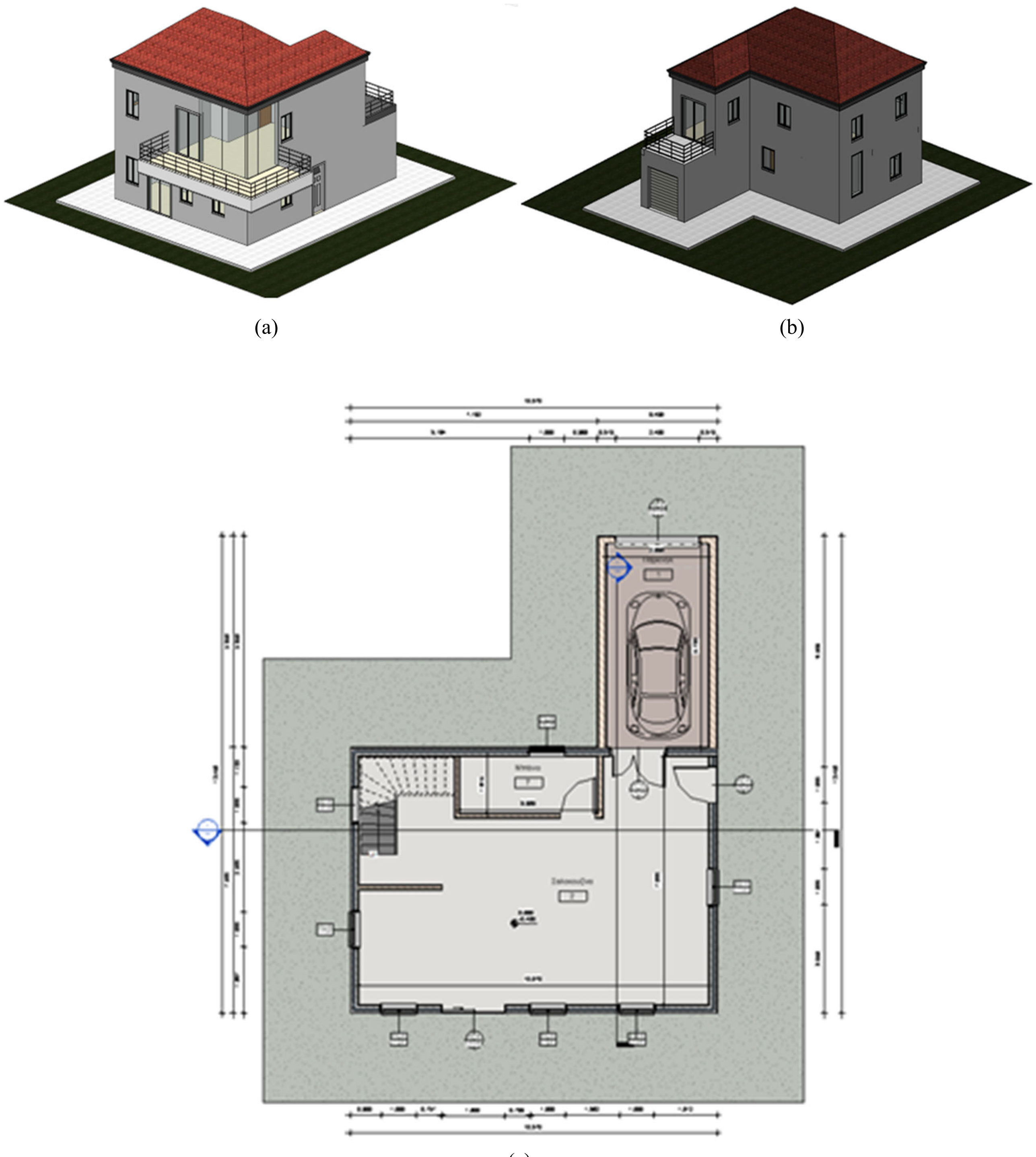
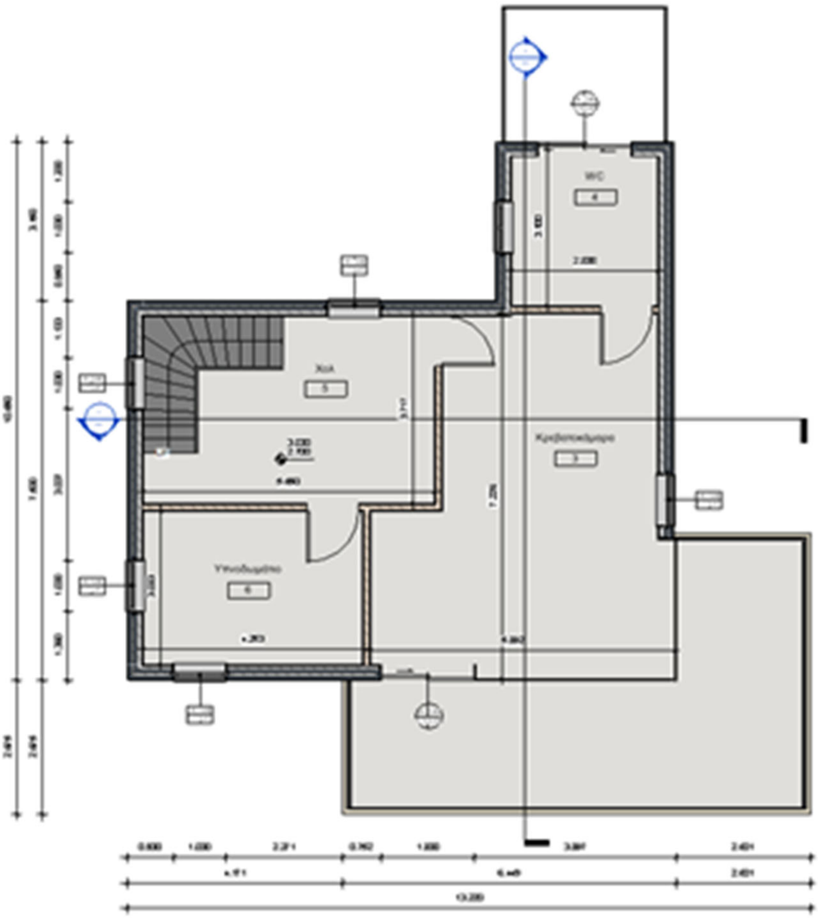

(a)
(b)
(c)

Fig. 2. Views and plans of the building's model



(d)

Fig. 2. Views and plans of the building' 5s model (continuous)

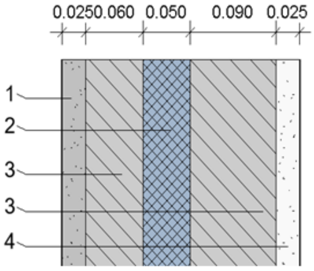
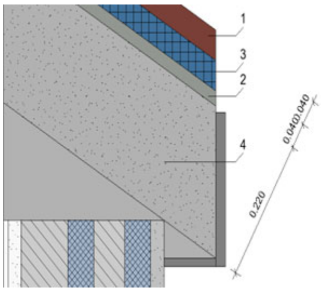
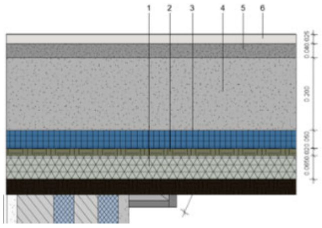
Table 2. Typical profiles of windows frames

Floor Level	Type/Material/Glass panel	Dimensions (m) (Height X Width)	R $(m^2*K)/W$
Ground	Double/PVC/Double	1,20 X 1,00	3,1292
1	Double/PVC/Double	1,20 X 1,00	3,1292
Ground	Single/PVC/Double	1,20 X 1,00	3,1292
Ground	Single/PVC/Double	2,20 X 1,00	3,1292

Table 3. Typical profiles of doors frames

Floor Level	Type/Material/ Glass panel	Dimensions (m) (Height X Width)	R $(m^2*K)/W$
Ground	Parking/Aluminum/No	2,40 X 2,20	3,7021
Ground	Single(entrance)/ PVC/Triple	1,00 X 2,20	2,0838
Ground	Single/Wood/No	1,00 X 2,20	2,1944
Ground	Double (Sliding)/ PVC/Double	1,80 X 2,10	4,1165
Ground	Double (security)/ Aluminum/No	1,50 X 2,10	3,7021
1	Single/Wood/No	1,00 X 2,20	2,1944
1	Double (Sliding)/ PVC/Double	1,80 X 2,10	4,1165

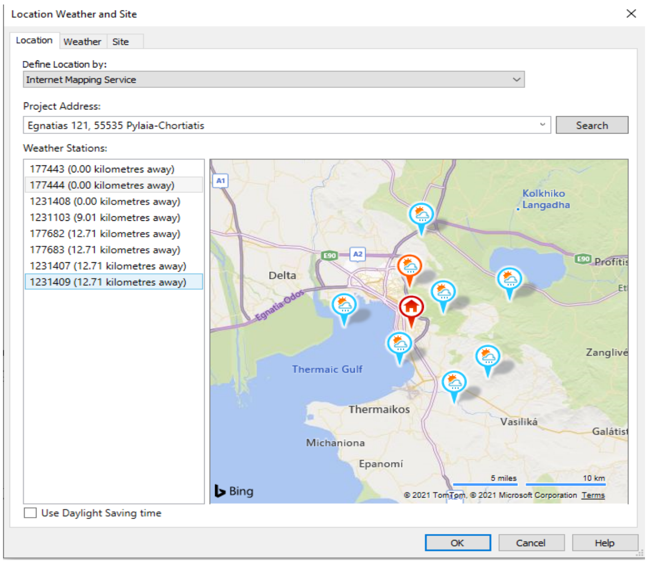
Table 4. Typical profiles of structural elements

Structural element	Structural detail	Memo	R $(m^2*K)/W$
Exterior masonry		(1) exterior finishing (plaster) (2) insulation (extruded polysterine XPS) (3) brick layer (4) interior finishing (plaster)	2,0369
Tiled roof		(1) tiles (ceramic) (2) bitumen sheet (3) insulation (extruded polysterine XPS) (4) concrete	1,7593
Ground floor		(1) light concrete (2) sand (3) insulation (extruded polysterine XPS) (4) concrete (5) cement dust (6) marble	2,1938

3.3. Maintenance Plan for Energy-Efficient Building

The first step of the planning process is the incorporation to Revit of the building's location. This task, which is depicted in Fig.3 aims at collecting data concerning weather conditions, such as maximum and minimum temperatures, and day length to support solar (Fig.4) and energy analysis. Then, based on the building's plan the initial area and volume calculations are performed. Overall, the building has an area of 164,85m^2 and a volume of 540,12m^3.

Once the standard model's descriptors (i.e., location and dimensions) are introduced to Revit, it is time for adjusting the energy settings. The software allows the introduction of several model's details that are required for the energy analysis, such as the building's type, use, area, volume, year of construction, and thermal and cooling system. An instance of the introduction of such details is depicted in Fig.5.



Define Location by: Internet Mapping Service

Project Address: Egnatias 121, 55535 Pylaia-Chortiatis

Weather Stations:

177443 (0.00 kilometres away)
177444 (0.00 kilometres away)
1231408 (0.00 kilometres away)
1231103 (9.01 kilometres away)
177682 (12.71 kilometres away)
177683 (12.71 kilometres away)
1231407 (12.71 kilometres away)
1231409 (12.71 kilometres away)

☐ Use Daylight Saving time

Fig. 3. Introduction of the model's location to Revit

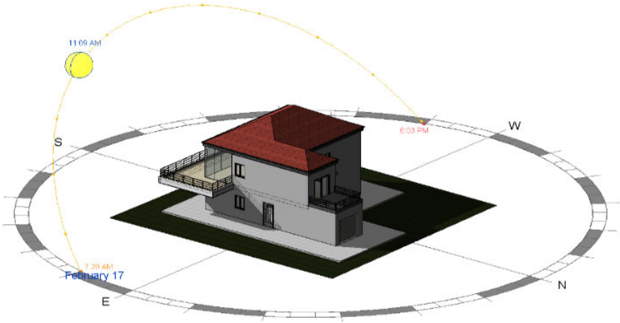
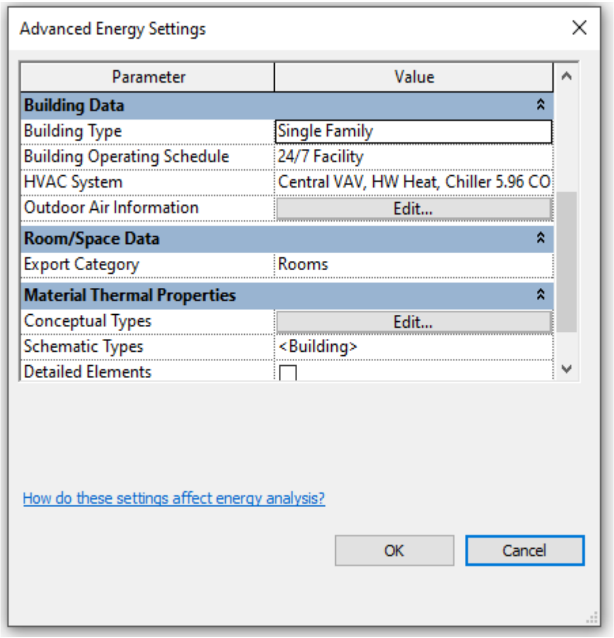


Fig. 4. Solar analysis for the case study's model


Advanced Energy Settings

Parameter	Value
Building Data	
Building Type	Single Family
Building Operating Schedule	24/7 Facility
HVAC System	Central VAV, HW Heat, Chiller 5.96 CO
Outdoor Air Information	Edit...
Room/Space Data	
Export Category	Rooms
Material Thermal Properties	
Conceptual Types	Edit...
Schematic Types	<Building>
Detailed Elements	☐

How do these settings affect energy analysis?

Fig. 5. Introduction of the model's details for the energy analysis

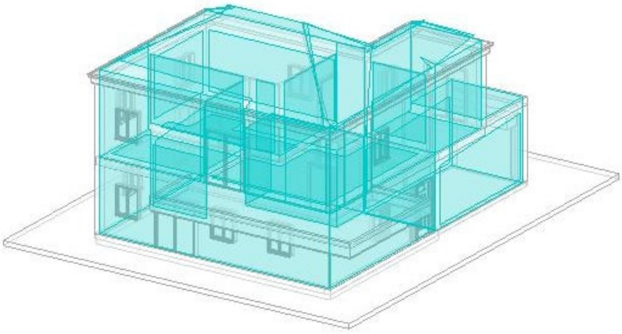


Fig. 6. The analytical energy model

Since all previous settings have been introduced to Revit, the analytical energy model is created as shown in Fig. 6. The energy model presents all the surfaces for which energy data have been introduced (e.g., an exterior wall bearing thermal insulation). A properly parameterized analytical energy model should be free from discontinuities and voids that would indicate excluded structural elements from the energy analysis.

The energy analysis is performed based on the building's area, volume, and structural elements with the use of Autodesk's Insight that makes all the calculations after introducing the costs of energy and heating for the building. For the case study, the respective unit costs were set from electricity and natural gas suppliers in Greece at the prices of 0.11058 €/kWh and 0.2374€/m^3, respectively.

The energy analysis yielded for the specific model an expected total cost of 18,20€/m^2 for the year 2021, and a maximum cost of 71,80€/m^2 (the minimum cost was 0€/m^2 corresponding to no use of the residence). Fig. 7 shows that the assessed expected total cost is significantly high as it exceeds, for example, the value that according to the ANSI/ASHRAE/IES Standard 90.1 corresponds to the optimal energy performance of a much larger establishment such as a building up to 20 floors that includes tenant spaces (with 1-3 bedrooms, a kitchen, a bathroom, and living space), first-floor spaces (such as common meeting rooms, a workout room, and management offices, leased offices, and light retail), vertical transportation, and laundry facilities (ASHRAE, 2022).

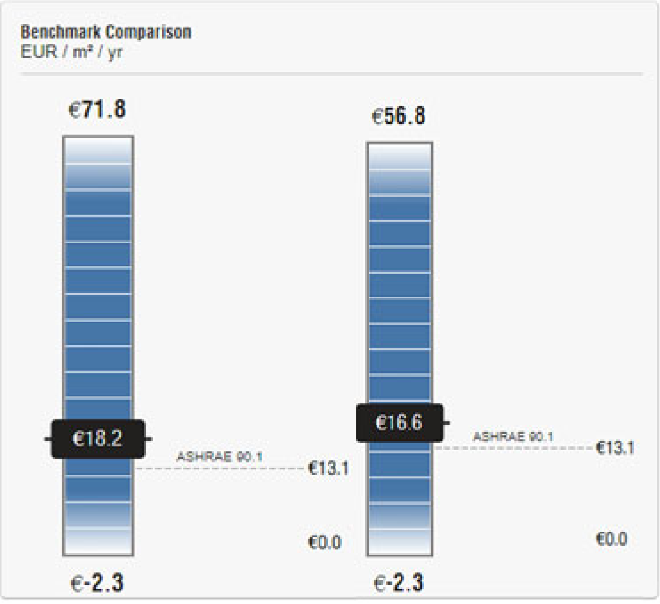


Fig. 7. Comparison of energy costs between the current condition and the maintenance plan of Scenario A

This finding on the one hand clearly indicates a planning failure regarding the building's energy efficiency, while on the other hand necessitates a highly sufficient maintenance plan that could preserve costs to minimum levels until intervening to the building. The scenarios that were studied in this context focused on the replacement of exterior doors and windows frames, the maintenance of thermal insulation and the concurrent implementation of both previous scenarios. The results per case are presented in Sections 3.3.1-3.3.3.

3.3.1. Scenario A: replacement of exterior doors and windows frames

Scenario A involved the replacement of the model's windows glass panels with new ones made by PVC and bearing a triple glass (energy triplex 3mm-3mm/5mm Ug ≅ 1,10). The respective calculations yielded a saving (starting immediately after the replacement) of the building's expected total energy costs by 1.60€/m^2/year, as shown in Fig.7. As also shown in the figure, the respective maximum total energy costs are proportionally reduced even more to 56.80€/m^2/year, according to the same calculations. Figures 8 and 9 show the energy costs in the building's north view, before and after the implementation of the investigated maintenance plan. As shown there, the achieved cost reduction reaches almost 85%, which is an outstanding result in terms of energy efficiency during the building's life cycle. The calculations performed for the rest views of the building have yielded similar results; however, they are not presented here due to paper's length limitations.

It is evident from the analysis so far, that Scenario A offers a significant reduction of the annual energy costs; however, the decision for applying this scenario should consider the total cost for maintenance and replacement of doors and windows frames, which is the sum of the respective costs. For an indicative price taken from the market, the overall cost can be calculated and then configured as a unit cost by dividing with the overall building's area. Nevertheless, this figure does not provide any hint for the year of replacement in the context of the maintenance plan.

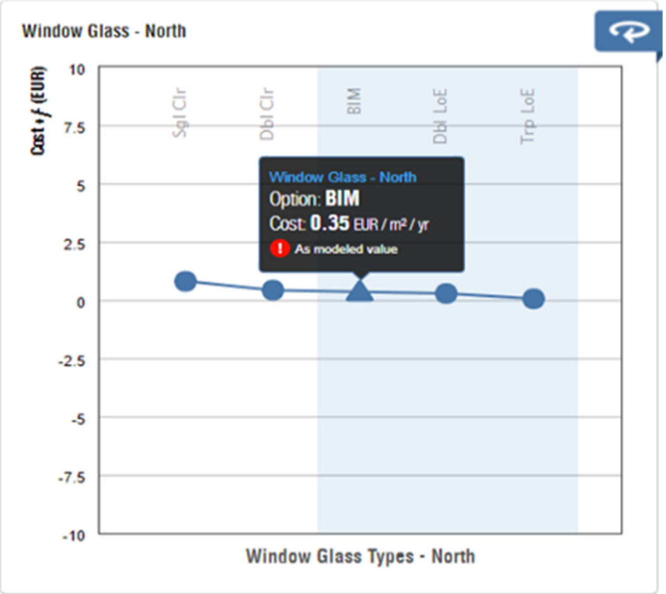


Fig. 8. Energy cost for the north view's windows glass panels before their replacement

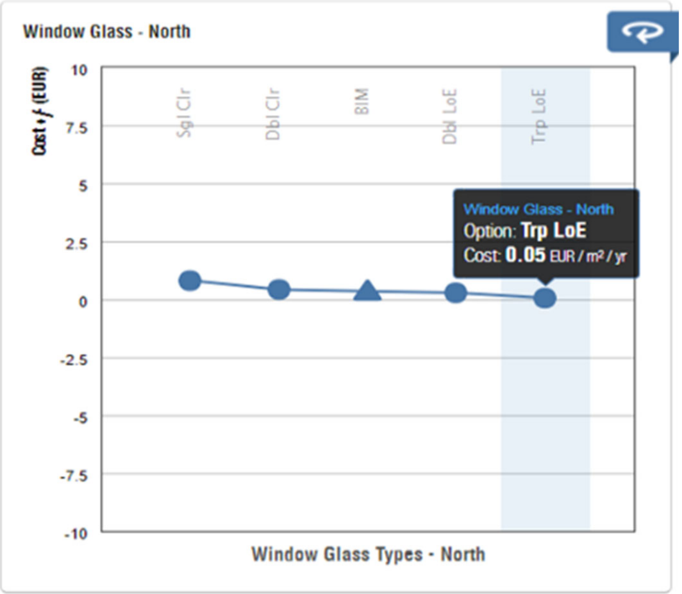


Fig. 9. Energy cost for the north view's windows glass panels after the replacement

Therefore, to decide on this critical parameter Eq. (1) must apply (as a boundary condition):

$$MC + ECa = ECb \tag{1}$$

where *MC* is the maintenance cost, *ECa* is the energy cost after maintenance, and *ECb* is the energy cost before maintenance, which should not exceed the sum on the other side of the equation.

To determine both *ECa* and *ECb*, it is required to consider the anticipated reduction in energy performance due to wear and tear from use. At the design stage, a usual approach is to apply the random deterioration rate method where the typical energy efficiency reduction is given by Eq. (2) (Huang et al., 2018):

$$Q_t = Q_0 * (1 - D_a t) \tag{2}$$

where D_a is the annual average degradation rate, Q_0 is the value of the initial performance, and *t* is the usage year.

As D_a may vary depending on material, performance, and occupancy variations, for this case study it is taken equal to a value of 4% in compliance with the useful life of materials according to Badiei and Micah Lang (2016).

The last factor that needs to be considered in the context of the analysis is the future value of money as the study spans a long period that corresponds to the building's life cycle, which in the presented case exceeds 60 years.

Eq. (3) is used for the discounting to future value:

$$F = P \times (1 + r)^t \tag{3}$$

where *F* is the future value at year *t*, *t* is the year in the future for which the discounting is required, *P* is the present value, and *r* is the update coefficient.

For the presented case study, *r* is taken according to the approach proposed by Stewart (2008), which uses the Consumer Price Index, i.e., the average change over time in the prices paid by urban consumers for a representative market basket of consumer goods and services. Based on the available data provided by the Bureau of Labor Statistics (2021) for a period of 20 years prior to the year of the performed analysis, the update coefficient for the presented case study is taken as equal to a value of 2%.

Once all factors and equations required for the assessments are determined, the respective calculations yield the results shown in Fig.10. As shown there, for Eq. (1) to apply, i.e., for achieving the optimal energy efficiency based on Scenario A two replacements as described in Scenario A should optimally take place, namely one in the 28th year and another one in the 60th year of the building's life cycle. This finding is consistent with the useful life cycle of PVC windows frames, which is reported to be between 20-40 years (Badiei and Micah Lang, 2016), while it, also, validates the analysis' assumptions concerning the values of the annual average degradation rate and the update coefficient.

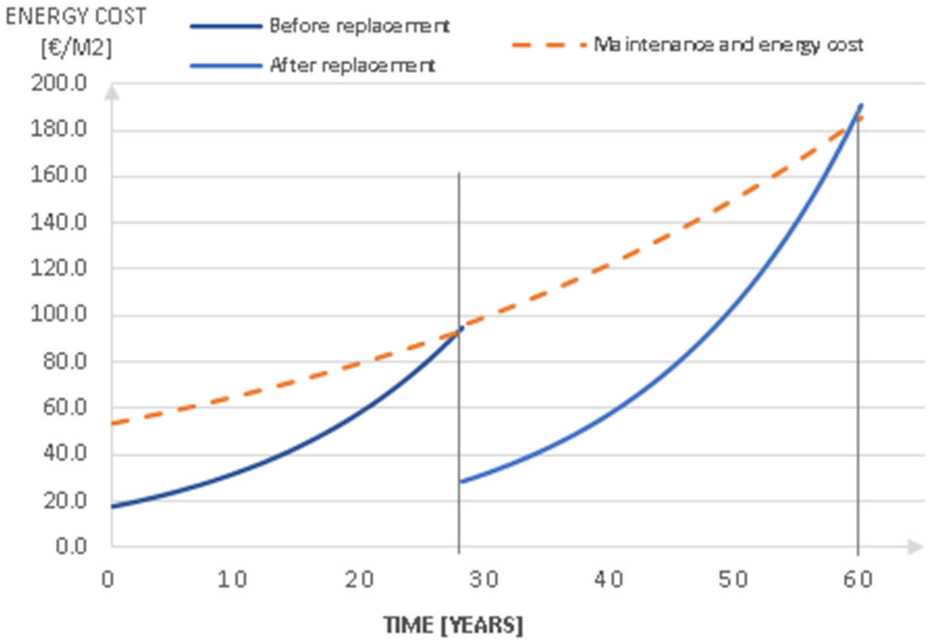


Fig. 10. Scenario A: costs and time of implementation

3.3.2. Scenario B: maintenance of thermal insulation

Scenario B involved the maintenance of the external thermal insulation with the addition to the building's external side of an extra layer of 5cm thick, extruded polysterine XPS. The new profile's thermal resistance was assessed equal to 3,888 (m^2*K)/W.

Following a similar analysis to the one performed for Scenario A, the respective calculations yielded a saving of the building's expected total energy costs by 1.40€/m^2/year, and a reduced amount of maximum total energy costs (66,70€/m^2/year), as shown in Fig.11. Then, by applying equations 1-3 and taking into consideration the same assumptions with regard to the determination of factors and coefficients of the analysis, the costs and time of implementation of the maintenance plan for Scenario B are shown in Fig.12.

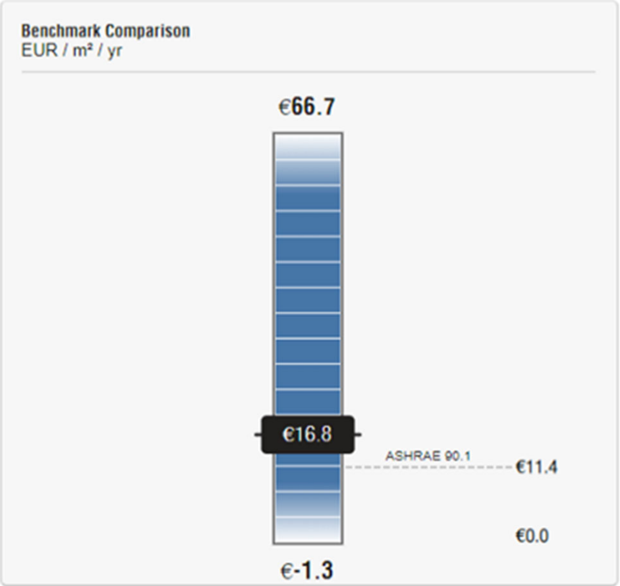


Fig. 11. Energy costs for maintenance plan of Scenario B

As shown in the figure, the achievement of the optimal energy efficiency based on Scenario B is feasible with an intervention to the external thermal insulation in the 10th year and in the 22nd year of the building's life cycle.

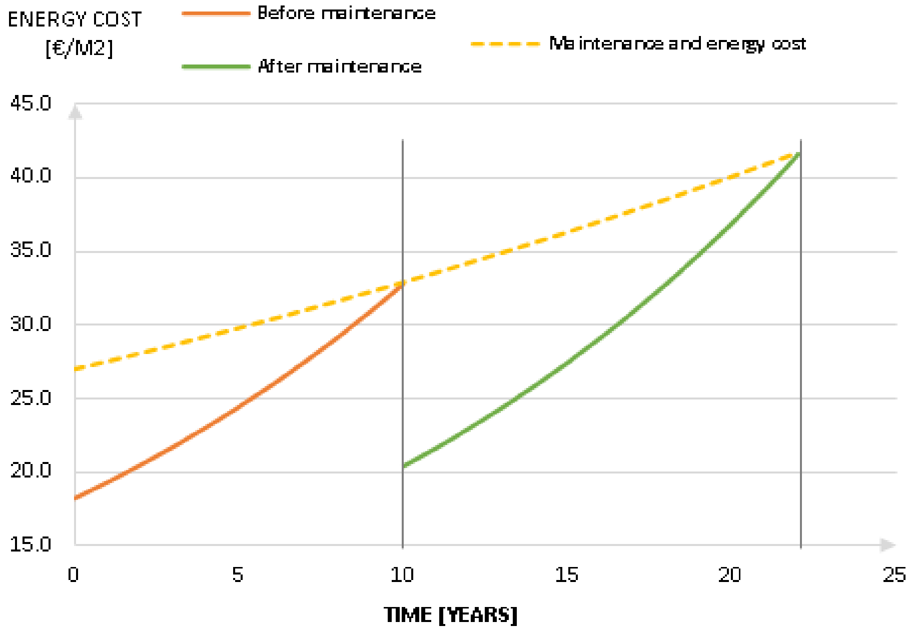


Fig. 12. Scenario B: costs and time of implementation

3.3.3. Scenario C: application of both scenarios A & B

The last scenario that was investigated, namely Scenario C involved the combination of the previous two scenarios, i.e., a concurrent intervention to the doors and windows frames and the external thermal insulation as described in Sections 3.3.1 and 3.3.2. The saving of the building's expected total energy costs in this case is – quite expectedly – significantly increased as it reaches the value of 2.80€/m^2/year (see Fig.13), which is a 75% increase of savings compared to Scenario A, and a respective 100% increase compared to Scenario B. A major increase of savings is also noted regarding the maximum total energy costs, which in this case is calculated as equal to 49,70€/m^2/year, a value decreased by 12,5% and 25% compared to scenarios A and B, respectively.

The last step for this scenario was, again, the application of equations 1-3 under the same assumptions with regard to the determination of factors and coefficients of the analysis. The respective results in this case are shown in Fig.14 and indicate an optimal energy efficiency when the interventions take place in the 32nd year and in the 68th year of the building's life cycle. It should be reminded here that in this maintenance plan the interventions are made at the same time.

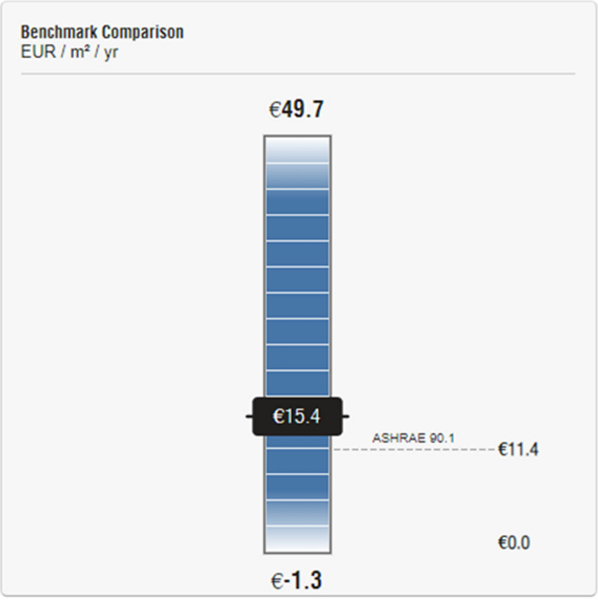


Fig. 13. Energy costs for maintenance plan of Scenario C

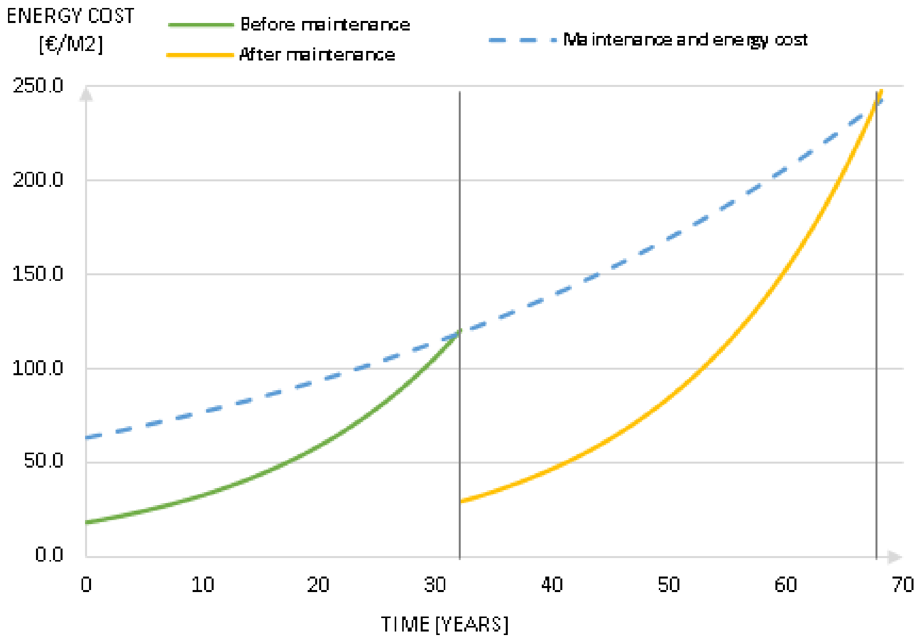


Fig. 14. Scenario C: costs and time of implementation

4. Discussion

The selection between different maintenance plans can be a very demanding task due to the large number of alternatives that may be available, the required computational effort for developing these plans and the great number of parameters that may be considered towards reaching a decision. The examined case study supports this conclusion.

As shown in Table 5 that summarizes the results of the condition-based maintenance analysis that was performed to achieve optimal energy efficiency of a residential building, there are several factors that could affect the final decision over the maintenance plan to apply:

- Scenarios A and C increase the useful life of the building by four years from the first to the second intervention, while scenario B increases it only by two years, respectively.

- Scenario B requires the fastest intervention, while at the same time it is concluded at the earliest period during the building's life cycle. On the opposite side, Scenario C provides more time for application of the first intervention, but it lasts more than any other scenario during the building's life cycle.

- Scenario C is by far the most efficient in terms of cost savings, while the other two scenarios are quite similar to this end.

The above remarks clearly show that the applied methodology for performing condition-based maintenance analysis with the use of BIM, whereas it is beneficial in terms of accuracy, plurality, and computational efficiency, it may create new issues with regard to the decision-making process due to the great number of alternatives that can produce, and the need for determining and weighting the decision-making criteria.

Table 5. Summary of conditional-based maintenance plans results

Maintenance Scenario	A	B	C
Type of maintenance	Replacement of exterior doors and windows frames	Maintenance of thermal insulation	Combination of scenarios A & B
1st intervention (years)	28	10	32
2nd intervention (years)	60	22	68
Useful life increase (years)	4	2	4
Energy costs savings (€/m^2/year)	1,60	1,40	2,80

5. Conclusions

The literature review has shown that the various maintenance strategies differ from each other in terms of benefits and implementation requirements, and, furthermore, no strategy is dominant among the others. While, for example, predictive and reliability-focused maintenance strategies could be considered as optimal based on the presented reduced maintenance costs, number of unexpected and sudden failures and downtime, and the subsequent increase of productivity, the initial deployment and computational costs are significantly high. Nevertheless, there is a clear indication that proactive maintenance is more beneficial to the reactive one.

Another finding from the literature review is that despite the fewer implementations of BIM in maintenance compared to those in the design and construction of an infrastructure, it is undoubted that it has a huge potential to support maintenance strategies and increase the efficiency of maintenance plans.

Based on the above, this paper presented an example of a comprehensive, easy to replicate implementation of BIM for condition-based maintenance of a typical residential building aiming at increasing its energy efficiency. The main conclusions inferred from this process are the following:

- The application of BIM for maintenance is equally beneficial to its application to design or construction. In fact, the continuous monitoring, the accuracy of assessments, the credibility of the applied processes in terms of meeting the required regulations and other constraints are BIM's features that may be of more significance during the operation and maintenance phase that spans a longer period of the project's lifecycle and presents more difficult interventions to the structure.

- The use of appropriate BIM software that minimizes compatibility issues and maximizes computational efficiency and reliability is essential; however, BIM-based maintenance is not an assumptions-free process. In the presented case, there were several such assumptions introduced by the operator, e.g., the change in the value of money over time, the reduction of the building's energy efficiency due to deteriorating material, etc. These assumptions remind that, still, maintenance is considerably depending on the human factor even when the best of software solutions is employed.

- The potential for investigating various scenarios is exponentially increased as BIM allows for rapid implementation of numerous plans with varying parameters and features. The alternative maintenance options to investigate can be so many that certain criteria should apply for keeping them at a manageable scale.

This paper aimed at providing a practical and useful insight to designers and operators both for the benefits as well as for the mode of application of BIM in O&M in construction, thus enhancing in real terms their understanding and efficiency in applying it in their every day's practice. The next steps of this research course are focusing on the increase of the accuracy and reliability of the predictions addressed in a maintenance plan through the definition of a deterioration factor of the structure according to some key characteristics of the structural elements. Such an index could facilitate and result to an even more reliable and efficient BIM-based maintenance of infrastructure.

Author Contributions

Evangelos Margaritopoulos has contributed to this paper to conceptualization, methodology, software, validation, analysis, investigation, data collection, and visualization. Yiannis Xenidis has contributed to this paper to conceptualization, methodology, draft preparation, manuscript editing, supervision, and project administration. All authors have read and agreed with the manuscript before its submission and publication.

Funding

This research received no specific financial support from any funding agency.

Institutional Review Board Statement

Not applicable.

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