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Integrating Life Cycle Cost Analysis for Sustainable Maintenance of Historic Buildings

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Abstract: This study examines the strategic use of life cycle cost analyses (LCCAs) in the management and conservation of heritage sites, emphasizing the need for comprehensive financial planning. With an increasing number of heritage sites showing signs of deterioration, our aim was to improve the sustainability and effectiveness of restoration practices. We used dynamic life cycle costing methods and developed the MONUREV software V2 to simulate different restoration scenarios, providing accurate, data-driven projections for maintaining structural, functional and aesthetic integrity. The field research involved testing these methods through case studies of heritage buildings in the Czech Republic, focusing on holistic cost management from initial analysis to practical application. The results showed that LCC analysis can significantly assist in making informed decisions, balancing economic and cultural values, and ensuring long-term conservation outcomes. This study concludes that the integration of a detailed LCC analysis into heritage conservation strategies represents a methodological advance that can significantly improve the economic and operational planning of the maintenance of heritage buildings, thereby ensuring their preservation for future generations.

Keywords: life cycle cost analysis; heritage conservation; cultural heritage management; economic sustainability; conservation strategies

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1. Introduction

Preserving cultural heritage is not merely a matter of maintaining physical structures; it is a profound commitment to safeguarding our collective identity and heritage for future generations. Across the globe, historic buildings stand as tangible testimonies to the richness of human history, reflecting the architectural prowess, cultural practices, and societal values of bygone eras. However, these venerable structures face numerous challenges, including structural degradation, aesthetic decline, and the pressures of modernization.

In the Czech Republic, a nation steeped in a rich historical legacy boasting over 40,000 national heritage sites, the plight of historic buildings in various states of disrepair underscores the urgency of effective preservation efforts. Neglect and inadequate maintenance not only diminish the economic value of these structures but also erode their cultural and historical significance, depriving future generations of invaluable connections to their past.

Recognizing the imperative to address these challenges, a research project titled "Sustainable Management of Cultural Heritage Buildings" undertaken by a dedicated team at the CTU in Prague and funded by the Ministry of Culture of the Czech Republic sought to revolutionize the approach to heritage preservation. Spanning from 2018 to 2023, this project aimed to enhance the efficiency and effectiveness of maintenance and rehabilitation activities for cultural heritage buildings through the development of innovative methodologies and practical tools.

Central to this endeavor was the integration of advanced techniques such as life cycle cost (LCC) analysis and the creation of specialized software like MONUREV. These tools, coupled with a comprehensive understanding of the historical and cultural contexts of heritage buildings, aimed to empower stakeholders with the knowledge and resources necessary to make informed decisions regarding the conservation and sustainable management of these invaluable assets.

In this paper, we delve into the outcomes of this groundbreaking project, detailing the development of the MONUREV software, the formulation of methodologies for heritage building rehabilitation principles, and the establishment of systematic procedures for maintenance planning. Furthermore, through case studies, we illustrate the practical application and validation of these methodologies, underscoring their potential to reshape heritage conservation practices and ensure the enduring legacy of cultural heritage buildings for generations to come.

2. Literature Review

For heritage buildings, decision-making regarding technical restoration solutions must consider economic, environmental, and cultural factors. Sustainable materials, like those developed by [1], offer cost-effective, environmentally friendly, and culturally appropriate options.

Paper [2] emphasize the importance of integrating multidisciplinary assessments, such as seismic and energy efficiency assessments, into the decision-making framework to improve the sustainability and efficacy of restoration projects. Advanced techniques like dynamic life cycle cost analyses provide a data-driven basis for these decisions, evaluating the economic sustainability of maintaining the integrity of heritage buildings [3].

Paper [4] propose a method balancing the preservation of heritage values with energy efficiency improvements in historic building stocks. This approach uses quantitative and qualitative analyses to create strategies that integrate energy-saving measures with heritage conservation guidelines, forming a basis for relevant policy development.

Paper [5] stress the importance of balancing energy efficiency and economic viability in the rehabilitation of historic buildings, highlighting the challenges of integrating energy improvements without compromising architectural integrity. They emphasize the need for a thorough evaluation process to achieve sustainability and economic viability.

The use of life cycle cost analysis in the maintenance and restoration of cultural heritage sites marks a significant development in conservation strategies. By accounting for an extensive range of costs and their long-term implications, stakeholders can make more informed decisions. Recent advances include integrating building information modelling (BIM) with LCA and LCC methodologies, enhancing the decision-making precision and operational efficiency [6]. Further research is needed to refine these techniques and expand their applications, improving the sustainability and impact of conservation efforts.

Cost analysis for the restoration and maintenance of heritage buildings is crucial and requires a comprehensive application of life cycle cost (LCC) analysis. This approach considers all costs over a product's lifetime, particularly relevant in construction for managing acquisition, maintenance, and renewal. The LCC primarily reflects costs during the operational phase, which are often underestimated yet form a substantial part of the life cycle costs [7].

Paper [8] conducted a systematic review highlighting the inadequacies of common sustainability rating systems like LEED and BREEAM for historic buildings. They advocate for a balanced approach that addresses environmental, economic, and social sustainability dimensions, ensuring that any interventions respect and enhance the heritage values of these structures.

Paper [9] analyzed degradation models and maintenance strategies for coastal structures affected by climate change and chloride-induced corrosion. They emphasize the importance of integrating comprehensive life cycle cost analyses and sustainable maintenance practices to ensure the long-term performance and preservation of marine and coastal heritage structures under evolving environmental conditions.

In cultural heritage management, activities such as maintenance, repair, reconstruction, and restoration are crucial for maintaining the integrity and value of historic monuments. Maintenance includes regular tasks like repainting to manage wear from use. Repair might involve fixing damage such as damage to a roof section, while reconstruction could entail either updates for technological conformity or restoration to a historically accurate state. These processes aim to prolong the technical and aesthetic life of these buildings, ensuring their functionality and preserving their cultural value [10].

LCC assessments are pivotal in the pre-investment phase, helping to select cost-effective solutions by forecasting cost development across a building's life. This forecasting is essential for maintaining economic sustainability and preserving historical significance, especially for projects funded by public budgets. Optimizing life cycle costs aligns with the public financial management principles of efficiency, economy, and expediency, crucial for complying with regulatory requirements such as those in the Public Procurement Act for assessing the economic viability of tenders [11].

Paper [12] address the challenges and strategies for energy retrofit projects in urban settings, emphasizing the impact of uncertainty on investment decisions. They highlight the utility of advanced risk management techniques like Monte Carlo simulations and sensitivity analyses to manage uncertainties, refining risk assessment methods for sustainable and economically viable energy transitions in cities, merging heritage preservation with modern energy efficiency goals.

Paper [13] explore the post-occupancy evaluation of refurbished historical buildings, highlighting the challenges of maintaining aesthetic values, managing high maintenance costs, and integrating modern safety features and amenities into older structures. This study outlines significant obstacles to retaining cultural and historical integrity during rehabilitation efforts.

Heritage reconstruction involves unique economic and engineering challenges, especially with immovable monuments where each project is distinct. Understanding the technical parameters of building structures and equipment is crucial for accurate cost estimates, affecting not only restoration costs but also ongoing operational expenses like energy consumption and maintenance. Given the uniqueness of each heritage asset, universal cost estimation methods are insufficient, and tailored assessments are necessary to address the particularities of each site [14].

Paper [15] examine structural and thermal retrofitting solutions for masonry walls within the Italian context, integrating a life cycle cost analysis. Their methodology emphasizes the interplay between economic and environmental evaluations, assessing the impact of thermal and structural improvements on sustainability requirements specifically with regard to local geographical and climatic conditions.

In contexts like the Czech Republic, where heritage buildings often have both private and public functions, the precise and transparent use of public funds through life cycle cost (LCC) analysis is critical. This requires accurate baseline data on the building's technical condition, architecture, equipment, and relevant time factors. Such comprehensive data ensure a reliable cost analysis, which is fundamental for selecting the most suitable refurbishment strategies [16–18].

Furthermore, planning the financing of cultural heritage site restoration involves more than immediate cost calculations; it includes strategizing for long-term financial sustainability covering future operating, maintenance, and partial restoration costs. This ensures the building remains preserved and functional over its extended lifespan [19]. Each monument, due to its unique characteristics, demands a bespoke approach to cost estimation involving a detailed analysis of each structural element to accurately determine both restoration and ongoing maintenance costs.

In conclusion, effective restoration and maintenance of cultural heritage sites require detailed planning and meticulous cost estimation based on economic and engineering expertise. The process balances the costs with the historical and cultural value of the monuments, requiring a comprehensive approach to ensure that fiscal prudence is maintained while preserving heritage [20,21].

2.1. Case Studies in Heritage Conservation: A Comparative International Perspective

2.1.1. Villa Heike in Berlin, Germany

To enrich our discussion on heritage conservation and adaptive reuse, we have included the case study of Villa Heike in Berlin, Germany, as an exemplary model of architectural transformation. Constructed in 1910 and abandoned since 1990, this villa once belonged to Richard Heike, a notable industrialist, who later served in various roles including a stint with the Stasi during the Cold War. In 2019, architect Christoph Schubert revitalized the space into an office and showroom which now hosts artists' works. This transformation not only repurposed the disused structure but also preserved its historical integrity, providing a vibrant space that intersects commercial and cultural activities.

This example demonstrates the potential of sensitive design interventions in historical buildings and how they can be adapted for modern use without discarding their historical narratives. By incorporating such specific international examples, our study broadens its scope and exemplifies successful global strategies in heritage building conservation. This supports our conclusions and provides a more comprehensive view, addressing the initial concerns from the review regarding the generalization of our findings [22].

2.1.2. Banco de España Library Restoration in Madrid

The international perspective of our study is further enriched by incorporating the Banco de España Library Restoration in Madrid, a prime example of meticulous heritage conservation within an institutional setting. Constructed in multiple phases starting in the 19th century, this historic bank headquarters features a remarkable reading room characterized by its cast iron lattices painted in a bright shade of white, symbolizing purity. During the restoration, these lattices and other historical elements were carefully preserved, balancing the aesthetic integrity of the past with the functional demands of the present.

This case highlights how heritage conservation principles can be applied universally yet tailored to suit specific cultural and historical contexts. The restoration of the Banco de España Library, with its focus on maintaining historical accuracy while updating it for current use, complements our study by demonstrating global practices in architectural conservation. By including such examples, our research deepens the understanding of international heritage restoration efforts and reinforces the adaptability and relevance of conservation strategies across different settings [23].

2.1.3. Castello di Dolceacqua, Italy

In our study, we incorporate another international example, Castello di Dolceacqua in Italy, highlighting effective conservation efforts in historical architecture. Originally subjected to multiple restoration attempts in the 19th century, this castle underwent a comprehensive restoration in 2015 under the direction of LD+SR architetti. The focus of this project was to enhance the visitor experience by establishing a continuous trail that provided picturesque views of the surrounding villages and the Nervia Valley River, emphasizing the castle's strategic location and scenic advantage.

This restoration not only preserved the historical integrity of Castello di Dolceacqua but also successfully transformed it into a significant cultural landmark, enhancing its accessibility and engagement with the public. Including this case in our study supports our broader discussions of architectural restoration and showcases the integration of heritage buildings into contemporary cultural and tourist frameworks. This example addresses earlier concerns about the scope of our research and underscores the global applicability of our findings in the field of heritage conservation [24].

2.1.4. Repos Maternel Women's Shelter Extension in France

In our analysis of restoration in architecture, we include the Repos Maternel Women's Shelter Extension in France, an inspiring example of architectural transformation focused on social responsibility. Built in 1920 as a vast country house covering 3082 m^2 and originally functioning as a nursery, this facility has undergone significant refurbishment and modernization of its services. The restoration project, led by Marjan Hessamfar and Joe Vérons architectes associés, repurposed the building to serve a vital societal role, now acting as a shelter offering accommodation and support services to financially unstable pregnant women and young mothers estranged from their families.

This example not only demonstrates the architectural revival of a historic structure, but it also highlights the building's adaptation to meet contemporary social needs. Including such innovative restoration projects in our study showcases the potential of architectural interventions to both preserve historical heritage and fulfill current humanitarian and social requirements. This case further extends our discussion on the global scope of restoration practices and their impact on community welfare, adding depth to our research and addressing concerns about the broader applicability of our findings [25].

2.2. Examples of Internationally Used Methods and Programs in Heritage Conservation

Internationally recognized heritage conservation methodologies and programs include, for example, Getty Projects' Conserving Modern Architecture Initiative, which focuses on the global conservation of twentieth-century heritage [26]. In addition, the Heritage Conservation Program at the University of Southern California offers courses such as Conservation Methods and Materials and Global Perspectives in Heritage Conservation, which provide a comprehensive view of heritage conservation through modern technologies and international policies [27]. Other programs include World Heritage USA's International Exchange Program, which connects heritage professionals with global conservation practices [28] and the International Masonry Institute's Historic Masonry Preservation Certificate Program, which trains members in traditional conservation materials and methods [29].

Furthering the international approach, CIPA Heritage Documentation, under the International Committee for Documentation of Cultural Heritage, is a leader in conservation training and advises on best practices in heritage documentation [30]. The World Heritage Centre's World Heritage Education Program focuses on engaging individuals worldwide in heritage conservation and promoting the importance of the UNESCO World Heritage Convention [31]. These diverse programs demonstrate different approaches, covering different methodologies and contexts, and emphasizing the conservation of both tangible architectural heritage and broader cultural heritage.

3. Presentation of the Methodology

Central to the project results are several key deliverables:

- MONUREV Software: This advanced software tool is designed for the detailed planning and management of maintenance and restoration activities specific to cultural heritage buildings. It allows users to simulate different scenarios and choose the most effective and sustainable strategies for building conservation.
- Restoration Principles Methodology: This methodology outlines the guiding principles for the rehabilitation of heritage buildings, ensuring that all interventions are sensitive to the architectural integrity and historical value of the structures.
- Heritage Maintenance Planning Procedure: This provides a structured approach to the planning of maintenance activities, ensuring that all actions are timely, effective and in accordance with heritage conservation standards.

These tools have been rigorously tested through three pilot case studies involving selected heritage buildings. These case studies served not only to demonstrate the practical application of the developed tools, but also to validate their effectiveness. The tests confirmed the usefulness of the MONUREV software in real-life scenarios and proved the efficiency of the newly established maintenance and rehabilitation procedures. The results of these tests have been instrumental in refining the tools to ensure that they meet the needs and complexities of heritage management.

The successful application and verification of these tools in the case studies underlined their potential to significantly improve the management and conservation of heritage buildings. This project not only contributes to the field of heritage conservation by providing practical, innovative solutions, but also sets a precedent for future initiatives aimed at safeguarding our cultural heritage.

3.1. Software MONUREV

The MONUREV software is a key output of the project focused on optimizing the maintenance and restoration of cultural heritage. Designed as a web interface, this application is user-friendly and facilitates the simulation of different maintenance and restoration strategies while emphasizing the preservation of cultural and historical values.

MONUREV allows users to generate maintenance and restoration plans for designated monuments, taking into account specific purposes and construction periods. The software is based on a database that aggregates primary data from structural elements, allowing users to tailor the input data to their specific buildings.

Extensive preparatory work laid the foundations for the development of MONUREV. This included analyzing bid and actual construction prices in the Czech Republic, collecting dimensional characteristics from a wide range of historical buildings, and determining the service life of structural components based on routine maintenance assessments.

Several key outputs generated by MONUREV enhance its usefulness to users. These include the balance sheet of the property, a detailed repair plan for structural components, a list of repairs required within a specified time period, and a corresponding repair schedule.

Throughout its development, MONUREV has undergone several rounds of verification and reprogramming. The accuracy of its predictions was tested using an inverse method to assess how well the model's outputs matched the actual data from the projects that served as inputs.

The testing took place on a sample of 20 buildings, where the dimensions of individual structural elements, which are part of the maintenance and renewal plan, were available. From the MONUREV application, the expected structural elements and their dimensions, which are expected for the mentioned objects, were generated for these objects according to the basic measurement characteristics and object type. Subsequently, a comparison of the output from the model and the actual values was made. This is the percentage agreement of the generated model from the point of view of structural elements and their size compared to real values. Average deviations for individual buildings are shown in Table 1.

Table 1. The average difference in dimensions of structural elements between reality and the model.

Building	Average Deviation
Town house Husovo nám. 88/16 Beroun	90.27
Veigertovský house Karlovo nám. 8 Kolín	92.66
Červinkovský house Brandlova 27 Kolín	90.51
Town house Masarykovo náměstí 98 Brandýs nad Labem	97.92
Town house Náměstí Přemyslovců 165/18 Nymburk	90.11
House U Tří bubnů Nám. Franze Kafky 14/8 Prague	99.4
House U Červeného jelena Malostranské nám. 265/6 Prague	94.46
House U Bílé řepy Nerudova 237/39 Prague	88.97
House U Černého orla Nerudova 205/2 Prague	94.64
House U Černého beránka Valdštejnská 150/4 Prague	99.38
House U Bílého orla Malostranské nám. 4/27 Prague	87.44

Table 1. *Cont.*

Building	Average Deviation
House u Zlatého bažanta U radnice 10/2 Prague	89.55
House U Tří lip Malé nám. 7/7 Prague	96.87
House U Tří kominíčků Malé nám. 9/5 Prague	97.25
House U Bílého jelínka Nám. Franze Kafky 18/6 Prague	80.89
House U Tří špačků Nám. Franze Kafky 17/7 Prague	88.96
House U Anděla na kohoutě Karlova 145/25 Prague	98.46
Buchalovský house Havlíčkova 1025/4 Prague	81.38
House U Ambrožů Školská 687/13 Prague	86.79
House Na Korábě Václavské nám. 824/29 Prague	84.13
Average	91.50

The results from Table 1 were further validated through hypothesis testing at the 90% confidence level, ensuring the reliability and applicability of the software in real-world scenarios.

3.2. Methodology of Heritage Building Rehabilitation Principles

The aim of the project was to provide a thorough overview of the principles of rehabilitation applicable to the repair of historic buildings. The developed methodology clarifies the fundamental context influencing the approach to the rehabilitation of heritage buildings and outlines the specific steps recommended for effective rehabilitation procedures. With a strong conservation focus, the articulated principles primarily advocate the structural conservation and life extension of existing structural elements, with a conscientious consideration of their future functionality and operation.

A key aim is to retain the original form and function of individual structures as far as possible. Conservation officers, designers, building owners and managers who deal with historic buildings are the primary audience for this methodology. This tool provides these stakeholders with a basic handbook to guide them through the preparation and design phases of conservation interventions.

Rooted in the general principles of heritage conservation, the methodology integrates contemporary strategies for addressing common problems encountered in historic buildings. Its innovative aspect lies in the refined definition of conservation facets in relation to necessary rehabilitation measures, which often require varying degrees of intervention in protected historic structures. It also examines the conflict between the need to maintain the structural and technical standards of the building, which often involves the incorporation of new elements for continued historic use, and the requirements of conservation. These requirements focus on preserving the structural integrity, technical features, materials or even the stylistic elements of older, significant phases of the structure that are primarily subject to conservation efforts. This methodology serves as a vital bridge between modern needs and traditional values, ensuring that interventions enhance the longevity and integrity of our cherished heritage buildings.

3.3. Heritage Procedure for Maintenance Plans for Heritage Buildings

The primary objective of this output was to provide a systematic tool for the planning, implementation and documentation of maintenance activities in the management of historic buildings. A further aim was to raise awareness of the vital importance of regular maintenance as the most effective strategy for ensuring the long-term and sustainable conservation of immovable cultural heritage, together with its intrinsic and utilitarian values. To achieve this awareness, we organized targeted outreach initiatives, including an exhibition and a workshop that brought together key stakeholders such as owners of historic properties, local authorities and conservation experts. These events were designed to showcase practical examples of best practice in conservation and to facilitate the exchange of knowledge and experience between participants.

The Heritage Procedure highlights the cultural and economic benefits of regular maintenance and timely repairs and proposes a system for their careful planning. This system is based on initial and periodic follow-up inspections to assess the condition of the structure. Maintenance activities are defined in terms of the nature of the tasks, their typical frequency, and the professional, time and financial requirements. The system also highlights the relationships between these different activities.

This approach provides a generalized yet functional system that can be adapted to specific structures. Its aim is to enable the efficient, long-term management and rationalization of maintenance work in the context of heritage conservation. In addition, the procedure includes a compendium of the most common types of failure and damage observed in these structures, identifying their causes and outlining the most common maintenance actions applicable to each structural element. This structured approach not only facilitates the conservation of heritage buildings, but also ensures that their historical and aesthetic values are preserved for future use and appreciation.

3.4. Case Studies for the Application and Verification of the Results of the Project

This section focuses on demonstrating how the project's findings have been applied and verified through a series of case studies, each of which represents an economically and technically sustainable model for restoration and maintenance. Based on a thorough assessment of the current condition of each building and the exploration of alternative options for their future operation, definitive construction solutions were proposed and their associated costs were carefully calculated.

The project has developed the following case studies:

- The St Martin's Church Rehabilitation Case Study: This study provides a detailed insight into the original architectural and structural condition of the church and proposes an appropriate structural design for its rehabilitation. It includes extensive photographic documentation of both the original and current state of the church, helping to visually compare and contrast the changes and maintain the transparency of the restoration process.
- A case study of the overall restoration of the parish of Dobrovice: Like the first case study, this study details the initial condition of the parish buildings and outlines robust restoration plans designed to enhance both their functionality and aesthetic values. Extensive photographic documentation helps to illustrate the progress made from the pre-restoration state to the present day.
- Case study of the reconstruction of the Museum of Sugar, Distilling and Beet Growing: Focusing on a specialist museum, this study examines the unique challenges posed by the building's specialist focus and its heritage significance. It includes a detailed look at the original structure, proposals for structural restoration and visual documentation of all stages of the restoration process.

Each case study also meticulously quantifies the costs associated with the restoration using the MONUREV software application. Key financial assessments provided include:

- A detailed breakdown of the building's structural configuration.
- A comprehensive plan for the restoration of structural elements over a defined period.
- Accumulated restoration costs, including a simulation of the impact of inflation.
- An assessment of construction costs using micro-budgeting techniques for selected structural elements.

These case studies not only validate the results of the project, but also provide tangible templates and methodologies that can be adapted for future restoration projects, ensuring sustainable maintenance and restoration practices that combine technological advances with economic feasibility.

4. Application of the Methodology—A Case Study of the Overall Restoration of the Parish of Dobrovice

In order to better visualize the practical application of our methodology, this chapter includes an analysis of a case study focused on the large-scale restoration of the parish of Dobrovice. The aim of this overview is to illustrate the step-by-step processes, the challenges that had to be faced and the impressive results achieved in this restoration project.

The subject of this study is a description of the construction and reconstruction modifications of the parish of Dobrovice. The address of the building is Palackeho namesti No. 70, 29441 Dobrovice (Mlada Boleslav district). The built-up area of the building is 312.60 m^2 and the volume of the building is 2.766 m^3. The owner of the building and the land is the town of Dobrovice.

The parish is a detached, two-storey, partial basement building with a rectangular ground plan (Figures 1–3). The building has a hipped roof. The dimensions of the building are 13.2 $\times$ 23.8 m, the height of the building is 15.0 m, and the clear height of the rooms is between 3.0 and 3.6 m. In the north-western corner of the former parsonage, there is an arched gate of mixed masonry (from the 18th century), which follows the line of the original enclosure wall of the parsonage grounds.

Figure 1. General view of the parish of Dobrovice—original condition.

Figure 2. Details of the original condition of the façade.

Figure 3. Photo documentation of the original condition of the interior.

The ground floor rooms are vaulted with cross and cloister vaults in good condition. In the central part is the entrance hall, from which a staircase leads up. The rooms on the first floor have flat roofs, which have been recently covered with a steel structure and a reinforced concrete slab. The baroque roof is covered with double-layered beaver tiles. There is a vaulted cellar under the south-eastern part of the building, from which a sunken staircase leads out to the south-east.

The building is a former vicarage, built in the early 18th century on the site of an earlier castle. Its present form dates from a rebuilding in the second half of the 19th century. In the 1990s, the most recent rebuilding began, as a youth rehabilitation center, which has not yet been completed. The work was stopped at the "rough" construction stage. The building was then secured against unauthorized entry.

After the construction and renovation works, the building will be used as a civic facility for the social activities of the town and as a primary art school in Dobrovice. The proposed building and construction solution must respect the original layout of the rooms as much as possible. The barrier-free access to the first floor cannot be realized due to the monument protection, but due to the multifunctional use of the building, all planned activities can be realized on the ground floor of the building. The thermal requirements for the buildings cannot be met for conservation reasons.

The following activities will be carried out as part of the structural design: sensitive clearance of the building with regard to conservation and storage of period artefacts; major building alterations; roof truss and roof repair; introducing water and gas supplies, rainwater drainage and LV supply; finishing; and landscaping.

The internal layout of the building will remain almost unchanged on the ground floor, with the addition of sanitary facilities on the first floor, and the attic and basement will remain unused. In terms of thermal performance, there will be a new glass vestibule to prevent cold ingress into the building. On the ground floor, four main vaulted rooms will be used as club and classrooms, two of which will be equipped with kitchens for light refreshments.

The whole ground floor is tiled with ceramic tiles, original to the surviving areas. Behind the main lobby are three toilets—men's, women's and disabled—and a cleaning room. A new doorway has been knocked through to create the toilet facilities. The entrance to the basement has been retained. In the basement, part of the original corridor in the partition will be removed and the existing sandstone portal in the perimeter wall will be bricked up and made accessible on both sides. The existing staircase to the first floor is retained with the removal of the existing door at its edge. The arched staircase has timber steps and risers which will be retained.

On the ground floor, the structural system remains unchanged, while on the first floor, the load-bearing walls have been repaired and reinforced with solid brickwork and lintels. The building is supported in a north–south direction by steel beams at the level of the ceiling structure above the second floor. New beams will be installed at the level of the ceiling structure above the first floor.

Moisture in the masonry in the basement and on the ground floor is a common problem that has affected the internal and external plaster. Unfortunately, the moisture is also caused by inadequate roof drainage. To improve the situation, it is essential that surface water is drained away from the perimeter of the building. Measures are proposed to reduce the manifestations of moisture in the building (ventilated gaps, drainage, remedial plastering).

5. Methodological Framework for Sustainable Management of Cultural Heritage Buildings

5.1. Project Overview

This paper presents a research project carried out by the team of authors at the CTU in Prague. The project is called Sustainable Management of Cultural Heritage Buildings and was funded by the Ministry of Culture of the Czech Republic. The project was carried out between 2018 and 2023.

The main objective of this project is to improve the effectiveness and efficiency of maintenance and rehabilitation activities for cultural heritage buildings through the development of a robust procedural framework. The initiative aims to provide building owners with the necessary tools to make informed and financially sound estimates regarding the ongoing care and necessary rehabilitation of their properties [32].

5.2. Software Development and Methodological Framework

A key outcome of this effort is the creation of specialized software designed to simulate different maintenance and rehabilitation scenarios. This software will assist in the selection of the most appropriate strategies, balancing sustainability with the imperative of preserving the cultural and historical essence of the buildings. The methodology developed facilitates the establishment of a comprehensive maintenance plan and the formulation of rehabilitation principles. These principles are designed to ensure the longevity of the building while being in line with contemporary conservation trends, thereby promoting a sustainable long-term condition of the cultural heritage [33,34].

At the heart of this project is a methodology based on a holistic understanding of the historical and cultural context of the buildings. This involves an amalgamation of several disciplines, including conservation practices, detailed investigations of the building's structure and history, an economic evaluation of structural restoration, and sustainable asset management strategies. The approach is complemented by the concept of building passporting, which provides a detailed record of the building's characteristics and history to support the development of tailored maintenance and refurbishment plans.

5.3. Validation and Application in Real-World Scenarios

The tools and processes developed in the project have been pre-tested through case studies of selected heritage sites to verify their applicability and impact. This pilot phase plays a crucial role in refining the tools and ensuring that they meet the specific needs and challenges of different types of heritage buildings. In summary, this project aims to equip stakeholders with advanced, practical tools that integrate cross-disciplinary knowledge to maintain the integrity and extend the life of cultural heritage buildings, while taking into account financial implications and sustainability. The ultimate goal is to pass on these immovable assets, rich in historical and cultural value, to future generations in a condition that respects their past and secures their future.

The project has successfully developed a detailed procedure for a maintenance plan specifically tailored to heritage buildings, addressing the unique challenges and requirements of these structures. This comprehensive maintenance plan serves as a critical framework for the systematic planning, execution and documentation of maintenance activities within the context of historic building management. This process ensures that all maintenance activities and rehabilitation practices are designed to promote a sustainable condition for the buildings, thereby increasing their longevity and aligning with modern conservation practices [35–37].

In response to the challenges of acquiring the precise characteristics of historical buildings, such as details of walls, windows, or potential insulation, our methodology employs multifaceted data collection.

To ensure accuracy and depth in our data, we conducted comprehensive on-site physical inspections. Each analyzed building underwent a detailed survey. We actively engaged with building owners to obtain both verbal descriptions and documented historical data, which enables a richer understanding of each structure's unique features and historical modifications. In addition, we acquire construction blueprints from the owners and relevant local building authorities to track changes in the building's structure over time, further enriching our dataset.

5.4. Balancing Economic Efficiency with Heritage Conservation

The methodology not only ensures the economic viability of maintenance plans, but also preserves the integrity and value of heritage assets. This integration is facilitated by a multidisciplinary approach that includes the selection of economically viable solutions that preserve monumental and historical values. These solutions include comprehensive decisions on restoration options, reconstruction designs and restoration of individual structures with a focus on internal installations such as heating, air conditioning and security equipment.

Optimal material and technological solutions for different functional parts of the building are identified based on their life cycle costs, required technical parameters and respect for monumental and historical values. An example of this would be the use of components that, despite higher initial costs, offer lower running costs—reflecting their superior quality—which in turn leads to longer maintenance intervals and extends the life of the building. It should be noted, however, that more expensive options do not automatically guarantee future cost savings; the relative cost-effectiveness depends heavily on the quality of the materials, the design of the technology, and the frequency and nature of maintenance.

5.5. Interdisciplinary Collaboration and Societal Impact

Critical to the success of the methodology is the interdisciplinary collaboration of various professionals, including architects, designers, structural engineers, energy engineers, technical equipment experts, economists and conservationists. Each of these professionals brings vital expertise to ensure that all aspects of the building's conservation are considered. For example, the restoration of a 19th-century library involved a remarkable collaboration between structural engineers and conservationists, who worked closely to find solutions that preserved the historic façade while incorporating modern climate control systems recommended by energy engineers. This project demonstrated how effective interdisciplinary collaboration can result in meeting all economic, technical and historic requirements, and exemplified the methodology in practice.

This robust interdisciplinary approach highlights the ability of the methodology to effectively integrate different disciplines and promote informed, holistic and sustainable decision-making in heritage conservation projects.

The methodology not only addresses the collection of data where details are less quantifiable but also enhances the general applicability of our research to various types of historical buildings, mitigating concerns regarding the generalization of the methodology to less quantifiable contexts.

The methodology and software MONUREV are indeed designed to be flexible across different scenarios in terms of data availability about the building. Where detailed and comprehensive data are available, the methodology can use them to produce highly accurate predictions and estimates of restoration and maintenance costs. This scenario allows precise quantification and adjustment of all relevant parameters, resulting in robust and detailed financial planning.

Conversely, in situations where data on the building are limited or rudimentary, the methodology still facilitates cost estimation, albeit with less accuracy. In these cases, the MONUREV software uses generalized assumptions and standard metrics to fill in information gaps, which are clearly stated and transparent in the output. Although less precise, these estimates provide valuable initial insights and a reliable basis for preliminary planning and decision-making.

We recognize that the accuracy of outputs is directly related to the quality and completeness of input data. Therefore, as part of future development, we are considering enhancing the methodology to improve predictions even in data-poor environments. This will further strengthen the utility of our approach for different building types, regardless of the availability of detailed information.

It can be argued that immovable cultural monuments function essentially as public goods for collective consumption. As such, their preservation is in the general interest of society. The benefits derived from an owner's investment in and use of immovable cultural heritage are not confined to the owner alone. Rather, these benefits are shared, to varying degrees, by society as a whole or by specific groups within it.

In economic terms, a situation where there are significant benefits or detriments that are beyond the control of the owner is referred to as a market failure. This market failure often results in a significant discrepancy between the market price and the actual value of the immovable cultural property. While the value of cultural heritage is highly subjective, influenced by individual perceptions of quality, the market value represents the sum that an individual is willing to pay for the range of benefits associated with such a purchase. If these benefits, both economic and non-economic, are not reciprocated to the 'investor', the market value of the immovable cultural heritage remains subdued, as greater benefits may be more readily obtained elsewhere, despite the increased societal value of preserving the cultural heritage.

Externalities, or the unintended consequences of an action, are inherent in any intervention:

- Intergenerational factor: Our current actions or inactions, which have associated costs, will either benefit or harm future generations.
- Existence in the public realm: Our interventions often have a significant visual and qualitative impact on both the immediate and wider environment of a monument, making these interventions subject to regulation. Conversely, changes in the public realm can have a reciprocal effect on the monument.

Furthermore, due to their specific location, these monuments face additional challenges related to the infeasibility of relocation. This infeasibility may be due to the unsuitability of the surrounding area for improvement, or the impossibility of moving the monument closer to a more 'market-friendly' location. Such complexities highlight the unique challenges and considerations in the management and conservation of immovable heritage.

5.6. Stakeholder Engagement in Heritage Conservation Decision-Making

The role of stakeholders in the decision-making process for heritage conservation is essential for the effective planning and implementation of conservation activities. Stakeholders, including property owners, local communities, historical societies, government agencies and conservation professionals, are actively involved throughout the conservation project. Their input is not only sought in the early stages but is continually integrated into the overall strategy to ensure that all perspectives and expertise are considered.

Workshops and consultations are held at the outset of each conservation project to gather insights and expectations from all stakeholders. This collaborative approach helps to identify the most valued aspects of the heritage site and any concerns about potential changes or interventions. For example, local communities often emphasize the importance of maintaining the cultural significance and accessibility of heritage buildings, while professionals may focus on the technical aspects of conservation.

Once the planning phase has begun, stakeholders regularly review the proposed conservation plans. These reviews ensure that interventions are in line with the latest conservation techniques and comply with legal and ethical standards. Stakeholder feedback is crucial in refining these plans, making them more comprehensive and tailored to the specific needs of the heritage property.

During the implementation phase, stakeholders are kept informed through regular updates and are often invited to participate in site visits. This ongoing engagement helps to maintain transparency and allows for real-time feedback, which can be critical in adapting plans to address unforeseen issues or opportunities.

Stakeholders are also involved in evaluating the effectiveness of the interventions once the maintenance activities have been completed. Their insights contribute to a continuous learning process, allowing strategies to evolve based on practical results and changing conservation priorities.

Overall, the active and structured involvement of stakeholders throughout the conservation process ensures that maintenance activities are not only well planned and executed, but also deeply aligned with the values and needs of all stakeholders. This inclusive approach fosters a sense of collective responsibility and commitment to preserving the heritage for future generations.

6. Results

6.1. Case Studies in Cultural Heritage Restoration

The project has developed three case studies:

1. St Martin's Church Rehabilitation Case Study: Focused on the church's architectural condition and structural design for rehabilitation, featuring extensive photographic documentation.
2. Restoration of the Parish of Dobrovice: This examines the initial condition and outlines restoration plans, supported by extensive photos showing progress.
3. Reconstruction of the Museum of Sugar, Distilling, and Beet Growing: This analyzes challenges due to the building's focus and heritage significance, including detailed structural proposals and visual documentation of the restoration stages.

6.2. The MONUREV Software

The MONUREV software application has been innovatively designed to facilitate the preparation of maintenance and restoration plans for monuments through a user-friendly web interface. This application uniquely processes data at the level of individual structural elements and incorporates a database of type objects to speed up and simplify the estimation process, thereby improving user experience and efficiency.

Here is a link to the website of our research project, where you can also find information about the software [38].

MONUREV allows users to quickly generate a preliminary estimate for a maintenance and refurbishment plan based on basic descriptive characteristics of the building, such as its type, height, length or number of floors. This initial model provides a basic overview that, although generalized, is a useful starting point for more detailed planning.

For users seeking a more tailored and accurate approach, MONUREV offers the flexibility to refine this model based on the specific conditions of the building and its structural elements. During this refinement process, the types and expected areas of the structural elements are meticulously estimated, and refurbishment costs are associated with each element. This facilitates the production of a detailed projected maintenance and renewal plan for the building over a selected reference period.

To obtain a more accurate picture of the building's condition and to further refine the maintenance and refurbishment plan, a personal inspection of the building is recommended. The data collected from such inspections can be used to adjust the model generated by MONUREV, allowing the specification of structural elements, dimensions, state of wear and, if necessary, restoration costs. This ensures that the resulting maintenance and restoration plans are not only comprehensive, but also closely aligned with the actual condition of the building, providing a more reliable and actionable plan for stakeholders.

The methodology is based on the expected life cycle costs (LCC) of individual structural elements of the object. The basis of the LCC calculation is the list of structural elements that are present in the given object. For each structural element, its size and unit prices for renewal and maintenance are determined, which are linked to the current price system using mini budgets. The given data, taking into account the current status of the scope, will be connected with the algorithm for calculating recovery and maintenance cycles to generate a recovery and maintenance plan.

The tool for assessing the economic sustainability of an immovable heritage asset is a life cycle cost analysis. It is based on relevant input data on the technical parameters of the building, structural elements and equipment, as well as the time period of the costs associated with them. The analysis becomes an important basis for the decision of the owner, designer and future user on the selection of the optimal variant of the technical solution for the restoration. Ecological aspects, cultural and historical value and long-term economic consequences should also be taken into account.

Life cycle costs (LCCs) are the total costs incurred over the lifetime of a product. In the case of construction, these include the cost of acquiring the building and civil engineering assets, the cost of maintaining and renewing the structures and equipment, the cost of operation and the cost of the end of life. In most appraisal cases, these are costs incurred over the economic lifetime of the asset. When choosing between options, it is often the case that only the initial cost is considered and the operating, maintenance and renewal costs are overlooked. However, it is the costs incurred during the use of the building that make up a significant proportion of the life cycle costs of the building.

In the case of immovable cultural heritage, the life cycle costs are mainly made up of restoration and maintenance costs, refurbishment, renovation of art and craft components and operating costs. These costs are incurred over the entire technical life of the building, which is very long in the case of immovable cultural heritage. The aim of restoration is to extend the technical life of the building and to preserve its historical and cultural significance.

Life cycle costs (LCCs) are typically determined during the pre-investment phase of a building project. This allows them to be used to select the most efficient alternative solutions. The LCC indicator is a cost criterion; a lower value is more advantageous for the investor. Information on the evolution of costs in the different phases and the possibilities and ways of influencing them, as well as information on the service life of structures and equipment, is crucial for the modelling of the LCC.

In the case of immovable cultural heritage, the LCC is determined in the operational phase, prior to the planned rehabilitation or restoration. The aim is to select an economically sustainable solution that offers the greatest potential for heritage conservation and historical value.

The aim of LCC analysis in the context of the restoration of immovable cultural heritage is not to quantify total life cycle costs, but rather to quantify their change. The criterion for selecting the restoration option will not be the lowest level of total life cycle costs for the period analyzed, as in the case of standard new buildings or refurbishments and upgrades. Instead, the potential to reduce the costs of operation, restoration and maintenance, while respecting the heritage value of the property, will be considered.

The change in life cycle cost (ΔLCC) can be expressed schematically as the sum of the renovation costs (ON), the increase/decrease in operating costs (ΔPN) and the increase/decrease in maintenance costs (ΔUN).

$$\Delta \text{LCC} = \text{ON} + \Delta \text{PN} + \Delta \text{UN} \tag{1}$$

The MONUREV application systematically tracks changes in construction costs by autonomously updating the cost data at regular intervals. Specifically, this update utilizes indices reflecting shifts in purchase prices, which are sourced from an established price normative system. These updates are scheduled to occur biannually, ensuring that the cost estimations remain current and reflective of market conditions. This structured updating mechanism allows the Heritage Maintenance Procedure to adapt effectively to economic changes in the construction environment, thereby maintaining reliability and accuracy in cost management.

6.2.1. Application Input Data

For the application to work effectively, it requires comprehensive input data that reflect the actual characteristics of the building as closely as possible. This minimizes the need for subsequent changes and increases the accuracy of the maintenance and refurbishment plans generated by the software. The primary data inputs include not only basic information such as the building's name, location and illustrative images, but also more detailed characteristic data describing the essential features of the building.

To illustrate the practical application of this approach, let us consider the case study of the overall restoration of the parish of Dobrovice. In this example, a building typically used for religious, cultural and social purposes was selected. The generative model for this building was then enriched with the following input parameters:

- Building type: Identifies the building as a parish, which is part of the broader category of religious, cultural and social buildings. This categorization helps the software to apply specific algorithms adapted to the typical needs and restoration patterns of such structures.
- Structural details: Information about the structural composition of the building, such as the materials used, the age of the building, typical wear and tear patterns, and any unique architectural features, that may require special attention during restoration.
- Dimensional data: Precise measurements of the building, including total area, height, number of floors and room configuration, which are essential for estimating the extent of maintenance and renovation required.
- Historical Significance: Details of the historical significance and any legal or conservation status affecting the building. This will influence decisions about acceptable materials and techniques during the restoration process.
- Present condition: A thorough assessment of the current condition of the building, highlighting areas in urgent need of repair or showing signs of significant deterioration.
- Functional Requirements: Information on how the building is used, which influences both the restoration approach and the prioritization of specific areas or features within the building.

These inputs are crucial as they directly influence the modelling and results produced by MONUREV. By accurately reflecting the real situation of the building in the software inputs, the generated maintenance and rehabilitation plan will be both accurate and highly tailored to the specific needs of the building, ensuring effective and efficient rehabilitation work.

The data entered into the MONUREV application in the first phase (Table 2) can be taken from the building's accompanying report and drawing documentation or found during a site inspection.

Table 2. Example of part of the basic input data for the MONUREV application.

Categories of Basic Input Data That Characterize the Building	Values
Year of construction	1820
Length	23.0 m
Width	13.0 m
Height	18.0 m
Height above ground	14.0 m

Table 2. *Cont.*

Categories of Basic Input Data That Characterize the Building	Values
Roof pitch	45°
Number of stores	2
Store height	4.0 m

Note: Detailed information about the building can be found in Section 4, "A Case Study of the Overall Restoration of the Parish of Dobrovice".

6.2.2. Building Structure of the MONUREV Application

Table 3 displays the expected maintenance and renewal design elements for the selected type of building, generated after the user inputs basic descriptive characteristics of the building. This initial dataset, obtained when users input details such as the building type, size, and condition, forms the foundation of the proposal generated by the MONUREV application. The unit price reflects the cost associated with the renewal of each specific structural element. The quantity is an estimated metric derived from the primary dimensional characteristics of the building, helping in assessing the scope of work required. The total cost represents the cumulative expense for the complete restoration of each structural element.

Table 3. Detailed cost breakdown for structural components using MONUREV software (at current prices—2024).

Construction Element	Unit Price (CZK)	Quantity	Unit of Measure	Total Cost (CZK)
Basics				
stone belts	10,925	215.3	m^3	2,352,153
Vertical load-bearing structures				
perimeter and load-bearing brickwork without surface treatment ceramic	4726	1053	m^2	4,976,478
Vertical non-load-bearing structures				
partitions and load-bearing masonry without ceramic surface treatment	2970	79.2	m^2	235,224
Horizontal load-bearing structures				
wooden	2020	568.1	m^2	1,147,562
Surface finishes of vertical structures				
plaster interior smooth without reinforcement	905	1400	m^2	1,267,000
plaster exterior with reinforcement	1554	1053	m^2	1,636,362
ceramic interior tiles	2600	95.6	m^2	248,560
paintings	107	1879.2	m^2	201,074
paint plaster exterior	552	645.8	m^2	356,482
metallic exterior paint	776	161.5	m^2	125,324
paint metal interior	599	215.3	m^2	128,965
wooden interior paints	684	188.4	m^2	128,866
wooden exterior coatings	768	80.7	m^2	61,978
Compositions of horizontal non-load-bearing structures				
tread layered wood	3977	466.4	m^2	1,854,873
spreading 100 thick grease layers	2104	478.4	m^2	1,006,554
insulating layer for waterproof clay tub	4755	388.7	m^2	1,848,269
embankment	1849	358.8	m^2	663,421
backlash	663	358.8	m^2	237,884

Table 3. *Cont.*

Construction Element	Unit Price (CZK)	Quantity	Unit of Measure	Total Cost (CZK)
surface treatment of plaster with reed reinforcement system	1766	508.3	m^2	897,658
surface treatments: wooden tiles	1839	508.3	m^2	934,764
surface treatment: paints	684	478.4	m^2	327,226
Artistic and decorative elements firmly connected to the building				
plasters and stucco profiles (reliefs)	6916	19.1	m^2	132,096
plaster and stucco anchored elements (stucco)	8398	14.3	m^2	120,091
anchored stone elements	49,153	53.8	m^3	2,644,431
wooden elements	35,321	53.8	m^3	1,900,270
ceramic elements	27,911	43.1	m^3	1,202,964
metal elements	35,939	53.8	m^3	1,933,518
Roof load-bearing structures				
roof wood	4261	475.2	m^2	2,024,827
roof sheathing				
folded ceramic covering	2028	422.8	m^2	857,438
slats	263	274.9	m^2	72,299
underlaying the board	763	71.8	m^2	54,783
tinsmith elements of plating and edging of walls, attics, cornices and roof elements and copper gutters	1436	97.2	m	139,579
plumbing elements and copper gutters	2918	50.6	m	147,651
copper plumbing elements	1231	35	m	43,085
Staircases				
supporting structure vault made of stone	15,193	5.5	m^2	83,562
grade stone	14,079	5.5	m^2	77,435
tread stone	7500	5.5	m^2	41,250
Fillings of openings				
wooden slatted windows	30,258	165.2	m^2	4,998,622
exterior door wood overhaul	22,848	32	m^2	731,136
interior door wood overhaul	20,378	35	m^2	713,230
additional construction of metal copper windowsills	1281	21	m	26,901
Railings				
wooden	9855	6.2	m	61,101

The figures provided in this table are intended as preliminary estimates based on the generative modelling capabilities of the software. They offer a foundational viewpoint that aids in the initial financial planning and logistical arrangements for maintenance projects. To enhance the precision of these estimates, it is advisable for users to input the actual dimensions of individual structural elements directly into the application. Moreover, if the estimated structural elements do not perfectly match the building's condition, they can be modified or replaced with others that more accurately reflect the actual state of the building. This flexibility ensures that the final maintenance and renewal plans are not only tailored to the specific needs of the building but also refined to accommodate unique structural nuances and conditions.

6.2.3. Estimation of Construction Costs and Rough Restoration Plan

Construction cost estimation in MONUREV is carried out using a parametric approach. This method uses selected or input parameters (such as basic dimensional variables) of the building to estimate construction costs. A key part of this approach is the decomposition of the building into structural and technological units, commonly referred to as structural elements. These elements are closely linked to input parameters such as the width, length and height of the building.

The unit price assigned to each defined structural element is derived through a process known as micro-budgeting. This detailed estimate is constructed from selected elements within the Construction Resource System (CRS) pricing system. The unit price of each structural element is calculated by aggregating the partial prices (also known as indicative prices) of all these items. The micro-estimates, as shown in the following subsection, are set at the 2024 price level and provide an example of the costs involved.

It is important to note that the costs shown in the table below are based on current prices. According to [39], actual costs are expected to increase due to inflation, a phenomenon that is particularly pronounced in the construction and housing industry compared to other sectors.

Table 4 illustrates a rough recovery plan for the next 50 years, generated from data entered into MONUREV.

Table 4. The restoration plan of structural elements (at current prices—2024).

Construction Part	Year	Cost (CZK)
plaster interior smooth without reinforcement	2025	101,360
paintings	2025	116,623
paint plaster exterior	2025	139,028
wooden exterior coatings	2025	32,229
surface treatments of plaster with reed reinforcement system	2025	188,508
folded ceramic covering	2025	102,893
folded ceramic covering	2025	102,893
wooden slatted windows	2025	299,917
wooden	2025	4888
Year total	2025	1,088,339
plaster interior smooth without reinforcement	2030	101,360
internal ceramic tiles	2030	29,827
paintings	2030	116,623
paint plaster exterior	2030	139,028
paintwork metal exterior	2030	43,863
wooden interior paints	2030	67,010
wooden exterior coatings	2030	32,229
surface treatments of plaster with reed reinforcement system	2030	188,508
surface treatment paints	2030	170,158
wooden elements	2030	114,016
folded ceramic covering	2030	102,893
folded ceramic covering	2030	102,893
grade stone	2030	24,779
steppingstone layer	2030	13,200
wooden slatted windows	2030	299,917
wooden	2030	4888
Year total	2030	1,551,192

Table 4. *Cont.*

Construction Part	Year	Cost (CZK)
plaster interior smooth without reinforcement	2035	101,360
paintings	2035	116,623
paint plaster exterior	2035	139,028
wooden exterior coatings	2035	32,229
surface treatments of plaster with reed reinforcement system	2035	188,508
folded ceramic covering	2035	102,893
folded ceramic covering	2035	102,893
wooden slatted windows	2035	299,917
wooden	2035	4888
Year total	2035	1,088,339
plaster interior smooth without reinforcement	2040	101,360
plaster exterior with reinforcement	2040	343,636
internal ceramic tiles	2040	29,827
paintings	2040	201,074
paint plaster exterior	2040	139,028
paintwork metal exterior	2040	43,863
paint metal interior	2040	45,138
wooden interior paints	2040	67,010
wooden exterior coatings	2040	61,978
surface treatments of plaster with reed reinforcement system	2040	188,508
surface treatment paints	2040	170,158
plasters and stucco profiles (reliefs)	2040	13,210
plaster and stucco anchored elements (stucco)	2040	14,411
anchored stone elements	2040	237,999
wooden elements	2040	114,016
ceramic elements	2040	72,178
metal elements	2040	154,681
folded ceramic covering	2040	102,893
folded ceramic covering	2040	102,893
tinsmith elements of plating and edging of walls, attics, cornices and roof elements and copper gutters	2040	16,749
plumbing elements and copper gutters	2040	17,718
copper plumbing elements	2040	6463
supporting structure vault made of stone	2040	10,863
wooden slatted windows	2040	299,917
additional construction of metal copper windowsills	2040	3228
wooden	2040	4888
Year total	2040	2,563,687
plaster interior smooth without reinforcement	2045	101,360
paintings	2045	116,623
paint plaster exterior	2045	139,028
wooden exterior coatings	2045	32,229

Table 4. *Cont.*

Construction Part	Year	Cost (CZK)
surface treatments of plaster with reed reinforcement system	2045	188,508
folded ceramic covering	2045	102,893
folded ceramic covering	2045	102,893
wooden slatted windows	2045	299,917
wooden	2045	4888
Year total	2045	1,088,339
plaster interior smooth without reinforcement	2050	101,360
internal ceramic tiles	2050	29,827
paintings	2050	116,623
paint plaster exterior	2050	139,028
paintwork metal exterior	2050	43,863
wooden interior paints	2050	67,010
wooden exterior coatings	2050	32,229
surface treatments of plaster with reed reinforcement system	2050	188,508
surface treatment paints	2050	170,158
wooden elements	2050	114,016
folded ceramic covering	2050	102,893
folded ceramic covering	2050	102,893
wooden slatted windows	2050	299,917
wooden	2050	4888
Year total	2050	1,513,213
plaster interior smooth without reinforcement	2055	101,360
paintings	2055	116,623
paint plaster exterior	2055	139,028
wooden exterior coatings	2055	32,229
surface treatments of plaster with reed reinforcement system	2055	188,508
folded ceramic covering	2055	102,893
folded ceramic covering	2055	102,893
wooden slatted windows	2055	299,917
wooden	2055	4888
Year total	2055	1,088,339
plaster interior smooth without reinforcement	2060	101,360
plaster exterior with reinforcement	2060	343,636
internal ceramic tiles	2060	29,827
paintings	2060	201,074
paint plaster exterior	2060	139,028
paintwork metal exterior	2060	43,863
paint metal interior	2060	45,138
wooden interior paints	2060	128,866
wooden exterior coatings	2060	61,978
tread layer wood	2060	408,072

Table 4. *Cont.*

Construction Part	Year	Cost (CZK)
surface treatments of plaster with reed reinforcement system	2060	188,508
surface treatment paints	2060	327,226
plasters and stucco profiles (reliefs)	2060	13,210
plaster and stucco anchored elements (stucco)	2060	14,411
anchored stone elements	2060	237,999
wooden elements	2060	114,016
ceramic elements	2060	72,178
metal elements	2060	154,681
folded ceramic covering	2060	857,438
folded ceramic covering	2060	857,438
tinsmith elements of plating and edging of walls, attics, cornices and roof elements and gutters copper	2060	16,749
plumbing elements copper gutters	2060	17,718
copper plumbing elements	2060	6463
supporting structure vault made of stone	2060	10,863
grade stone	2060	24,779
steppingstone layer	2060	13,200
wooden slatted windows	2060	299,917
additional construction of metal copper windowsills	2060	3228
wooden	2060	4888
Year total	2060	4,737,752
plaster interior smooth without reinforcement	2065	101,360
paintings	2065	116,623
paint plaster exterior	2065	139,028
wooden exterior coatings	2065	32,229
surface treatments of plaster with reed reinforcement system	2065	188,508
folded ceramic covering	2065	102,893
folded ceramic covering	2065	102,893
wooden slatted windows	2065	299,917
wooden	2065	4888
Year total	2065	1,088,339
plaster interior smooth without reinforcement	2070	101,360
ceramic interior tiles	2070	29,827
paintings	2070	116,623
paint plaster exterior	2070	139,028
paintwork metal exterior	2070	43,863
wooden interior paints	2070	67,010
wooden exterior coatings	2070	32,229
surface treatments of plaster with reed reinforcement system	2070	188,508
surface treatment paints	2070	170,158
wooden elements	2070	114,016
folded ceramic covering	2070	102,893

Table 4. *Cont.*

Construction Part	Year	Cost (CZK)
folded ceramic covering	2070	102,893
wooden slatted windows	2070	299,917
wooden	2070	4888
Year total	2070	1,513,213
Total for the period under review		17,320,752

Figure 4 illustrates the cumulative total annual costs projected for the restoration of the building over the next 50 years, specifically excluding any remediation work. The aim of this graph is to highlight the impact of inflation on the actual increase in costs. In order to provide a comprehensive analysis, three different levels of inflation have been chosen for comparison: 0% (representing current prices), 3% and 6%.

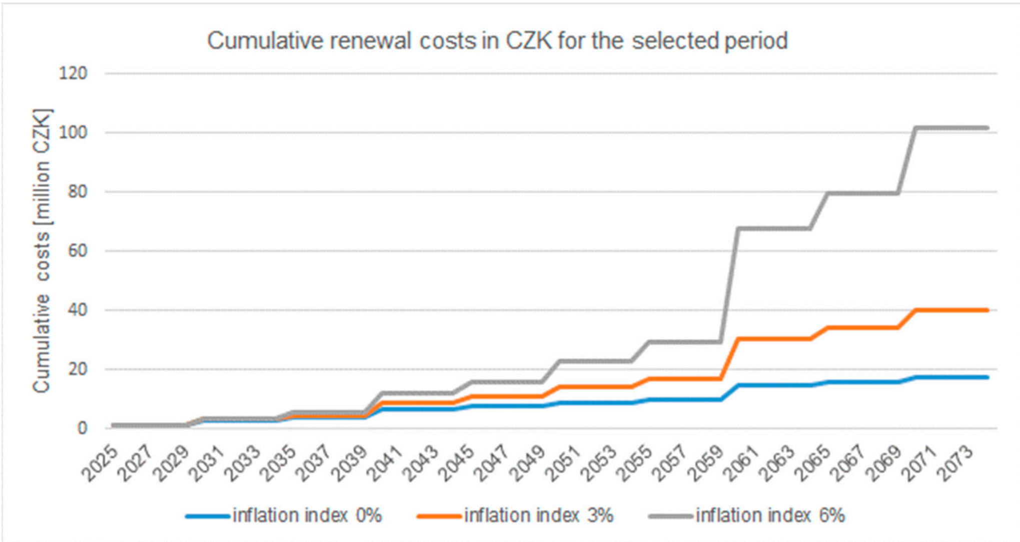

Figure 4. Restoration plan for structural elements.

By using these inflation indices, Figure 4 allows stakeholders to visualize and understand how different rates of inflation could affect the long-term financial requirements for the refurbishment of the building. The 0% inflation scenario represents a stable cost scenario, reflecting what expenditure would be without the impact of inflation. The 3% and 6% scenarios, on the other hand, provide insight into more realistic economic conditions where inflation is factored in, showing progressively higher total costs over time.

This visualization (Figure 4) is crucial for effective financial planning and risk management in heritage projects, enabling decision-makers to allocate resources more strategically and anticipate potential future adjustments due to economic fluctuations. Such foresight is particularly valuable in the conservation and maintenance of heritage buildings, where funding and budgeting play a critical role in ensuring that these buildings can be maintained and enjoyed by future generations. Figure 4 shows that the impact of inflation on real costs is significant in the long run, with costs more than five times higher at 6% inflation than at current prices.

This model and associated costs serve as a basic guide to assist stakeholders in strategic planning and budgeting for the sustainable maintenance and recovery of building projects in the volatile economic landscape of the construction industry.

Figure 5 shows the key structural elements that cumulatively contribute the most to life cycle costs (LCCs) from the perspective of structural element renewal. It identifies seven elements that account for more than 75% of the cumulative LCC costs associated with all structural elements. These elements are folded ceramic tiles, painted exterior plaster, painting, smooth interior plaster without reinforcement, surface treatment paints, surface treatment of plaster with reed reinforcement system, and wooden slatted windows. The cost summaries in this figure are derived from the data presented in Table 4. The percentages given in Figure 5 represent the ratio of costs between the items listed.

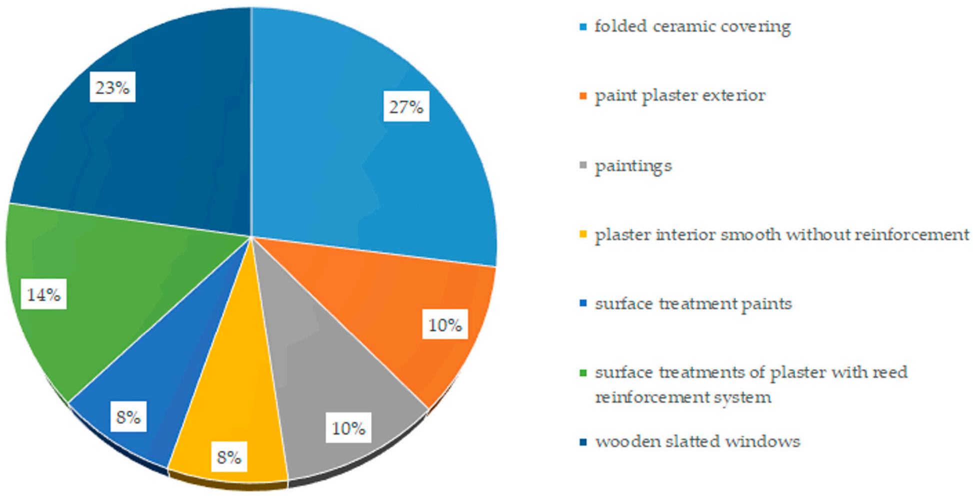

Figure 5. Share of the most important elements from an LCC point of view.

6.2.4. Maintenance and Renewal Plan

This segment of the project details the planning and implementation of periodic and operational activities aimed at ensuring the long-term sustainability of the buildings from both a technical and economic perspective. The planned construction and refurbishment works are designed to maintain the current condition of the historic buildings after refurbishment, prevent further deterioration and maximize their lifespan and usability.

It is highly recommended that key information is gathered through site visits to the property. These visits provide not only basic information, but also a deeper insight into the specific needs and conditions of the building. During a comprehensive inspection of the Dobrovice Parish, the following observations were made:

- Structural integrity: The overall structural condition of the buildings was assessed, with particular attention paid to areas showing signs of wear or damage. This assessment helps to prioritize the necessary rehabilitation works.
- Material condition: Detailed assessments were made of the materials used in the construction and their current condition. This includes checking for signs of ageing, erosion and other forms of deterioration that could affect the durability of the building.
- Historical authenticity: During the tour, efforts were made to document and evaluate the consistency of existing structures with historical records to ensure that restoration plans maintain the architectural integrity and historical significance of the community.
- Functional suitability: The current usability of the buildings was reviewed to determine if they adequately meet the needs of their current use. This included an assessment of security measures, accessibility and the suitability of the space for its intended purpose.
- Environmental impact: Observations were made of the environmental conditions surrounding the buildings, including any factors that could adversely affect the structure, such as water drainage, vegetation overgrowth and exposure to adverse weather conditions.
- Maintenance practices: Existing maintenance practices were reviewed to identify any gaps or areas where improvements could be made to increase the efficiency and effectiveness of ongoing maintenance.

Following a thorough inspection and collection of data, a detailed case study was developed to accurately represent both the original condition of the building and the scope of the proposed construction and rehabilitation works necessary for its overall restoration. This case study incorporates calculations provided by the MONUREV application, which helped to estimate the costs associated with the repair and restoration of each structural element of the building.

The actual cost of the construction and restoration work to be carried out in 2022 is CZK 1.65 million, excluding VAT. The study also projected future costs, estimating that if the planned construction and refurbishment activities were extended to 2024, the costs would increase to CZK 1.87 million, excluding VAT. This projection is based on an index that tracks changes in construction prices, reflecting the dynamic nature of construction costs influenced by market conditions and material prices.

This financial estimate plays a crucial role in the planning and budgeting of the restoration project. By using a tool such as MONUREV to identify cost elements and forecast future changes through the Construction Price Index, stakeholders can make informed decisions about resource allocation, timing and the scope of restoration work. This rigorous approach ensures that the historic community is preserved and enhanced in a financially and structurally sound manner.

7. Discussion

In examining the maintenance and restoration of cultural heritage buildings in the Czech Republic, it is clear that the diversity of visual and technical aspects is largely due to the period of construction and the materials and technologies used at that time. The integration of a life cycle cost analysis (LCCA), as explored in this study, highlights a comprehensive approach to understanding and forecasting the costs associated with the maintenance and restoration of these buildings. The incorporation of a dynamic LCCA, as enabled by MONUREV software, is an example of a methodological advance capable of producing detailed, data-driven projections that are crucial for effective management [40].

The practical implementation of the MONUREV software and the development of the comprehensive Heritage Maintenance Procedure have been tested through several case studies, demonstrating their applicability and effectiveness. These tools allow for systematic planning and careful execution of maintenance activities, which are critical to preserving the structural and aesthetic integrity of historic buildings. They provide a more nuanced understanding of costs over the life of a building, taking into account direct restoration costs as well as potential economic benefits and societal impacts, thereby enhancing stakeholders' decision-making capabilities.

The project's findings also highlight the importance of adaptive strategies in heritage conservation. Adaptive strategies refer to approaches that are flexible and responsive to the specific conditions and historic values of each building. Unlike traditional conservation practices, which often rely on routine procedures, adaptive strategies involve tailoring interventions to the unique environmental and economic contexts of heritage properties. This approach facilitates the integration of sustainable practices by considering factors such as energy efficiency, use of local materials and minimization of interventions. It demonstrates the need for a shift from traditional maintenance practices to more holistic, economically and environmentally sustainable practices. The ability of stakeholders to make informed decisions based on comprehensive projections of economic and environmental impacts represents a mature approach to heritage conservation. This adaptive methodology addresses both contemporary needs and the preservation of cultural significance, ensuring that heritage buildings can withstand changing conditions while retaining their historic value.

The challenges of heritage conservation in different economic and regulatory environments underline the need for continuous adaptation and improvement of tools such as MONUREV. These challenges include dealing with rapidly changing construction costs and the need for tailored solutions to preserve architectural authenticity while maintaining financial prudence.

While the MONUREV software significantly aids in managing maintenance and renewal costs through regular updates using price indices, this approach does have certain limitations. The primary challenge lies in the reliance on price indexation, which may result in minor inaccuracies in the cost calculations. This is because the indices used may not fully capture real-time price fluctuations or specific market conditions that affect the cost elements of heritage maintenance.

Furthermore, these indices are generalized and may not reflect the unique circumstances or bespoke materials often required in heritage conservation, leading to potential discrepancies between estimated and actual expenses. A more direct integration with real-time pricing systems, perhaps through automated data feeds from construction market databases, could enhance the accuracy of cost estimations. This change would allow the software to adjust more dynamically to market conditions, thereby providing more precise financial planning tools for heritage maintenance projects.

8. Conclusions

This study has made significant strides in advancing the field of conservation and restoration of heritage buildings by developing methodological approaches that refine the management and sustainability of such projects. Through rigorous research and development, the MONUREV software has emerged as an essential tool to facilitate detailed planning and effective management of the life cycle costs of heritage buildings. Its implementation not only improves the accuracy of financial forecasts, but also supports proactive long-term maintenance strategies.

The methodology of heritage building rehabilitation principles underpins this progress by providing a structured approach that raises the standard of maintenance and restoration practice. The methodology ensures that interventions are economically and environmentally sustainable, while being effective in conserving buildings, thus supporting their continued viability and conservation into the future.

Furthermore, the application of the tools in different case studies demonstrates their robustness and adaptability to different architectural styles and historical periods. This versatility meets the unique needs of individual heritage sites and reinforces the effectiveness of tailored solutions in heritage conservation. Each case study has validated the usefulness of these tools and highlighted their potential to significantly improve the management dynamics of heritage conservation efforts. These conservation measures include, for example, structural stabilization, façade restoration, the use of conservation-compatible materials and the introduction of modern amenities in a historic context, all aimed at prolonging the life and maintaining the integrity of heritage sites.

Restoration projects also generate significant positive externalities, such as increased employment opportunities, both during and after restoration, and improvements to the cultural and economic aspects of the local community. In addition to providing employment, these projects also increase the attractiveness of the area, increase visitor and local spending, and contribute to the cultural enrichment of the community.

Considering the broader implications of this study, the integration of economic and technical disciplines with historical sensitivity represents a holistic approach to heritage conservation. This approach promotes a deeper understanding of the complexities involved in heritage management. It is essential for developing strategies that not only meet conservation needs, but also meet modern sustainability requirements, such as minimizing energy consumption, using environmentally friendly materials, and ensuring that interventions enhance the building's resilience to environmental change.

By using innovative tools and methodologies, this research project not only contributes to a sustainable future for heritage conservation, but also ensures that these cultural landmarks are preserved and adapted to contemporary standards. This proactive approach balances historical integrity with modern performance standards, advocating a dynamic intersection between traditional practices, modern technology and innovative financial planning. In the future, our research team will continue to refine these techniques and expand their application, ensuring that heritage conservation evolves into a more sustainable, accurate and culturally respectful practice.

A key perspective for improving our conservation efforts is the proposed quantification of indoor environmental quality, particularly under favorable hygrothermal conditions. This approach will include monitoring of key factors such as temperature and humidity, which are critical for maintaining the integrity of materials in heritage buildings.

We aim to integrate these metrics with life cycle assessments (LCAs) in future studies to fully understand the environmental impacts and quantify the carbon costs of conservation methods. This integration will facilitate the selection of sustainable conservation strategies that effectively balance heritage conservation with environmental responsibility.

Our future research will focus on developing protocols for measuring indoor environmental quality within the LCA framework and exploring simulation tools to evaluate different conservation strategies. These planned initiatives are expected to refine our methodologies and promote more sustainable, accurate practices in heritage conservation.

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