

BIM and AI-Supported Decision-Making for the Adaptive Reuse of Historic Buildings: The Osmaneli Aya Yorgi Church Case Study

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Abstract: This study proposes an innovative assessment framework that integrates Building Information Modeling (BIM) with AI-supported multi-criteria decision-making to guide the adaptive reuse of the Aya Yorgi Church in Osmaneli. Using historical and architectural data, an HBIM-based digital model of the building was developed, and three potential reuse scenarios—museum, cultural center, and exhibition hall—were evaluated quantitatively. The assessment focused on three main criteria: energy consumption/environmental performance, maintenance and operating cost/economic dimension, and visitor capacity with spatial compatibility/social-functional dimension. Numerical simulation outputs were incorporated into a TOPSIS-based decision model to compare the alternatives. The findings indicate that the museum scenario, with a score of 0.82, is the most suitable option. The cultural center ranked second due to its higher energy use and operating costs despite its social advantages, whereas the exhibition hall ranked third because of its limited visitor capacity. The study demonstrates that integrating BIM and AI can enhance decision-making processes by providing a more objective, measurable, and innovative approach to the conservation and sustainable adaptive reuse of cultural heritage buildings.

Keywords: Cultural heritage, Adaptive reuse, Building information modeling (BIM), Heritage building information modeling (HBIM), Multi-criteria decision-making.

Tarihi Yapıların Yeniden İşlevlendirilmesinde BIM ve Yapay Zeka Destekli Karar Verme: Osmaneli Aya Yorgi Kilisesi Örneği

Öz: Bu çalışma, Osmaneli'deki Aya Yorgi Kilisesi'nin yeniden işlevlendirilmesine yönelik olarak Yapı Bilgi Modellemesi (BIM) ve yapay zeka destekli çok kriterli karar verme yöntemlerini bütünleştiren yenilikçi bir değerlendirme çerçevesi sunmaktadır. Tarihsel ve mimari veriler kullanılarak yapı için HBIM tabanlı bir dijital model oluşturulmuş ve üç potansiyel yeniden kullanım senaryosu—müze, kültür merkezi ve sergi salonu—nicel olarak analiz edilmiştir. Değerlendirme, enerji tüketimi/çevresel performans, bakım ve işletme maliyeti/ekonomik boyut ve ziyaretçi kapasitesi ile mekansal uyum/sosyal-işlevsel boyut olmak üzere üç temel kriterle dayandırılmıştır. Senaryoları karşılaştırmak için sayısal simülasyonlardan elde edilen veriler TOPSIS yöntemiyle bütünleştirilmiş ve sonuçlar çok kriterli bir perspektifle değerlendirilmiştir. Bulgular, 0.82 puanla müze senaryosunun en uygun alternatif olduğunu göstermektedir. Kültür merkezi, sosyal faydalarına rağmen yüksek enerji tüketimi ve işletme maliyetleri nedeniyle ikinci sırada yer alırken; sergi salonu sınırlı ziyaretçi kapasitesi nedeniyle üçüncü sırada kalmıştır. Çalışma, BIM ve yapay zeka entegrasyonunun kültürel miras yapılarının korunması ve sürdürülebilir yeniden kullanımı için karar verme süreçlerine daha nesnel, ölçülebilir ve yenilikçi bir yaklaşım sunma potansiyeline sahip olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Kültürel miras, Yeniden işlevlendirme, Yapı bilgi modelleme (BIM), Miras yapı bilgi modellemesi (HBIM), Çok kriterli karar verme.

1. Introduction

Cultural heritage buildings represent significant spatial values that reflect the historical continuity, identity, and collective memory of societies [1,2]. However, these structures are increasingly under threat due to the deteriorating effects of time, natural disasters, abandonment, or the loss of their original functions, which makes their conservation progressively more challenging [3]. In this context, the adaptive reuse approach has emerged as a fundamental strategy that enables the preservation of historic buildings while integrating them into contemporary life [4,5].

Although traditional adaptive reuse studies have primarily been addressed within the disciplines of architecture, restoration, and history, recent advances in computer science have introduced new opportunities for

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the conservation and sustainable use of cultural heritage. In particular, Building Information Modeling (BIM) and AI-supported decision-making systems have provided innovative solutions in this field [6,7].

BIM-based models allow for the digital documentation of cultural heritage buildings, the creation of multilayered databases, and the technical and spatial evaluation of adaptive reuse scenarios [8,9]. By integrating artificial intelligence algorithms into these models, multidimensional criteria—such as cost, energy efficiency, structural safety, visitor density, and sustainability—can be systematically analyzed. This integration enables adaptive reuse decisions to be grounded in more objective, data-driven, and measurable frameworks [10,11].

This study focuses on the Aya Yorgi Church located in the district of Osmaneli, Bilecik Province, Turkey. Constructed in the 19th century and having served various functions throughout its history, the building currently stands unused while remaining a significant example of cultural heritage [12]. The primary aim of this research is to determine the most suitable adaptive reuse option for the Aya Yorgi Church by employing BIM-based data and AI algorithms. Within this scope, alternative usage scenarios—namely a museum, cultural center, and exhibition hall—are evaluated using multi-criteria decision-making methods.

The research seeks to demonstrate the effectiveness of computer science-based methods in the conservation and sustainable reuse of cultural heritage and to propose a digital decision-support framework that can guide future adaptive reuse decisions for similar historic structures.

2. Theoretical Background

This section outlines the theoretical foundations of the study by examining the principles of Building Information Modeling (BIM), Heritage BIM (HBIM), and AI-supported multi-criteria decision-making approaches relevant to adaptive reuse.

2.1. Building Information Modeling (BIM) and Heritage BIM (HBIM)

Building Information Modeling (BIM) is a process that enables the integrated management of geometric and semantic data of buildings throughout their life cycle in a digital environment [13]. In the field of cultural heritage, the BIM approach has evolved into Heritage BIM (HBIM), which has been adapted for the documentation and management of historic buildings. Unlike conventional BIM, HBIM focuses on irregular geometries, traditional construction techniques, and the integration of multi-source data such as laser scanning and photogrammetry. HBIM functions not only as a digital documentation tool but also as a comprehensive database that allows simulations and analyses [8]. In adaptive reuse projects, HBIM provides strong support to decision-makers by enabling the visualization of different scenarios and the assessment of their structural, functional, and economic impacts [10]. Thus, HBIM serves as a bridge between the conservation of cultural heritage buildings and the integration of advanced information technologies.

2.2. AI-Supported Decision-Making Approaches

Artificial intelligence (AI) is increasingly being applied in the fields of architecture, engineering, and cultural heritage management. In adaptive reuse studies, AI contributes to multi-criteria decision-making (MCDM) processes by enabling the balancing of multidimensional variables such as cost, structural safety, energy efficiency, sustainability, and visitor experience [11].

In this context, methods such as the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are widely used for the weighting and ranking of alternatives [14]. Furthermore, machine learning-based optimization algorithms provide a more flexible, data-driven, and predictive contribution to the decision-making process [15].

Therefore, AI-supported decision-support systems emerge not only as technical tools but also as scientific and objective methods for the adaptive reuse of cultural heritage buildings. Within this framework, combining the detailed digital documentation and scenario modeling capabilities offered by HBIM with AI-supported multi-criteria decision-making approaches provides an innovative methodological framework for adaptive reuse. In this way, both spatial and technical data are transferred into a digital basis, and different reuse scenarios can be compared objectively and in a data-driven manner. This integrated approach constitutes the methodological foundation of the study.

3. Method and Materials

The primary objective of this study is to develop a BIM-based and AI-supported multi-criteria decision-support framework for the adaptive reuse of the Aya Yorgi Church in Osmaneli, and to evaluate different reuse scenarios in a quantitative, transparent, and comparable manner. The scope of the study is not limited to documenting the current physical condition of the building; it also includes the numerical testing of potential functions—such as a museum, cultural center, and exhibition hall—through BIM-based models, as well as the comparative evaluation of these scenarios using AI-supported multi-criteria analysis.

In recent years, the integration of digital technologies into heritage conservation has increasingly emphasized the use of BIM and HBIM as tools not only for documentation but also for supporting decision-making processes in adaptive reuse projects [6]. Within this context, the present study adopts a data-driven analytical framework that combines BIM-based modeling with AI-supported multi-criteria evaluation methods. This approach distinguishes the study from the descriptive documentation-oriented research commonly found in the literature by aiming to assess adaptive reuse decisions through measurable performance indicators rather than solely qualitative evaluations.

3.1. Data Sources and Collection Process

The data collection process was carried out in two stages. In the first stage, the building was documented using photogrammetry, laser scanning outputs, and archival records. No physical intervention was conducted on the structure during this phase; on-site observations were supported solely through visual documentation obtained from publicly accessible areas.

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In the second stage, the collected data were transferred into a digital environment using the Building Information Modeling (BIM) approach, and a comprehensive HBIM dataset was generated. HBIM has become an important tool for the digital documentation and management of heritage structures, enabling the integration of geometric, historical, and material information into a unified digital model [6,8]. In this study, the HBIM model served as the primary data source for both the consistent representation of the existing condition of the building and the testing of alternative adaptive reuse scenarios in terms of energy demand trends, maintenance and operating requirements, and spatial utilization potential.

3.2. Method Selection and Rationale

In this study, a BIM- and AI-based multi-criteria decision-support approach was adopted as the methodological framework. BIM enables the precise digital representation of irregular geometries and multilayered data of historic buildings, while also providing the necessary infrastructure for scenario-based analyses [6].

AI-supported multi-criteria decision-making (MCDM) methods allow decision criteria that are not directly comparable—such as energy performance, cost, capacity, and spatial compatibility—to be evaluated within a unified analytical framework. Such approaches have been widely applied in architectural planning, infrastructure management, and heritage conservation to support complex decision-making processes. In this context, the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were selected due to their widespread application in architectural and cultural heritage studies, as well as their transparent and reproducible structures. Previous studies have demonstrated that the combined use of AHP and TOPSIS can effectively support multi-criteria evaluation processes in architectural decision-making [14].

The AHP method systematically structures the subjective aspects of the decision-making process by determining the relative importance of criteria through pairwise comparisons. The TOPSIS method, in turn, ranks alternatives based on their relative closeness to an ideal solution, enabling a quantitative comparison of different scenarios. The combined use of these two methods is widely recognized in the literature as a complementary approach that enhances the reliability and robustness of multi-criteria decision-making outcomes.

3.3. Data Analysis Method

The analysis process was structured in four main stages (Figure 1). This multi-stage evaluation process was visualized through a methodological workflow diagram that summarizes the overall methodological framework of the study, and it is explained in detail within this section.

Scenario-based evaluation approaches have been widely used in adaptive reuse studies to explore alternative functional transformations of historic buildings and assess their technical and social feasibility [4]. In this context, the present study employs BIM-based scenario simulations combined with multi-criteria decision-making methods to provide a systematic comparison of alternative reuse options.

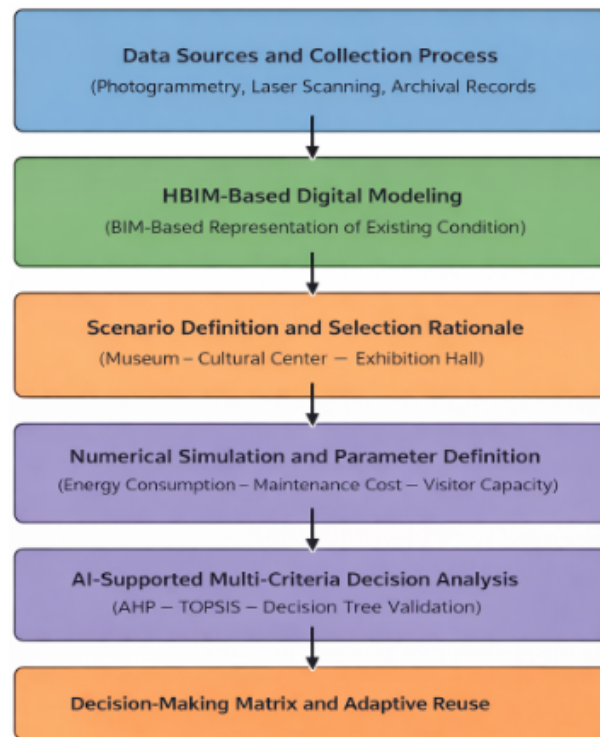


Figure 1. Methodological workflow of the BIM- and AI-based multi-criteria decision-support framework for adaptive reuse

- **Scenario Definition and Selection Rationale:** Three adaptive reuse alternatives were identified for the Aya Yorgi Church: a museum, a cultural center, and an exhibition hall. These functions were selected not only because they are among the most frequently proposed reuse types for cultural heritage buildings in the literature, but also due to their compatibility with the building's spatial configuration, historical identity, and environmental context.

- *Museum:* Selected to emphasize the historical continuity of the building and its role in collective memory.
- *Cultural Center:* Chosen for its potential to respond to the contemporary social and cultural needs of local communities.
- *Exhibition Hall:* Preferred due to the building's single-volume spatial organization and its façade arrangement, which allows flexible use supported by natural lighting.

Although alternative functions such as a library, concert hall, or gastronomy venue are theoretically feasible for historic buildings, this study was limited to three scenarios in order to enhance analytical depth and ensure methodological comparability.

- **Numerical Simulation and Parameter Definition;** For each scenario, three main evaluation criteria were assessed:

- *Energy Consumption / Environmental Performance:* This criterion aims to examine how the lighting, heating-cooling, and ventilation requirements of each scenario vary depending on usage intensity. Taking into account the existing building envelope, natural lighting potential, and volumetric characteristics of the historic structure, projected energy demand trends for different functional scenarios were evaluated. At this stage, spatial data derived from the BIM model were combined with coefficients recommended in the literature for cultural buildings to establish a comparable energy performance indicator. Rather than

absolute energy calculations, this criterion focuses on identifying relative performance differences among scenarios.

- *Maintenance and Operating Cost*: This criterion evaluates the economic impact of each functional scenario on the long-term conservation of the building. Periodic maintenance, repair, and operating requirements were projected based on factors such as usage intensity, technical infrastructure demands, and expected user circulation. It was assumed that functions requiring intensive technical systems and high levels of use would impose a greater economic burden in terms of sustainability. Accordingly, this criterion enables the assessment of adaptive reuse decisions not only from a short-term perspective but also in terms of long-term feasibility.
- *Visitor Capacity and Spatial Compatibility*: This criterion focuses on the relationship between the existing spatial organization of the building and the proposed function. The analysis considered the single-volume spatial configuration, circulation scheme, entrance–exit arrangement, safety and evacuation conditions, and the building’s capacity to accommodate user density. In addition, the degree to which each function aligns with the original architectural character of the building was evaluated, and the potential negative impacts of excessive density on the physical fabric were taken into account. In this respect, the criterion represents one of the key indicators of the conservation–use balance.

These three criteria aim to comprehensively reveal the strengths and weaknesses of adaptive reuse scenarios in architectural, environmental, and functional terms. Consequently, a transparent methodological framework was established that allows the scenarios to be evaluated in a comparable and traceable manner within a multi-criteria decision-making process.

- **AI-Supported Evaluation and Comparative Analysis**; In the AI-supported evaluation phase, the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were jointly employed to compare the scenarios within a multi-criteria decision-making framework. First, the relative importance levels of the defined criteria were calculated using AHP. Subsequently, the alternative scenarios were ranked using the TOPSIS method based on these weights. This approach enables different criteria to be integrated and assessed holistically within a single decision space.

To test the consistency of the MCDM results, a machine learning–based supportive validation analysis was conducted. In this context, a decision tree algorithm was used to examine the effects of different criterion combinations on the final outcomes and to verify the extent to which the AHP–TOPSIS results aligned with overall decision trends. Accordingly, artificial intelligence was conceptualized not as a tool for generating an alternative ranking, but as a validation mechanism to test the robustness and sensitivity of the AHP–TOPSIS outputs.

In the comparative analysis stage, the obtained findings were interpreted by comparing them with similar HBIM-based adaptive reuse studies in the literature. This allowed the strengths and weaknesses of the proposed functions to be evaluated not only at the building scale but also within a broader academic context.

- **Decision-Making Matrix and Methodological Checklist**; In order to present the methodological steps described above in a clearer, more traceable, and systematic manner, the adaptive reuse process was structured as a decision-making matrix and a methodological checklist. Table 1 summarizes the decision steps followed in the study, the types of data used, the analytical tools applied, and the rationale for each stage in an integrated manner. This structure enhances the transparency of the methodological choices and provides an adaptable methodological reference for similar cultural heritage buildings. In this context, Table 1 should be considered as a summarizing tool that brings together all decision steps explained in the Methods section within a single framework.

Table 1. Decision-making matrix and methodological checklist for BIM- and AI-based adaptive reuse

Stage	Data Used	Decision/ Action	Method / Tool Applied	Rationale and Explanation
1	Identification of the Existing Condition of the Building	Photogrammetry, laser scanning, archival documents	HBIM-based digital modeling	To represent the building’s irregular geometries, current state of deterioration, and spatial organization in a holistic and measurable manner
2	Selection of Adaptive Reuse Scenarios	Historical context, spatial configuration, literature	Scenario definition (qualitative pre-selection)	Museum, cultural center, and exhibition hall functions are among the most frequently proposed reuse options for cultural heritage buildings in the literature and are compatible with the building’s spatial capacity
3	Definition of Evaluation Criteria	Literature, conservation principles,	Criteria definition	Energy/environmental performance, maintenance and operating cost, and spatial compatibility–visitor

		building characteristics		capacity were selected in terms of sustainability, feasibility, and the conservation–use balance
4	Generation of Numerical Parameters	HBIM model, usage intensity assumptions	BIM-based scenario simulation	Relative calculation of energy demand trends, cost burden, and spatial capacity values for each scenario
5	Determination of Criteria Weights	Expert opinions, literature priorities	AHP (Analytic Hierarchy Process)	Systematic and transparent calculation of the relative importance levels of criteria with different dimensions
6	Ranking of Scenarios	Numerical performance values	TOPSIS	Comparison of alternatives based on their closeness to the ideal solution and distance from the negative ideal
7	AI-Supported Validation	AHP–TOPSIS outputs	Decision Tree algorithm	Testing the influence of criterion combinations on the results and examining the consistency of the obtained ranking
8	Comparative Evaluation	Similar studies in the literature	Qualitative comparison	Interpretation of the strengths and weaknesses of the proposed scenarios within an academic context

This decision-making matrix functions as a complementary instrument that encapsulates the methodological structure of the study, enhancing the transparency, traceability, and comparability of BIM- and AI-based adaptive reuse decisions.

3.4. Gaps in the Literature and Contributions

In the existing literature, BIM and Heritage BIM (HBIM) applications for the documentation and digital representation of cultural heritage buildings are widely adopted [16]. In particular, the approaches developed by Banfi et al. in Italy to enhance HBIM infrastructures for basilica documentation [17], the energy simulations adapted to heritage buildings by Ferrero Bermejo et al. in Spain [18], and the digital reconstruction of the wooden architectural heritage of Suwon Hwaseong Fortress by Kim et al. in Korea [19] constitute significant examples demonstrating the documentation and technical analysis potential of HBIM.

However, the majority of these studies primarily address HBIM at the level of documentation, geometric modeling, or limited technical simulation, and do not sufficiently focus on the scientific, comparative, and multi-criteria evaluation of adaptive reuse decisions. Although performance indicators such as energy consumption, maintenance and operating costs, or user capacity are occasionally considered, these assessments are often confined to single-dimensional analyses or rely heavily on qualitative interpretations.

The integration of artificial intelligence and multi-criteria decision-making (MCDM) methods into the adaptive reuse of cultural heritage buildings remains limited in the literature. While some studies conceptually associate BIM with artificial intelligence, such integrations frequently remain at a theoretical level, and the numerical data flow, algorithmic evaluation processes, and validation of results are not explicitly articulated [7]. This limitation significantly restricts the reproducibility and analytical reliability of the proposed approaches.

In particular, the numerical testing of alternative adaptive reuse scenarios for cultural heritage buildings, their systematic comparison through multi-criteria decision-making methods, and the validation of the obtained results using AI-based algorithms represent an underexplored research area. In this context, transforming HBIM from a static digital documentation tool into an active component of the decision-making process emerges as a critical methodological requirement.

In response to these gaps, the present study distinguishes itself from existing approaches in the literature in three fundamental aspects:

1. The direct integration of HBIM-based quantitative data into AI-supported multi-criteria decision-making processes for the adaptive reuse of a historic building;
2. The quantitative and comparative evaluation of adaptive reuse alternatives based on energy, cost, and spatial–social performance criteria;
3. The proposal of a repeatable, transparent, and data-driven methodological framework grounded in computer science for the conservation and sustainable reuse of cultural heritage.

Through these contributions, the study advances beyond the predominantly documentation-oriented trajectory of HBIM research by presenting an integrated approach in which digital models actively inform decision-support processes. Accordingly, the proposed framework enhances objectivity, measurability, and analytical depth in adaptive reuse decision-making for cultural heritage buildings. A comparative summary of the methodological approach in relation to the existing literature is presented in Table 2.

Table 2. Comparative summary of the methodological approach and the literature.

Stage	Method Used	Purpose	Gap in the Literature	Contribution of This Study
Documentation	Photogrammetry, laser scanning	Recording of the current state	Most studies rely only on architectural drawings	More precise and digitally based data production
BIM Model	HBIM	Detailed modeling in a digital environment	Often limited to static documentation	Provides infrastructure for scenario analysis
Artificial Intelligence	Multi-criteria decision-making (AHP/ TOPSIS) + ML algorithms	Comparison of scenarios	Rare in the literature	Objective, data-driven decision-support mechanism

4. Case Study: Aya Yorgi Church in Osmaneli

This section examines the case of Aya Yorgi Church in Osmaneli, which constitutes the empirical basis of the proposed BIM- and AI-supported adaptive reuse approach. Within the scope of the study, the historical background, architectural characteristics, defined evaluation criteria, and BIM-based scenario analyses of the building are analyzed. The structure is evaluated in terms of both its cultural heritage value and performance-based criteria, thereby establishing the methodological framework for the multi-criteria decision-making process.

4.1. Historical Background and Structural Features

Osmaneli (historically known as Lefke) is a long-established settlement located 35 km from the city of Bilecik, situated along the northwest–southeast transportation axis of Anatolia. Known as “Leucaē” and “Leukai” during the Roman and Byzantine periods, the settlement came under Ottoman rule in 1308 during the reign of Osman Gazi. Owing to its strategic location, it became an important stop along the Istanbul–Baghdad–Mecca route and was referred to as “Lefke” during the Ottoman period. In 1914, its name was changed to “Osmaneli,” and in 1926 it was granted district status. Archaeological remains from the Thracian, Roman, and Byzantine periods found in the region reveal the multi-layered historical structure of the settlement [12].

One of the significant components of this historical fabric is the Aya Yorgi (Hagios Georgios) Church, which was constructed in the late 19th century. Although there is no inscription indicating its exact construction date, Ottoman archival documents provide various insights. Documents dated 1870 indicate that permission was granted to expand the women’s section due to its insufficiency. Records from 1893 reveal unauthorized installation and ringing of a bell and indicate that the church was affiliated with the Metropolis of Gemlik. Documents from 1897 include measurements and cost estimates for the reconstruction of the ruined church, suggesting that the structure was planned as a three-aisled basilica. Records from 1903 indicate discrepancies between the approved and actual dimensions, noting that the building height reached 13 meters. This document is also the only official record in which the church is referred to as “Aya Yorgi” [20-23].

Architecturally, the Aya Yorgi Church follows a cross-in-square plan scheme. Oriented along the east–west axis, the building measures 26.35 m in length and 14.70 m in width. The narthex and two bell towers are located on the western side, while a semicircular apse is positioned to the east. The women’s gallery (gynekaion), located above the narthex, has been largely destroyed. The naos was originally covered by a central dome supported by pendentives; however, this structural system has not survived. Symmetrical entrances are located on the north and south walls of the naos, while the prothesis and diakonikon spaces are positioned on either side of the apse [12].

The western façade is distinguished by its monumental triple-arched entrance, multi-window composition at the upper level, and flanking bell towers. The façade design is articulated through round-arched openings divided by pilasters, triangular pediments, and stone cornices [21]. While the northern and southern façades display similar arrangements, the eastern façade presents a more modest character. Despite being constructed on a high stylobate, the absence of steps at the entrances suggests that the building may not have been fully completed.

Lefke stone, brick, wood, and iron were used together in the construction of the building. An alternating masonry technique was employed, iron-reinforced vaults were used in the bell towers, and timber elements were utilized in the roof system. The limited use of decorative elements suggests either that the building remained unfinished or reflects the economic conditions of the period [12,24].

Following the population exchange, the departure of the Greek community rendered the building functionless. In the 1950s, it passed into private ownership and was used as a storage space and stable. It was vacated by the municipality in the 1990s, and its surroundings were enclosed with fencing. Today, the structure survives with its roof largely collapsed and interior decorations lost, standing as an endangered cultural heritage building in need of conservation [12] (Figures 2, 3, and 4).

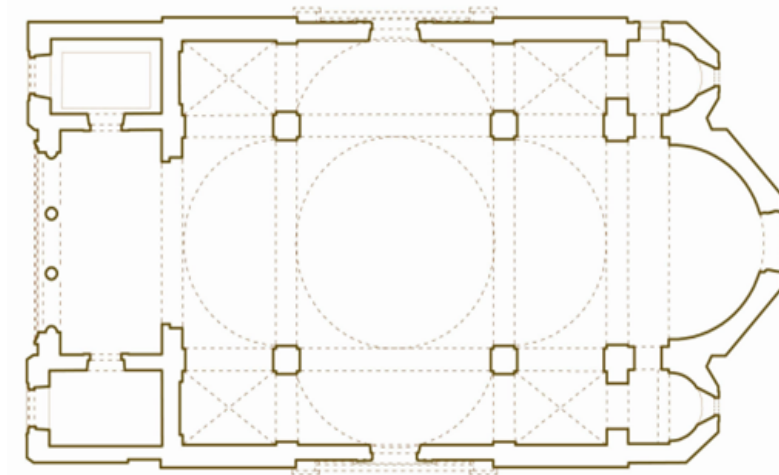


Figure 2. Ground floor plan and possible roofing system of the church [21].

As shown in Figure 2, the building exhibits a spatial organization reflecting a cross-in-square plan typology. The side aisles and supporting piers arranged around the central naos form an integrated plan composition. The central area, defined by four main supporting piers, indicates the location of the main dome—now lost—which was originally carried by pendentives. This provides important insights into the original structural system and spatial hierarchy of the building [12].

The narthex on the western side and the semicircular apse on the eastern side clearly reveal the liturgical orientation of the structure. The dashed circular traces shown on the plan illustrate the possible geometric configuration of the original roofing system, allowing for the reinterpretation of structural elements that have not survived [21]. The arrangement of the side aisles and the spatial subdivisions make both the circulation organization and the structural logic of the building legible. In this respect, the plan scheme serves as a fundamental spatial dataset for evaluating spatial suitability in the adaptive reuse process.



Figure 3. Western and southern elevation drawings of the church [12].

The elevation drawings presented in Figure 3 reveal the symmetrical façade organization of the building and its vertically articulated architectural elements. The triple-arched entrance on the western façade, the upper-level window arrangement, and the flanking bell towers are the primary components that define the monumental character of the structure [21].

The round-arched openings, surface articulation divided by pilasters, and pediment elements reflect the architectural language and stylistic features of the period. The proportions of the openings and the mass distribution create a balanced and rhythmic composition on the façade, while a simpler yet continuous arrangement is observed on the southern façade [12]. These drawings constitute an important reference for understanding and conserving the original architectural character of the building.



Figure 4. Western and southern façade views of the church.

The photographs presented in Figure 4 reveal the current physical condition of the building, clearly illustrating material losses and structural deterioration. In particular, it is evident that the roofing system has largely disappeared, and the dome and roof elements have not survived to the present day [12]. This condition directly affects the structural integrity of the building and the preservation conditions of the interior space.

The weathering and material losses observed on the façade surfaces indicate that the building has remained neglected for a long period and has been exposed to environmental effects [24]. Although the monumental entrance composition on the western façade is largely preserved, deformations in the detailing are noticeable. On the southern façade, while the overall mass integrity is maintained, surface deterioration is clearly evident.

These visual data provide important insights for assessing the conservation condition of the building, identifying intervention requirements, and defining the original architectural elements that need to be preserved.

The spatial, structural, and physical data obtained through these visual analyses were transferred into the HBIM model and used as key inputs in the evaluation of adaptive reuse scenarios. In this context, the plan scheme (Figure 2) contributed to spatial suitability analysis, the elevation drawings (Figure 3) informed the determination of intervention boundaries, and the current photographs (Figure 4) supported the assessment of conservation conditions.

These historical and architectural data were incorporated into the BIM-based digital model in the second stage of the study and served as the core dataset for evaluating different adaptive reuse scenarios.

4.2. Determination of Criteria

The evaluation of adaptive reuse scenarios is not limited to architectural compatibility or aesthetic considerations alone. Historic buildings must be examined through multidimensional criteria due to both their intrinsic values that need to be preserved and their relationship with contemporary social needs. In this context, three main criteria were defined in the analysis process: energy consumption/environmental performance, maintenance and operating cost/economic dimension, and visitor capacity with spatial compatibility/social-functional dimension. These criteria were selected based on sustainability indicators frequently emphasized in adaptive reuse studies of cultural heritage and were adapted to the specific building by considering both its physical characteristics and conservation principles [25-27].

Energy consumption/environmental performance is one of the most critical outcomes of functional change. Different usage scenarios such as museum, cultural center, or exhibition hall generate varying energy demands in terms of lighting, heating-cooling, and ventilation systems. Since historic buildings were not constructed

according to modern energy efficiency standards, this criterion constitutes a decisive performance indicator in terms of both economic and environmental sustainability [28,29].

Maintenance and operating cost/economic dimension is one of the most frequently overlooked factors in the adaptive reuse of cultural heritage buildings. Functions that require intensive maintenance may threaten the long-term sustainability of the structure and directly affect the feasibility of alternatives. Functions with heavy circulation and high technical requirements lead to higher costs in the short term, whereas low-intensity uses can ensure sustainability in the long term. Therefore, this criterion is critical not only for the building's current condition but also for its transfer to future generations [30,31].

Visitor capacity and spatial compatibility/social-functional dimension are directly related to the building's single-volume spatial configuration, circulation scheme, entry-exit points, and safety conditions. In this respect, visitor capacity represents not only functional efficiency but also the balance between conservation and use. Excessive density may cause irreversible damage to the physical fabric of the building, making this criterion critical for sustainable conservation. Furthermore, spatial compatibility is an important indicator for evaluating the extent to which the selected function can be integrated with the architectural character of the building [32,33].

In order to address the criteria more systematically in the numerical analysis process, abbreviations were used. Here, the letter "E" represents energy and economic dimensions, while the letter "S" represents social and spatial dimensions. This approach allows the criteria to be presented more clearly and legibly, particularly in multi-criteria decision-making methods (e.g., AHP, TOPSIS) and visual comparison tools. The explanations, rationales, and literature support of the criteria are summarized in Table 3.

Table 3. Rationales and literature support of the criteria used in the analysis process.

Criterion	Description	Rationale	Literature
Energy Consumption – Environmental Performance (E1)	Refers to the intensity of use of lighting, HVAC, and ventilation systems.	Ensuring energy efficiency in historic buildings is critical for both economic and environmental sustainability.	[28,29]
Maintenance and Operating Cost – Economic Dimension (E2)	Covers the long-term maintenance, repair, and operating expenses of the building.	High-cost functions hinder sustainability, whereas low-cost functions facilitate transmission to future generations.	[30,31]
Visitor Capacity and Spatial Compatibility – Social-Functional Dimension (S1)	Evaluates circulation layout, entry-exit points, safety conditions, and user density.	Preventing excessive density is necessary for maintaining the conservation-use balance; the compatibility of the function with the architectural character is also important.	[32,33]

In conclusion, the main purpose of defining these three criteria is to assess energy efficiency, economic sustainability, and spatial functionality from a holistic perspective, thereby demonstrating the scientific and practical applicability of adaptive reuse scenarios.

4.3. BIM-Based Scenario Analysis

Scenario analyses for the adaptive reuse of the Aya Yorgi Church were carried out through a Building Information Modeling (BIM)-based approach. At this stage, BIM was used not only for the geometric and architectural representation of the building but also to create a parametric database that enables the multidimensional testing of functional transformation scenarios. During the modeling process, archival documents, on-site measurement data, photogrammetry outputs, and literature sources were integrated, thereby transferring the building's plan scheme, façade composition, structural features, and spatial organization into the digital environment.

Three reuse functions were considered in the scenario analysis: museum, cultural center, and exhibition hall. These options were selected by taking into account the building's historical identity, spatial configuration, and potential social benefits. On the BIM-based model, each scenario was tested according to three main criteria:

Energy Consumption (E1): The requirements for lighting, heating-cooling, and ventilation were calculated for each function based on different levels of use intensity. This analysis enabled the evaluation of energy efficiency and environmental sustainability.

Maintenance and Operating Cost (E2): The regular maintenance, repair, and operating expenses of the building were projected separately for each function and compared with long-term estimates. In this way, the feasibility of each alternative was evaluated within the context of economic sustainability.

Visitor Capacity and Spatial Compatibility (S1): The circulation scheme, entry–exit points, safety conditions, and the building’s ability to accommodate user density were analyzed. In addition, the spatial compatibility of each function was assessed in relation to the original architectural character of the building.

The results obtained from the BIM-based analyses revealed that each alternative function has different strengths and weaknesses. For example, the cultural center scenario reached the highest values in terms of energy consumption due to intensive usage requirements, whereas the exhibition hall scenario stood out with lower maintenance and operating costs. The museum scenario, on the other hand, proved to be the most advantageous option in terms of spatial circulation and visitor capacity.

To present the analysis results more clearly, the performance of the scenarios according to the criteria was visualized through graphical representations. The bar chart comparatively illustrates the performance of the three alternative functions (museum, cultural center, and exhibition hall) with respect to energy consumption, maintenance cost, and visitor capacity. The exhibition hall achieved the highest score in terms of energy consumption and visitor capacity, while the cultural center demonstrated a more balanced performance particularly in terms of maintenance costs. The museum scenario, although prominent in visitor capacity, obtained relatively lower scores in maintenance cost (Figure 5).

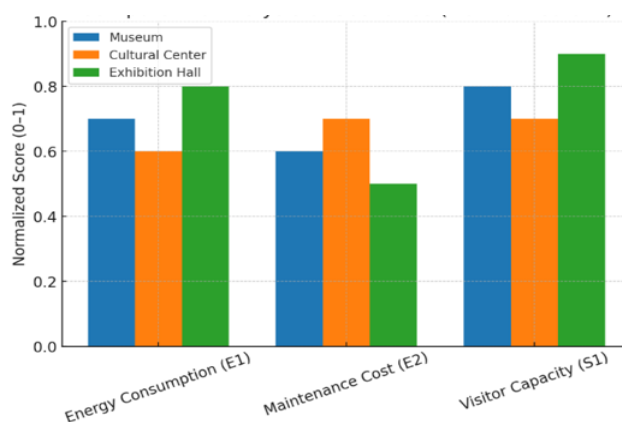


Figure 5. Comparative analysis of alternative scenarios based on evaluation criteria.

Following the findings obtain from bar chart, a radar chart was employed to enable a more holistic comparison of the strengths and weaknesses of the alternative reuse scenarios across the evaluation criteria. As illustrated in Figure 6, the radar chart visualizes the relative performance of the museum, cultural center, and exhibition hall scenarios in terms of energy consumption (E1), maintenance and operating cost (E2), and visitor capacity/spatial compatibility (S1).

According to the radar chart, the exhibition hall scenario demonstrates relatively strong performance in terms of energy efficiency (E1) and visitor capacity (S1), indicating that the building’s spatial configuration can accommodate exhibition activities with comparatively lower energy demand. However, its performance remains more limited in terms of maintenance and operating costs (E2) compared to the other alternatives.

The cultural center scenario, on the other hand, presents the highest maintenance and operating cost values (E2) among the alternatives. This result reflects the intensive usage patterns and increased technical infrastructure requirements associated with cultural activities. While this function may offer significant social and cultural benefits, its higher energy demand and maintenance requirements reduce its overall efficiency within the evaluation framework.

The museum scenario shows a balanced performance across the three criteria, particularly standing out in terms of visitor capacity and spatial compatibility (S1). This indicates that the spatial organization and circulation scheme of the Aya Yorgi Church are highly compatible with museum functions, allowing for effective visitor movement while maintaining the architectural integrity of the historic structure.

Thus, the radar chart provides a comprehensive visualization of how each adaptive reuse alternative performs across the evaluation criteria, highlighting the relative strengths and weaknesses of the scenarios and supporting the subsequent multi-criteria decision-making process (Figure 6).

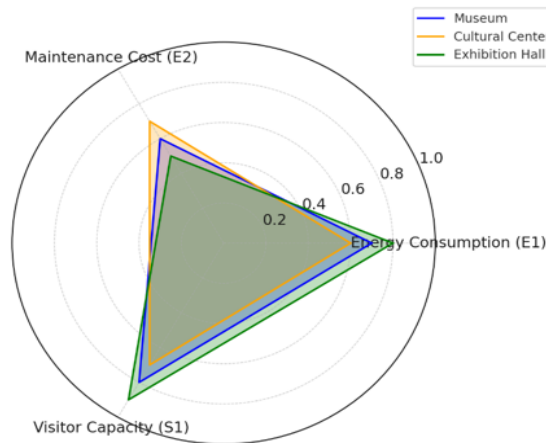


Figure 6. Comparative analysis of scenarios based on evaluation criteria (Radar chart).

Overall, the BIM-based scenario analyses enabled the adaptive reuse decision-making process for the Aya Yorgi Church to integrate not only technical and spatial data but also the broader dimensions of heritage conservation, social benefit, and sustainability. In this way, the analysis provides a robust analytical foundation for the subsequent application of AI-supported multi-criteria decision-making methods.

4.4. AI-Supported Multi-Criteria Decision Analysis

The data obtained from the BIM-based scenario analysis alone are not sufficient to determine which adaptive reuse option is the most appropriate. This is because the criteria of energy consumption, maintenance and operating cost, and visitor capacity represent different dimensions and are independent of each other. Therefore, to ensure a more objective and holistic decision-making process, multi-criteria decision-making (MCDM) methods and AI-based evaluation mechanisms were employed.

First, the relative importance levels of the criteria were determined. According to findings from the literature, energy consumption (E1) was regarded as one of the priority criteria in the context of sustainability; maintenance and operating cost (E2) was considered a parameter directly affecting long-term feasibility; and visitor capacity and spatial compatibility (S1) emerged as indicators of functional appropriateness and social benefit. Based on this, the criterion weights were calculated using the Analytic Hierarchy Process (AHP). Subsequently, the alternative scenarios (museum, cultural center, exhibition hall) were ranked using the TOPSIS method. This method identifies the most suitable option by measuring the closeness of each alternative to the ideal solution and its distance from the negative ideal.

In addition, a supplementary analysis based on machine learning was conducted, in which decision tree algorithms were applied to test the performance of alternatives under different combinations of criteria.

The criterion weights and the TOPSIS scores obtained for each scenario are presented in Table 4 below.

Table 4. Comparison of alternatives using the TOPSIS method.

Criteria	Weight (w)	Museum	Cultural Center	Exhibition Hall
Energy Consumption (E1)	0.35	0.72	0.61	0.80
Maintenance and Operation (E2)	0.30	0.65	0.58	0.84
Visitor Capacity (S1)	0.35	0.88	0.75	0.62
TOPSIS Score	1.00	0.82	0.72	0.69
Ranking		1	2	3

As shown in Table 4, the museum scenario emerged as the most suitable alternative with a score of 0.82 according to the TOPSIS analysis. The cultural center ranked second with a score of 0.72, while the exhibition hall remained in third place due to its limited visitor capacity. The fact that the museum scenario achieved the highest score particularly in terms of visitor capacity and spatial compatibility indicates that it enables an adaptive reuse aligned with the historical identity of the building. The cultural center stands out as a strong option in terms

of social functionality, whereas the exhibition hall offers advantages with its low maintenance and operating costs. Therefore, the final evaluation demonstrates that the museum scenario is the most appropriate alternative overall, while the other scenarios may provide certain advantages in specific contexts and could also be considered for potential hybrid uses in the future.

5. Conclusion and Discussion

This study proposes an original methodological framework that integrates BIM-based modeling with AI-supported multi-criteria decision-making methods for the adaptive reuse of the Aya Yorgi Church in Osmaneli. The multi-criteria evaluation of three alternative reuse scenarios developed through the HBIM-based digital model enabled the building to be addressed not only in physical terms but also in its social and sustainability dimensions. This approach is consistent with the literature emphasizing the need for multidimensional evaluation processes in adaptive reuse practices [4,25,30].

The findings indicate that the museum scenario emerges as the most suitable alternative, aligning with studies that emphasize the importance of cultural heritage buildings in terms of public accessibility and the production of collective memory [32,33]. In particular, the high performance achieved in visitor capacity and spatial suitability criteria demonstrates that the museum function is compatible with the spatial organization of the building and provides a sustainable usage model in terms of user density. Similar conclusions have been reported in studies evaluating cultural heritage within the context of tourism and public use [33].

On the other hand, the ranking of the cultural center scenario as the second most suitable option points to a commonly discussed contradiction in the literature. While cultural centers have high potential for social interaction and community engagement, they may be disadvantageous in terms of sustainability due to high energy demands and the need for intensive technical interventions, especially in historic buildings [30,31]. In this study, although the cultural center scenario demonstrates strong social benefits, it exhibits lower performance in terms of energy consumption and operational costs. This finding highlights the critical importance of balancing social and technical criteria in adaptive reuse decisions.

The relatively lower performance of the exhibition hall scenario is also consistent with discussions in the literature regarding the relationship between economic efficiency and social impact. Although exhibition-oriented uses often offer advantages in terms of lower operational costs, they may remain limited in terms of long-term user engagement and spatial continuity [25,32]. Similarly, in this study, despite its cost advantage, the exhibition scenario received a lower score due to its limited visitor capacity and low potential for social interaction. This result clearly demonstrates that economic criteria alone cannot be the sole determinants in adaptive reuse decisions.

When compared with the multi-criteria decision-making literature, the findings of this study show strong consistency. Studies employing methods such as AHP and TOPSIS emphasize that criterion weights directly influence final decisions and that different weight configurations may lead to different outcomes [14,26,27]. In this study, the relatively high weights assigned to energy consumption and visitor capacity contributed to the prominence of the museum scenario. This indicates that adaptive reuse decisions are not entirely objective but are influenced by decision-maker priorities, thereby underscoring the importance of transparency in decision-support systems.

From the perspective of HBIM literature, this study differs significantly from existing approaches. HBIM applications are generally focused on documentation, digital archiving, and reconstruction [6,16,17]. With the recent development of digital twin approaches, there has been growing interest in integrating these models into management and performance analysis processes [7,28,29]. However, such integrations are often limited to energy performance or maintenance processes. In contrast, this study directly incorporates the HBIM model into the decision-making process, enabling a comparative evaluation of alternative adaptive reuse scenarios. In this respect, the study contributes to the emerging field of data-driven decision-support systems and advances the application of HBIM beyond its conventional uses.

Furthermore, the study is consistent with the literature on the application of AI-supported decision-making methods in the field of cultural heritage. In recent years, the integration of artificial intelligence and optimization techniques into adaptive reuse processes has been increasing [15,18]. However, many of these studies remain at a theoretical level or are based on limited datasets. In this study, a more applicable model is proposed by integrating an HBIM model developed for a real cultural heritage building with an AI-supported decision-making process.

In this context, the study makes three main contributions to the adaptive reuse literature:

- (i) grounding reuse decisions not only in qualitative assessments but also in quantitative and comparable data,
- (ii) actively integrating the HBIM model into the decision-support process,
- (iii) combining multi-criteria decision-making methods with AI-supported analyses.

These contributions address the need for interdisciplinary integration frequently emphasized in the literature but still limited in practice.

The study has certain limitations. The analyses are based on scenario-based relative data and are not supported by real-time user data. In addition, only three reuse scenarios were evaluated, while hybrid usage models were excluded. As emphasized in the literature, adaptive reuse processes are contextual and dynamic, requiring the evaluation of multiple scenarios [30]. Future studies are recommended to incorporate a greater number of scenarios, diverse criteria sets, and participatory approaches involving users.

In conclusion, although the museum function emerges as the most suitable alternative for the Aya Yorgi Church, it should be noted that this result is contingent upon the selected criteria and their weighting. This once again highlights the contextual nature of adaptive reuse decisions. The proposed integration of BIM and artificial intelligence offers an applicable, transparent, and scientifically grounded decision-support model not only for this building but also for similar cultural heritage structures. Such approaches are aligned with the growing body of literature advocating data-driven methods for balancing heritage conservation with contemporary functional needs [6,17].

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