



Sustainable material selection for the reconstruction of historical buildings using building information modeling (BIM) in developing countries

Alireza Valipour^a, Mehdi Salman Manesh^a, Amirhossein Balali^{b,*}

^a Department of Civil Engineering, Shiraz Branch, Islamic Azad University, Shiraz, Iran

^b Centre for Engineering Research, School of Physics, Engineering and Computer Science (SPECS), University of Hertfordshire, Hatfield AL10 9AB, United Kingdom

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ABSTRACT

The sustainable reconstruction of deteriorated and historical buildings, particularly within the urban fabrics of developing countries, presents a complex challenge that requires a delicate balance between preserving historical and cultural heritage and achieving sustainable development goals. This research aims to fill the gap by providing a comprehensive and systematic framework for selecting sustainable materials to reconstruct historical contexts. The novelty of this study lies in its presentation of a novel integrated methodology that combines Building Information Modeling (BIM) for accurate simulation, Life Cycle Assessment (LCA) for measuring environmental impacts, and the COPRAS multi-criteria decision-making model for the optimal ranking and selection of building materials. This framework was implemented in a case study on the historical fabric of Shiraz, Iran. The simulation results indicated that using optimized sustainable materials, which combine local materials and modern technologies, leads to an approximate 25% reduction in annual energy consumption and a 30% reduction in carbon emissions compared to conventional materials. Ultimately, this research introduces a practical, data-driven approach that, while preserving historical authenticity, significantly improves the environmental performance of reconstruction projects and can serve as a valuable guide for architects, urban planners, and policymakers in similar contexts.

1. Introduction

The reconstruction of historic buildings is a multifaceted challenge that requires a delicate balance between preserving cultural heritage and promoting sustainable development goals (Annibaldi et al., 2020). This balance is crucial in a city renowned for its historical and cultural significance, like Shiraz. Integrating modern technologies, such as Building Information Modeling (BIM), with traditional restoration techniques offers a promising approach to achieving this balance (Waqar et al., 2023). By providing detailed digital representations of buildings, BIM enables accurate documentation and simulation of restoration processes, ensuring that the historical integrity of structures is maintained while incorporating sustainable practices.

One of the key advantages of BIM is its ability to integrate various data sources and provide a comprehensive platform for managing the entire lifecycle of a building (Azhar et al., 2011). This capability is particularly valuable in historical reconstruction, where accurate documentation of existing structures is essential (Alves et al., 2025). BIM allows for creating detailed 3D models of buildings, which can be used to simulate different restoration scenarios and assess their environmental impact through Life Cycle Assessment (LCA) (Panteli et al., 2020). This

integration of BIM with LCA enables a more holistic approach to material selection, considering not only the immediate needs of the restoration project but also the long-term sustainability of the materials and methods used (Spudys et al., 2025).

The use of BIM in historical reconstruction is not without challenges (Charlton et al., 2021). One of the main limitations is the lack of comprehensive methodologies that integrate BIM with sustainable development principles (Li & Feng, 2025). Many restoration projects focus primarily on aesthetic and structural integrity, neglecting the broader environmental implications of material choices and construction methods (Bertolin & Loli, 2018). This oversight can lead to the use of materials and techniques that are not sustainable in the long term, ultimately compromising the goals of sustainable development (Iacovidou et al., 2017).

Previous studies have primarily focused on structural and aesthetic preservation; however, limited research has comprehensively integrated Building Information Modeling (BIM) with Life Cycle Assessment (LCA) specifically for historical contexts. This study bridges this gap by proposing a novel integration of BIM and LCA methodologies combined with the COPRAS decision-making model to systematically address sustainable material selection challenges in historical urban fab-

* Corresponding author.

E-mail addresses: a.valipour@iau.ac.ir (A. Valipour), a.salmanmanesh@iau.ac.ir (M.S. Manesh), a.balali@herts.ac.uk (A. Balali).

ric restoration, particularly within Shiraz's unique climatic and cultural context.

The sustainable restoration of historical urban fabric presents a complex challenge, requiring a careful balance between preserving cultural and aesthetic integrity and addressing long-term environmental impacts (Jiang et al., 2023). A significant concern in this domain is the selection of materials and reconstruction techniques that align with sustainable development principles. This issue gains further complexity within many historical cities' unique climatic, cultural, and economic contexts (Foster, 2020).

Previous research on restoring historical textures has made strides in certain areas but exhibits notable limitations. Many studies have predominantly focused on preservation's structural and aesthetic aspects, with less detailed assessment of the whole life cycle environmental burdens (Hafez et al., 2023a). Similarly, investigations into digital documentation techniques have advanced significantly; however, their integration with comprehensive sustainability assessments often remains superficial (Penjor et al., 2024). A summary of previous studies in this domain is provided in Table 1.

This study confronts the challenges of material selection in historical contexts by proposing and validating a novel, integrated methodology tailored for sustainable restoration. The core novelty of this research is not rooted in the creation of its individual components, but rather in their systematic synthesis. It combines three distinct fields: Building Information Modeling (BIM) to ensure high-fidelity data management of geometry and materials; Life Cycle Assessment (LCA) to quantify environmental impacts precisely; and Multi-Criteria Decision-Making (MCDM), employing the COPRAS method, to facilitate a transparent and comprehensive evaluation. Although these tools have been utilized in isolation or for new construction, their unified application to the complex, multi-objective problem of harmonizing cultural authenticity with environmental performance, economic viability, and social considerations in heritage projects remains underexplored (Franzoni et al., 2020; Verticchio et al., 2024). By addressing this, especially within the unique constraints of a developing nation, our work fills a critical gap in the literature. Consequently, the proposed framework offers a repeatable, data-driven workflow intended to supersede the subjective and often ad-hoc decision-making processes common in this domain, thus contributing significantly to the fields of sustainable architecture and heritage conservation (Haroun et al., 2019).

Synthesizing the findings from the literature, this study directly confronts several of the gaps identified above. In particular, we address the deficiency of integrated assessment frameworks that merge digital simulation with comprehensive sustainability metrics—a limitation previously cited by studies such as RS3 and RS4. Furthermore, we respond to the call for systematic and transparent MCDM tools capable of navigating the complex trade-offs inherent in heritage contexts, an issue underscored by RS11. Most critically, our work targets the overarching gap concerning the application of these sophisticated methodologies within the distinct material, economic, and cultural constraints characteristic of developing nations.

A significant overarching limitation observed in the existing body of literature is the insufficient attention given to the sustainable restoration of historical urban fabrics within developing countries. Much of the advanced research integrating BIM, LCA, and sophisticated decision-making models has been contextualized within developed nations, often overlooking the distinct material availabilities, economic constraints, climatic conditions, and local building traditions prevalent in other parts of the world. Consequently, effective methodologies in one context may not be directly transferable or optimal for developing nations, where historical areas are often extensive and resources for advanced analysis and intervention can be limited.

This study aims to address the complex issue of material selection in historical reconstruction by integrating sustainable development principles into architectural practices. Through the innovative use of Building Information Modeling (BIM) and Life Cycle Assessment (LCA), this

research offers a comprehensive framework for evaluating the sustainability of various materials and methods. The novelty of this study lies in its application of advanced digital tools, specifically BIM, to enhance the efficiency and accuracy of material selection processes in historical contexts. To achieve this, the study proposes a novel integrated methodology that combines BIM and LCA with the COPRAS (Complex Proportional Assessment) decision-making model for systematic and transparent material selection. This approach allows for a holistic evaluation of environmental impacts and navigates safety concerns, welfare considerations, and urban environmental challenges within deteriorated historical contexts, significantly contributing to sustainable architecture. Ultimately, the study bridges the gap between historical preservation and modern sustainability practices by offering a practical, data-driven methodology for decision-making, paving the way for more environmentally responsible reconstruction practices.

Shiraz, Iran, has been selected as a representative case study. As one of the leading and historically rich large cities in a developing country, Shiraz embodies many of the global challenges similar urban centers face. Its historical building stock is invaluable, yet it faces significant deterioration and pressure from urban development. The sustainable selection of materials for the reconstruction and restoration of these old buildings in Shiraz is paramount, not only for preserving its unique cultural heritage and aesthetic character but also for promoting environmental responsibility, ensuring the longevity of interventions, and contributing to the broader sustainable development goals of the region. This research seeks to provide a practical and adaptable framework that can aid policymakers, architects, and conservation engineers in such contexts to make more informed and sustainable decisions.

The remainder of this paper is structured as follows. Section 2 details the integrated methodology, first outlining the theoretical framework for material selection based on the COPRAS approach. It then describes the implementation of this framework through a specific case study, detailing the simulation setup, design constraints, and model assumptions. Section 2.3 presents and discusses the results derived from this case study. Finally, Section 3 critically reflects on the research, discusses its strengths and limitations, and offers concluding remarks that summarize the key findings and their implications for sustainable restoration.

2. Integrated methodology and case study implementation

The research methodology utilized to explore degraded urban fabrics in Shiraz focuses on developing a sustainable model through Building Information Modelling (BIM) technology, conducting a Life Cycle Assessment (LCA), identifying and categorizing key criteria, and modeling and evaluating materials. This research aims to identify environmentally sustainable materials for building refurbishment that align with historical and cultural heritage and adhere to principles of sustainable development. Building materials are categorized by sustainability attributes such as durability, renewability, energy efficiency, environmental impact, health and safety, and recyclability. This initiative comprises multiple phases, beginning with thorough documentation of existing structures using BIM-based modeling and simulation to create accurate and detailed models, which facilitate the simulation of different reconstruction scenarios and allow for an assessment of environmental impacts using LCA. Integrating BIM and LCA enables a comprehensive evaluation of the sustainability of different materials and methods by considering factors such as carbon footprint, resource consumption, and long-term durability.

Additionally, the COPRAS (Complex Proportional Assessment) method is incorporated as a multi-criteria decision-making technique to systematically evaluate and rank materials based on qualitative and quantitative factors. This method allows conflicting criteria to be considered and ensures that selected materials optimize environmental, economic, and functional performance. Through this approach, project efficiency is improved, sustainable development is promoted, and effective

Table 1

Summary of previous relevant studies (RS) on the sustainable restoration of historical buildings.

Code	Author	Year	Journal	Focus of the study	Key Approach/Tools Used	Location Covered	Research Gap
RS1	Annibaldi et al.	2019	Journal of Cleaner Production	To establish an integrated, sustainable, and profitable methodology for improving energy efficiency in heritage buildings, considering their historical and cultural context.	A multi-criteria matrix to identify the most effective energy efficiency measures	Italy (in general), with a specific case study in the Province of L'Aquila.	A lack of established methods and tools for improving energy efficiency in historic buildings, particularly within an urban context.
RS2	Ahsan Waqar et al.	2023	Case Studies in Construction Materials	To explore and demonstrate the role of Building Information Modeling (BIM) in enhancing sustainability and green building practices specifically in small-scale construction projects.	• Exploratory Factor Analysis (EFA)	Perak, Malaysia	A lack of research focused on the application and benefits of BIM for sustainability within the specific context of smaller-scale construction projects, as opposed to large-scale ones.
RS3	Spudys et al.	2025	Energy	To develop and demonstrate a digitized framework that integrates Energy Audits, Operational Energy Assessments, and Life Cycle Assessments (LCA) for a holistic and enhanced building sustainability assessment.	• Case Study of a residential building. • Digital Tools: Building Information Modeling (BIM), Digital Twins, IoT sensors, and One Click LCA software. • Integrated Analysis: Combining the three assessment types. • Novel Indicator: Proposed a metric to evaluate the trade-off between energy savings and embodied Global Warming Potential (GWP).	Lithuania	Traditional building assessments (audits, operational, LCA) are performed as stand-alone procedures, preventing a comprehensive understanding of the trade-offs between operational energy efficiency and the environmental impact of improvement measures.
RS4	Li et al.	2025	Renewable and Sustainable Energy Reviews	To provide a comprehensive review that systematically investigates, compares, and identifies opportunities for integrating Urban Building Energy Modeling (UBEM) and Urban-Building Environmental Impact Assessment (UB-EIA) for enhanced urban sustainability assessments.	• Systematic Literature Review of 157 articles. • Scientometric Analysis using tools like VOSviewer to map research trends. • Comparative Analysis of UBEM and UB-EIA methodologies, strengths, and limitations.	Global	While UBEM and UB-EIA have been studied extensively, they have been researched in isolation . A detailed comparative analysis and a framework for their integration have been lacking, limiting holistic urban sustainability assessments.
RS5	Iacovidou et al.	2017	Journal of Cleaner Production	To critically review the existing metrics used for assessing resource recovery from waste (RRfW) and to advocate for a multi-dimensional framework that evaluates the "complex value" across environmental, economic, social, and technical domains.	• Critical Literature Review of established assessment frameworks, methods, and tools (e.g., LCA, CBA, sLCA, MFA). • Identification and Classification of existing metrics into four value domains (environmental, economic, social, technical). • Analysis of the shortcomings of single-domain approaches and the need for a holistic, integrated assessment.	Global	Existing assessment methods for RRfW are often partial or single-domain, which can provide misleading results and hide negative trade-offs. There is a lack of a coherent framework for selecting metrics that capture the multi-dimensional value of recovered resources in a circular economy.
RS6	Jiang et al.	2023	Sustainable Cities and Society	To establish a framework for the adaptive reuse and energy transition of historic buildings and their associated historic gardens, balancing heritage conservation with modern needs for comfort and renewable energy (specifically PV systems).	• Case Study Methodology (Casa Jelinek, Trieste). • Phase 1 (Analysis): Documental research, on-site survey (photogrammetry, IR Thermography), SWOT analysis. • Phase 2 (Selection): Co-design workshops, energy load simulations (Grasshopper-Honeybee), solar radiation analysis. • Phase 3 (Design): PV system design (BIPV/BAPV) and a risk-benefit assessment.	Italy	The lack of an operative framework that addresses the integrated conservation of historic buildings <i>and</i> their gardens as a single entity during an energy transition, especially concerning the compatible integration of PV systems in such sensitive landscapes.

(continued on next page)

Table 1 (continued)

Code	Author	Year	Journal	Focus of the study	Key Approach/Tools Used	Location Covered	Research Gap
RS7	Gillian Foster	2019	Resources, Conservation and Recycling	To develop a new, comprehensive circular economy (CE) framework that provides actionable strategies for the adaptive reuse of cultural heritage buildings to reduce their lifecycle environmental impacts.	• Systematic Literature Review and Synthesis. • Adoption of the R0-R9 circularity strategies framework (from Potting et al.). • Definition of a five-phase building lifecycle. • Synthesis and mapping of 46 discrete circular strategies onto the new framework.	Global	A lack of knowledge and practical tools for decision-makers to implement CE principles in the building sector. Existing CE literature is often fragmented, theoretical, or focused on single lifecycle phases (like waste), lacking a holistic, practical framework for projects.
RS8	S. Hafez et al.	2022	Energy Strategy Reviews	To conduct a systematic review of the literature on energy efficiency in sustainable buildings, creating a taxonomy and identifying the main challenges, motivations, recommendations, and pathways for future research.	• Systematic Literature Review following PRISMA guidelines. • Analysis of 134 articles from three major databases (Web of Science, ScienceDirect, IEEE Xplore). • Taxonomy development to map and classify the research landscape.	Global	Despite numerous studies on energy efficiency, there has been no comprehensive systematic review to map the research landscape coherently, making it difficult to understand the current gaps, trends, and key focus areas in the field.
RS9	Penjor et al.	2024	Developments in the Built Environment	To systematically review and analyze the application of Heritage Building Information Modeling (HBIM) in the conservation of cultural heritage buildings, outlining its workflow, challenges, and limitations to propose a framework for future research.	• Systematic Literature Review (SLR) following PRISMA guidelines. • In-depth analysis of 59 selected studies published between 2013 and 2023. • Thematic analysis of the HBIM workflow, including data acquisition (laser scanning, photogrammetry) and modeling.	Global	Despite the potential of HBIM, its adoption by heritage professionals is limited. There is a need for a holistic approach and comprehensive analysis of HBIM concepts, technologies, challenges, and applications to streamline its use in heritage conservation projects.
RS10	Verticchio et al.	2024	Building and Environment	To conduct a systematic literature review of case studies on the whole-building dynamic simulation of historical buildings, in order to identify common practices, challenges, and open issues across the entire simulation process (from data gathering to output analysis).	• Systematic Literature Review of 105 scientific papers published between 2011 and 2022. • Thematic Analysis of the papers, focusing on case study characteristics, input data, simulation approach (including software and calibration), and output analysis (energy, comfort, conservation).	Global (Literature Review, with a strong focus on European case studies, particularly from Italy).	Despite the increasing use of dynamic simulations for historical buildings, there is a lack of a comprehensive, integrated review that systematizes the highly inhomogeneous and customized approaches used by researchers. A standardized methodological framework is needed to guide practitioners and foster a coherent scientific community.
RS11	Haroun et al.	2019	Ain Shams Engineering Journal	To introduce and apply a Multi-Criteria Decision-Making (MCDM) tool, specifically the Analytic Hierarchy Process (AHP), to support the selection of an optimal new use for heritage buildings, thereby improving the efficiency and success of adaptive reuse projects.	• Literature Review to establish evaluation criteria for adaptive reuse (e.g., heritage value, economic performance, social value). • Selection and application of the Analytic Hierarchy Process (AHP) as the MCDM tool. • Case Study: Applying the AHP to evaluate four potential reuse alternatives (hotel, museum, office, mixed-use) for the Aziza Fahmy Palace.	Egypt	Decision-makers lack a structured, objective, and efficient tool to select the best new use for heritage buildings from among multiple alternatives, often leading to inappropriate choices that can degrade the building's value. The selection process is a complex problem involving multiple conflicting criteria that needs a systematic approach.

restoration methods are identified. The case study of Shiraz's historic fabric demonstrates the importance of identifying enhancement opportunities, selecting sustainable materials and technologies, implementing sustainable practices, and continuously monitoring and evaluating their effectiveness.

To guarantee a robust and standardized evaluation of environmental impacts, this study employs a Life Cycle Assessment (LCA) methodology framed in compliance with the ISO 14,040/14,044 and EN 15,978 international standards. The scope and system boundaries for this assessment are delineated as follows:

- **Life Cycle Stages:** The system boundary is defined as "cradle-to-gate plus operational energy use." This scope includes the Product Stage (Modules A1-A3), comprising raw material extraction, transportation, and product manufacturing, alongside the Operational Energy Use stage (Module B6). Excluded from this analysis are modules pertaining to the construction process (A5), use-stage maintenance and repair (B2-B5), and end-of-life scenarios (C1-C4). This specific boundary was established to concentrate the analysis on two pivotal design variables: the embodied impacts stemming from initial material choices and the building's long-term operational energy performance.
- **Functional Unit:** A standard functional unit of "one square meter of the retrofitted building over a 60-year service life" is adopted. This unit serves as a consistent reference for normalizing all inputs and outputs, thereby permitting a coherent comparison across various material alternatives.
- **Impact Categories:** Although carbon emissions represent the primary focus, the analysis incorporates a broader spectrum of environmental impacts. Key indicators evaluated include Global Warming Potential (GWP), expressed in kg equivalent; Acidification Potential (AP); Eutrophication Potential (EP); and Ozone Depletion Potential (ODP).
- **Data Sources and Integration:** The Life Cycle Inventory (LCI) is compiled using data from standardized Environmental Product Declarations (EPDs) housed within the LCA software's database. A cornerstone of this methodology is the seamless integration of BIM and LCA. Material take-offs are automatically generated from the Revit model and mapped to their corresponding EPDs within the analysis tool. This automated workflow significantly enhances the efficiency of the LCI phase and mitigates the risk of human error associated with manual data entry.

2.1. Methodological framework for material selection: the COPRAS approach

This case study examines a historically significant area in Shiraz, addressing the challenges and opportunities associated with its reconstruction. The selected site comprises multiple heritage buildings that require careful restoration to balance preservation efforts with modern sustainability practices. Utilizing Building Information Modeling (BIM), the study enables detailed simulations of various reconstruction scenarios, providing critical insights into the environmental impact of different approaches. For instance, BIM facilitates comparative analyses between locally sourced and imported materials, allowing for informed decision-making based on carbon footprint and resource consumption. This application of BIM underscores its role in historical reconstruction and highlights its potential to support broader sustainable development goals. To further enhance the decision-making framework, the research integrates the Complex Proportional Assessment (COPRAS) method, a multi-criteria decision-making (MCDM) approach designed to assess and rank alternatives based on diverse and often conflicting factors. Unlike conventional MCDM techniques, COPRAS evaluates the significance of different criteria and quantifies their utility, ensuring a comprehensive assessment of sustainability, efficiency, and historical authenticity. This methodology prioritizes resident well-being, heritage preservation, and urban ecosystem resilience, involving a broad range of stakeholders, including local government officials, urban regeneration experts, sustainability specialists, and historical conservationists. By combining BIM-driven simulations with the COPRAS decision-making framework, this research provides an innovative and systematic approach to the sustainable rehabilitation of Shiraz's historical architecture, offering valuable insights for policymakers, architects, and conservationists striving to harmonize modern urban development with cultural heritage preservation.

2.1.1. Rationale for employing the COPRAS method

A crucial step in this research is the selection of an appropriate Multi-Criteria Decision-Making (MCDM) method to guarantee a valid and transparent assessment framework. Although established MCDM techniques such as the Analytic Hierarchy Process (AHP), TOPSIS, and PROMETHEE are available, this study purposefully employs the COPRAS method. The rationale for this choice is grounded in its unique suitability for addressing the inherent complexities of selecting sustainable materials for heritage structures.

Alternative methods present certain limitations in this context. For instance, AHP, despite its utility in structuring hierarchies, becomes cognitively burdensome and susceptible to inconsistency when applied to the extensive set of criteria and options under consideration. Similarly, the TOPSIS method, which relies on proximity to an idealized solution, can exhibit a lack of transparency in its final aggregation rationale. COPRAS, however, presents a compelling synthesis of computational simplicity and a distinct logical framework. Its primary advantage lies in its capacity to independently evaluate and summate an alternative's performance on both beneficial (maximizing) and non-beneficial (minimizing) criteria before calculating a final utility index. This architecture directly reflects the central challenge of this research—the imperative to concurrently maximize attributes such as energy efficiency, durability, and historical authenticity, while minimizing drawbacks like environmental footprint and initial capital investment. Such a clear and bifurcated assessment process significantly improves the clarity and interpretability of the findings for all stakeholders. A comparative analysis of MCDM methods is provided in Table 2.

COPRAS method establishes a direct and proportional relationship between the significance and utility degree of alternatives and the criteria, including their weights and values, that effectively define the alternatives. The criteria and their corresponding weights used in the COPRAS method were determined through expert interviews and consultation with urban planners, conservation professionals, and sustainability specialists familiar with the historical context of Shiraz. A structured questionnaire was used to elicit expert opinions, ensuring robustness and precision in the criteria selection and weighting process. A critical challenge in this process was the operationalization of qualitative heritage values within a quantitative framework. The 'Historical Authenticity' criterion, which is paramount in any conservation project, was not treated as a single, monolithic factor. Instead, based on consultation with conservation experts, it was disaggregated into several measurable sub-criteria, which were individually weighted and incorporated into the COPRAS model. These sub-criteria included: (1) Material Compatibility, which assesses the chemical and physical compatibility of new materials with the existing historic fabric to prevent long-term damage; (2) Visual Congruence, which measures the similarity of texture, color, and finish to the original materials; and (3) Reversibility, a fundamental principle in conservation that evaluates the ease with which a new intervention can be removed in the future without harming the original structure. These sub-criteria were assigned high importance weights by the consulting experts, ensuring that heritage conservation principles were mathematically integrated into the model and rigorously considered alongside environmental and economic performance in the final material ranking. The methodological workflow for ranking the evaluated alternatives is illustrated in Fig. 1.

The COPRAS method entails a systematic procedure for the ranking and evaluation of alternatives. This procedure is initiated by formulating a decision matrix where each alternative is assessed against a suite of weighted criteria. Following the normalization of this matrix, the central tenet of the COPRAS methodology is employed. For each alternative, the weighted normalized values are aggregated separately for beneficial (maximizing) criteria and non-beneficial (minimizing) criteria. Subsequently, a final relative importance value, or degree of utility, is calculated from these aggregate sums, enabling a comprehensive ranking of the alternatives. This approach yields a transparent and pro-

Table 2
Comparative analysis of multi-criteria decision-making (MCDM) methods.

Method	Fundamental Principle	Input Data Requirement	Handling of Conflicting Criteria	Key Advantage for This Study
AHP	Hierarchical decomposition and pairwise comparison	High cognitive load; requires extensive pairwise comparisons of criteria and alternatives	Aggregates preferences into a single priority vector through eigenvector calculation	Excellent for structuring complex problems and capturing subjective expert judgments
TOPSIS	Distance to an ideal solution	Requires a performance matrix and criteria weights	Ranks alternatives based on their relative closeness to the positive-ideal solution and distance from the negative-ideal solution	Simple, intuitive logic and computational efficiency
PROMETHEE	Outranking relations	Requires a performance matrix, weights, and preference functions	Ranks alternatives based on a net outranking flow, allowing for the consideration of uncertainty and indifference thresholds	Flexibility in preference modeling and robustness against rank reversal in some cases
COPRAS	Complex Proportional Assessment	Requires a performance matrix and criteria weights	Separately calculates and aggregates the influence of maximizing (benefit) and minimizing (cost) criteria before determining the final utility degree	Transparent, computationally efficient, and provides a clear, proportional assessment of an alternative's performance on beneficial versus non-beneficial attributes

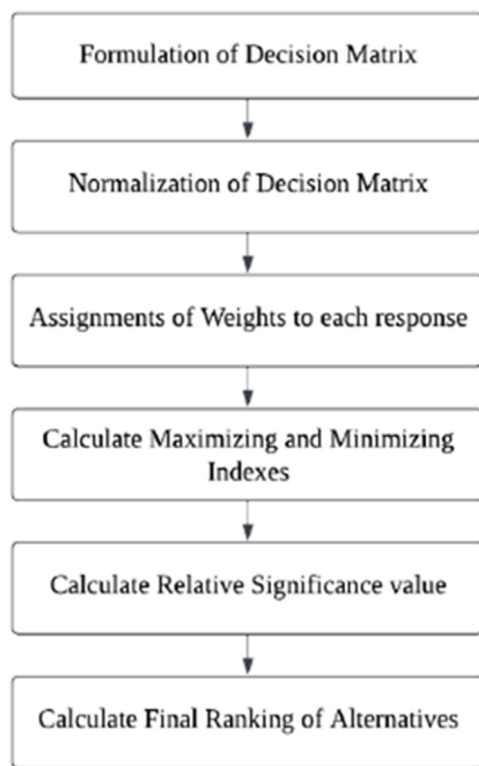


Fig. 1. The methodological workflow for ranking the evaluated alternatives.

portional evaluation of each alternative's performance in relation to its competitors.

This method is particularly suitable for selecting materials for building rehabilitation. Recent studies have shown that Multi-Criteria Decision-Making (MCDM) methods can effectively evaluate and select sustainable options for various building components, including structural systems, external walls, insulation, and facades (Bajwa et al., 2025). Researchers have also utilized these approaches to optimize material selection for flooring systems and interior coverings (Yasantha Abeysundara et al., 2009). By incorporating multiple criteria, methods like COPRAS help select the most sustainable and appropriate materials (Mousavi-Nasab & Sotoudeh-Anvari, 2018).

The COPRAS-based approach was selected to address several existing challenges and gaps in the process of urban regeneration in Shiraz, particularly in rehabilitating historic buildings. One key issue is the lack of a comprehensive methodology that integrates diverse stakeholder

perspectives, often leading to conflicts and inefficiencies in decision-making (Curşeu & Schrujjer, 2017). The traditional methods of material selection for historical structures were often based on limited criteria, ignoring the complexities of sustainability, environmental impact, and heritage compatibility (Panakaduwa et al., 2024). Additionally, there was a gap in effectively assessing the trade-offs between factors such as cost, durability, environmental footprint, and aesthetic value, especially when considering historic preservation and energy efficiency (Hafez et al., 2023b). The previous methods lacked advanced data analysis and software tools to make informed, optimal material selections tailored to specific geographical conditions and building types.

By employing the COPRAS method, these gaps are addressed effectively. Including stakeholders ensures that all relevant viewpoints are considered, preventing conflicts and fostering collaboration (Al-Rawas et al., 2024). The multi-criteria evaluation method allows for a more holistic approach to material selection, where the complexities of historic buildings and their unique sustainability needs are better considered (Akadiri et al., 2013). Integrating software tools allows for data-driven, context-specific material choices, improving the accuracy of the selection process. Moreover, the method prioritizes resource efficiency by selecting materials that reduce waste, offer recycling potential, and have minimal environmental impact (Khan et al., 2025). The goal is to provide a balanced approach that addresses building restoration's sustainability and heritage aspects, ultimately achieving a more sustainable framework for rehabilitating historic buildings in Shiraz. The COPRAS approach aims to overcome the limitations of traditional methods, offering a more comprehensive, efficient, and data-driven solution to urban regeneration challenges. Fig. 2 illustrates a BIM-based decision-making workflow for the selection of restorative materials.

2.2. Case study: modelling and simulation setup

This section outlines the detailed process for setting up the case study model and simulation environment. The previously discussed methodological framework is applied to a practical scenario involving the sustainable rehabilitation of heritage buildings in Shiraz. The setup process is broken down into three key stages. First, the specific case study and its geographical and architectural context are introduced. The detailed local climate data required for accurate energy analysis has also been prepared. Second, the core simulation problem is defined. The key objectives, practical constraints, and specific design variables—such as the material options to be tested—are established as part of this process. Finally, the technical toolchain is specified; the Building Information Modeling (BIM) and energy simulation software are detailed, along with the key assumptions and workflows governing the analysis. This systematic setup provides a robust and data-driven foundation for the simulations, the results of which are presented in the subsequent section.

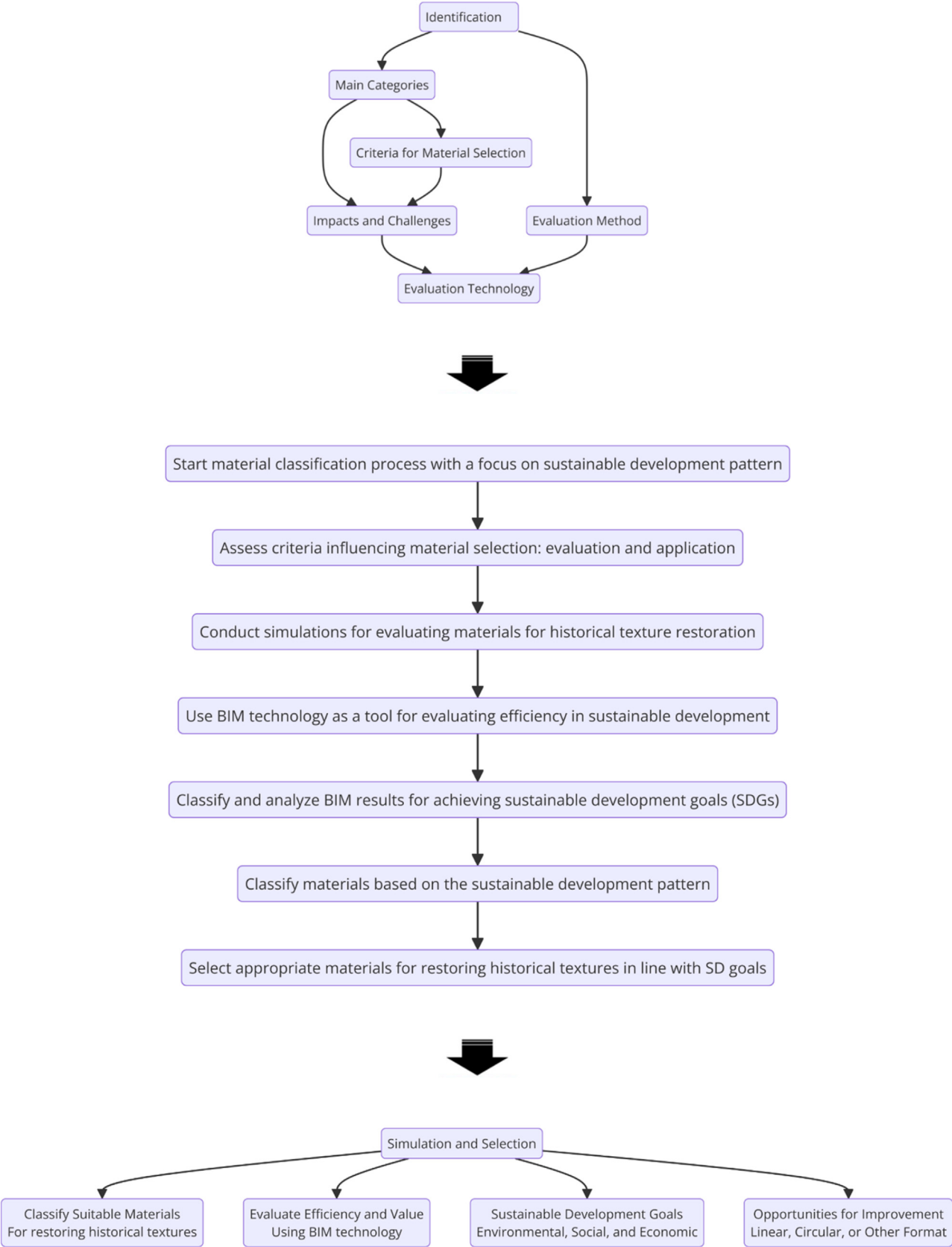


Fig. 2. A BIM-based decision-making workflow for the selection of restorative materials.

2.2.1. Case study & weather file

The selected area within Shiraz’s historical district includes buildings from the late 18th to early 20th centuries, characterized by traditional Persian architectural styles and unique material compositions such as adobe, brick masonry, and wooden structural elements. The buildings exhibit significant deterioration due to environmental exposure, lack of maintenance, and inappropriate past interventions, necessitating sustainable and historically sensitive restoration strategies.

Shiraz is one of the largest cities in Iran, located in the southwest of the country along the seasonal river "Khorram-Rud." The city has a moderate climate, with winters that are not excessively cold and summers that are not extremely hot. According to the latest census conducted by the Shiraz municipality in 2024, the city’s population exceeds 2000,000 residents. With the rapid expansion of the construction industry in Shiraz, it is crucial to implement strategies for reducing energy consumption in existing and future buildings. In this regard, passive energy-saving methods are strongly recommended.

Shiraz’s climate is characterized by sweltering summers and cold winters, with annual temperatures fluctuating between 32°F and 99°F. The hot season lasts for 3.9 months, with July as the hottest month. The cool season lasts 3.3 months, with January experiencing the coldest temperatures. Shiraz experiences significant seasonal variations in cloud cover, precipitation patterns, and wind dynamics. A clearer period prevails for 5.2 months, with June as the clearest month. The wet season lasts 5 months, with January having the highest number of wet days. The dry season lasts for 7 months, with September having the fewest. Rain is the predominant form of precipitation throughout the year. Wind dynamics show mild seasonal variation, with a windier period lasting 7.4 months and a calmer period lasting 4.6 months. The predominant wind direction fluctuates throughout the year, with northerly winds dominating for 2.1 months and westerly winds dominating the remaining 9.9 months. Shiraz experiences significant variation in daylight hours, with the shortest day occurring on December 21 and the longest on June 21. The daily incident of shortwave solar energy reaching Shiraz’s surface exhibits extreme seasonal variations, with a brighter and darker periods. Shiraz’s growing season typically lasts 8.8 months, indicating favorable conditions for plant growth.

For building performance simulations, the use of accurate and representative climatic data is imperative. This study utilizes a standard EnergyPlus weather (EPW) file for Shiraz, specifically a Typical Meteorological Year (TMYx) dataset sourced from the reputable Climate OneBuilding repository. It is crucial to note that TMYx files, which are generated in accordance with the ISO 15,927–4:2005 standard methodology, are not based on a single historical year. Instead, they represent a statistical composite derived from a recent multi-year period of historical data (2017–2021), engineered to represent typical, rather than extreme, meteorological conditions. This approach directly mitigates concerns associated with utilizing antiquated climate data from previous decades, ensuring that simulation inputs reflect contemporary climatic patterns, a trend also highlighted by global climate data aggregators like Our World in Data. Table 3, as well as Figs. 3-6, present the key meteorological characteristics of the investigating area based on this recent data:

2.2.2. Problem constraints and design variables

The selection of objective functions in sustainable building rehabilitation, particularly for historic structures, involves balancing various factors to optimize the benefits of rehabilitation measures. These benefits can be categorized into environmental, economic, and social aspects.

1. Economic Benefits

The economic benefits of objective function selection in building rehabilitation can be assessed through life-cycle cost (LCC) analysis, which considers all costs associated with a building over its lifespan. Key economic factors include:

Table 3
Key meteorological characteristics of the weather file.

Parameter	Value / Description	Source / Standard
File Type	Typical Meteorological Year (TMYx)	ISO 15,927–4:2005 Methodology
Data Source	Climate OneBuilding Repository (NCEI ISD/ERA5)	–
Source Data Period	2007–2021	–
Annual Mean Dry-Bulb Temperature	18.5 °C	From EPW data file
Annual Mean Global Horizontal Radiation	214.9 W/m ²	From EPW data file
Annual Mean Wind Speed	2.8 m/s	From EPW data file

- Cost Reduction: Minimizing material, construction, and operational costs through efficient resource management.
- Long-term Value: Ensuring that rehabilitation investments contribute to the long-term economic value of the property.
- Economic Incentives: Utilizing government incentives and tax benefits for sustainable rehabilitation.
- Resource Management: Optimizing material use to reduce expenses and improve financial sustainability.

2. Environmental Benefits

Sustainable rehabilitation aims to minimize the environmental footprint of buildings. The main environmental objectives include:

- Carbon Emission Reduction: Implementing materials and energy systems that reduce greenhouse gas emissions.
- Life Cycle Assessment (LCA): Evaluating the environmental impact of materials and processes from extraction to disposal.
- Fossil Fuel Conservation: Reducing dependence on non-renewable energy sources through energy-efficient building design.
- Waste Management: Promoting recycling, reuse, and responsible material sourcing to minimize construction and operational waste.
- Ecosystem Protection: Ensuring rehabilitation measures do not adversely affect local biodiversity and natural environments.

3. Social Benefits

The social impacts of building rehabilitation are crucial in enhancing community well-being. These benefits include:

- Health and Comfort: Improving indoor air quality, ventilation, and thermal comfort for occupants.
- Community Engagement: Involving local communities in rehabilitation projects to align with social and cultural values.
- Equity and Accessibility: Ensuring rehabilitated buildings are accessible and beneficial to all social groups.
- Safety and Security: Enhancing historic buildings’ structural integrity and fire safety while maintaining their heritage value.
- Cultural Heritage Preservation: Protecting and restoring historic buildings to maintain their aesthetic and historical significance.

4. Building Performance and Technological Integration

Optimizing building performance is essential for achieving sustainability goals. The integration of modern technology can significantly enhance efficiency, including:

- Structural Integrity: Ensuring that rehabilitated buildings meet modern safety and durability standards.
- Operational Efficiency: Implementing systems for better energy, water, and material use.
- Building Information Modeling (BIM): Utilizing digital tools to optimize planning, design, and execution of rehabilitation projects.

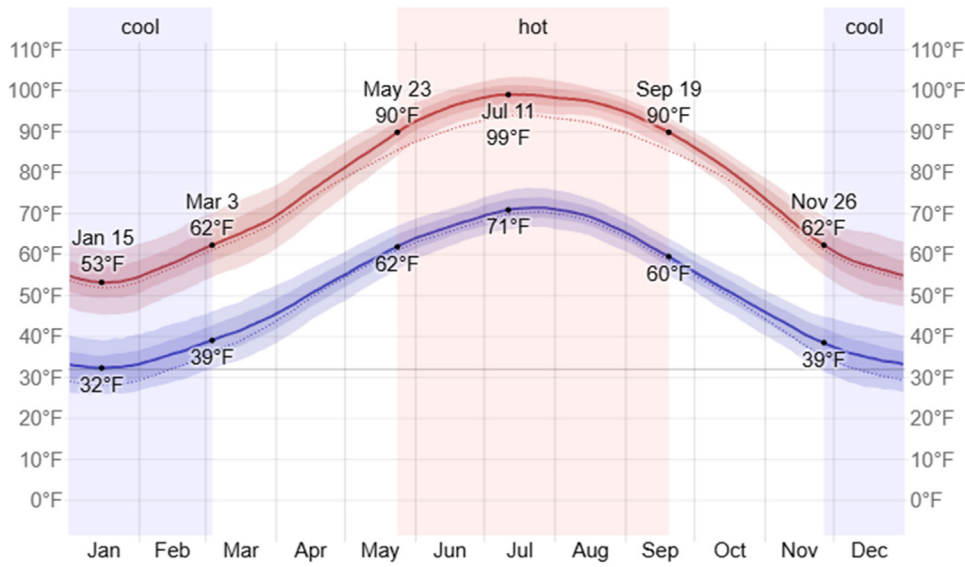


Fig. 3. Seasonal temperature variation and climatic seasons for Shiraz.

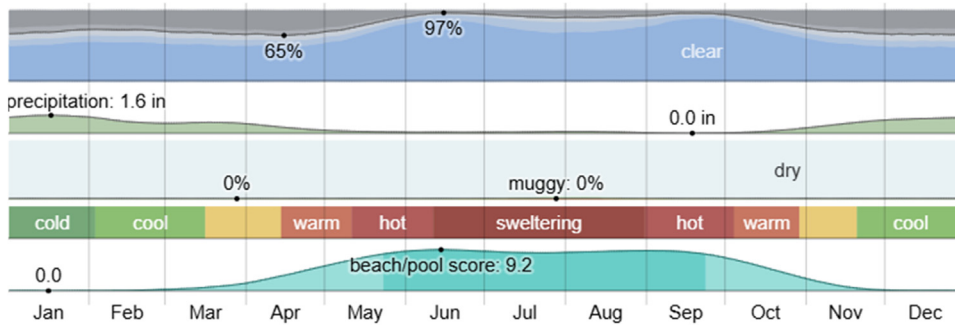


Fig. 4. Comprehensive annual climate summary for Shiraz.

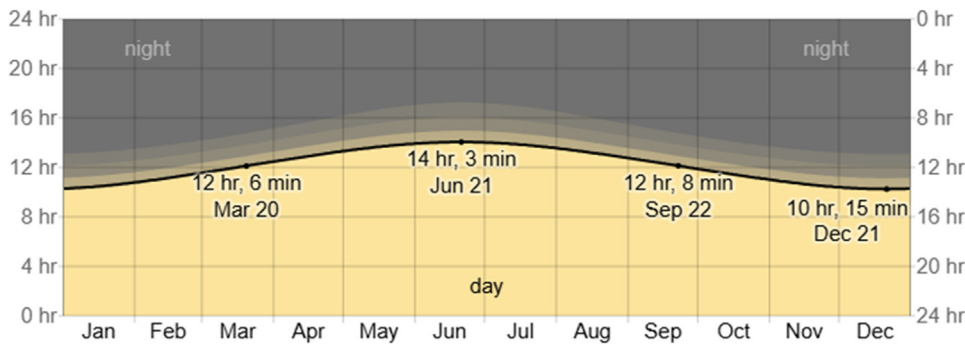


Fig. 5. The annual photoperiod cycle at Shiraz.

By considering these objectives, sustainable building rehabilitation can effectively balance environmental preservation, economic viability, and social well-being, ensuring long-term benefits for all stakeholders. Specifications of the aforementioned framework within sustainable construction domain is provided in Table 4.

The revitalization of Shiraz's historic district presents several critical constraints that must be addressed to ensure a successful and sustainable outcome. Financial constraints remain a primary challenge, as limited funding can restrict the scope of restoration projects, the selection of sustainable materials, and the integration of innovative technologies (Agrawal et al., 2024). The economic feasibility of incorporating advanced digital tools, such as Building Information Modeling (BIM) and Life Cycle Assessment (LCA), requires thorough cost-benefit analyses, as their implementation costs can be a significant barrier (Santos et al., 2020). Social and cultural challenges further complicate the process, as the need to balance modernization with heritage preservation

often leads to resistance from local communities and concerns over gentrification (Boussaa & Madandola, 2024). Engaging stakeholders—including policymakers, conservationists, and residents—is crucial to mitigating these conflicts and maintaining the historical authenticity of the district (Sterling et al., 2017). Environmental constraints, such as water scarcity and climate-related factors, impact material durability and energy efficiency considerations, necessitating carefully selecting sustainable yet historically compatible construction solutions (Pérez-Sánchez et al., 2022). Technological limitations also pose significant hurdles, as the complexity of BIM, LCA, and simulation software may hinder their practical application in historical contexts due to a lack of standardized methodologies and technical expertise among restoration professionals (Firoozi et al., 2024).

Additionally, regulatory and administrative barriers can cause delays, with stringent heritage protection laws, lengthy bureaucratic approval processes, and conflicts between local and international con-

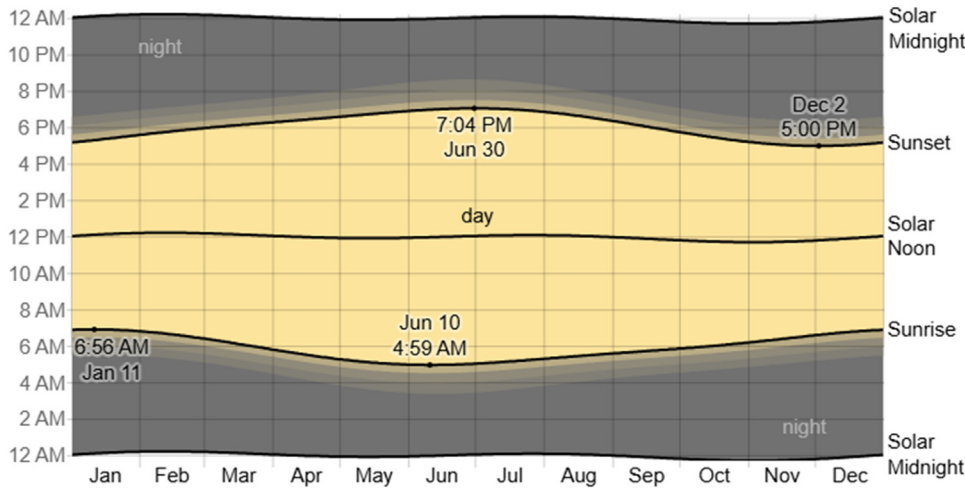


Fig. 6. The annual cycle of sunrise, solar noon, and sunset at Shiraz.

Table 4
A framework for multi-stakeholder decision analysis in sustainable construction.

Objective	Owner-occupant	Absent Owner	External Stakeholder
Economic	- Investment Cost - Energy Consumption Costs - Maintenance & Replacement Costs - Property Tax - Resale Value	- Investment Cost - Maintenance & Replacement Costs - Property Tax - Resale Value - Rental Value	- Investment Cost - Property Tax - Environmental Costs - Social Costs
Environmental	- CO ₂ emissions - Environmental Impacts - Fossil Fuel Conserving	- CO ₂ emissions - Environmental Impacts - Fossil Fuel Conserving	- CO ₂ emissions - Environmental Impacts - Fossil Fuel Conserving
Social	- Community impact - Building impact: - Health - Comfort & Satisfaction - Productivity - Security - Pride & Satisfaction	- Community impact - Building impact: - Comfort & Satisfaction - Security	- Society impact

servation guidelines limiting the flexibility of reconstruction efforts (Klumbyte et al., 2020). Finally, data availability and research limitations exacerbate these challenges, as incomplete or inaccurate documentation of historical structures can hinder digital modeling and informed decision-making (Pocobelli et al., 2018). Addressing these multifaceted constraints requires a combination of innovative funding mechanisms, interdisciplinary collaboration, technological advancements, policy reforms, and enhanced education and training to equip professionals with the necessary skills (Perret et al., 2025). A holistic approach that integrates these solutions will enable a more efficient and sustainable revitalization process, ensuring that the historical and cultural integrity of Shiraz's historic district is preserved while embracing modern restoration practices.

The design variables for revitalizing Shiraz's historic district are based on the Sustainable Development Goals (SDGs), which provide a comprehensive framework for balancing environmental, social, and economic priorities in urban heritage contexts. These variables include material selection, energy efficiency, passive design strategies, active systems, innovative building technologies, water conservation, social and cultural integration, economic viability, and adaptive reuse. Material selection should consider a wide range of factors, such as embodied energy, greenhouse gas emissions, water usage, recycling potential, end-of-life management, durability, local sourcing, and compatibility with historic aesthetics, often evaluated through a Life Cycle Assessment (LCA) approach. Active systems should incorporate energy-efficient technologies, such as high-performance insulation, efficient heating, ventilation, and air conditioning (HVAC) systems, and renewable energy sources, which are critical for reducing the operational footprint of restored buildings (Hafez et al., 2023c). Water conservation is crucial due to the region's water scarcity concerns, necessitating efficient fixtures and water-saving strategies (Jacque et al., 2024). Social and cultural integration must involve community engagement, preservation of cultural heritage, ensuring accessibility, and creating vibrant public spaces to maintain the district's living identity (Maghsoodi Tilaki & Farhad, 2024).

(Guarini et al., 2024). Economic viability is also essential and can be enhanced through cost-effective material selection, promoting local job creation, and particularly through adaptive reuse, which gives historic buildings new life while generating economic value (Gravagnuolo et al., 2024). These interconnected design variables need to be carefully balanced and optimized to achieve a successful and sustainable revitalization of Shiraz's historic district.

The overall framework of design variables was specifically customized for the context of Shiraz. The city's climate, characterized by hot, dry summers and cool winters (as detailed in Section 2.2.1), directly influenced the multi-criteria analysis; criteria related to thermal performance (such as thermal resistance, thermal mass) and operational energy efficiency were assigned higher weights in the COPRAS model, directly impacting the ranking of insulation materials and wall assemblies. Furthermore, the region's historical construction traditions, which utilized materials like adobe, fired brick, and timber, informed the initial selection of material alternatives for evaluation. The framework was therefore designed to rigorously compare these traditional, local options against modern, high-performance materials, ensuring that the final "optimal" choice is rooted in local context, availability, and heritage. Input parameters for conceptual construction types used in building performance simulation is provided in Table 5.

2.2.2.1. Optimal material selection. Based on previous research by Valipour and Moalemi and utilizing the COPRAS method, the best materials for each group of sustainable materials have been identified:

- Group 1 (Insulation): SIP panels, Polystyrene insulation, and Isocyanurate insulation
- Group 2 (Flooring): Lightweight blocks and ready-mixed concrete
- Group 3 (Structural Systems): Steel roof panels and ready-mixed concrete
- Group 4 (Masonry): Lightweight blocks and Portland slag cement
- Group 5 (Facade and Finishing): Stretch ceilings and Hempcrete
- Group 6 (Floor Coverings): MDF boards and Trazo flooring

Table 5

Input parameters for the conceptual construction types used in the building performance simulation.

Mass Model	Construction
Mass Exterior Wall	Lightweight Construction – Typical Mild Climate Insulation
Mass Interior Wall	Lightweight Construction – No Insulation
Mass Exterior Wall – Underground	High Mass Construction – Typical Mild Climate Insulation
Mass Roof	Typical Insulation – Cool Roof
Mass Floor	Lightweight Construction – No Insulation
Mass Slab	High Mass Construction – No Insulation
Mass Glazing	Double Pane Clear – No Coating
Mass Skylight	Double Pane Clear – No Coating
Mass Shade	Basic Shade
Mass Opening	Air

Table 6

Optimal material selections for key building systems.

Material Group	Optimal Materials
MATERIAL GROUP	OPTIMAL MATERIALS
Insulation	SIP panels, Polystyrene insulation, Isocyanurate insulation
Flooring	Lightweight blocks, Ready-mixed concrete
Structural Systems	Steel roof panels, Ready-mixed concrete
Masonry	Lightweight blocks, Portland slag cement
Facade and Finishing	Stretch ceilings, Hempcrete
Floor Coverings	MDF boards, Trazo flooring

The software also incorporates its proposed optimal materials into its functions for model analysis based on regional and environmental conditions, as illustrated in Table 6. These optimized materials can contribute to better resource management and increased efficiency in the construction process.

2.2.3. Simulation software and model assumptions

The execution of simulation models based on the Revit model. The simulation tools used include Sefaira, Green Building Studio, and IES-VE. These tools import the Revit model using gbXML files and use weather data for the simulations. Sefaira uses the Energy-plus (EPW) weather file format, while Green Building Studio defines climate zones according to the International Energy Conservation Code 2009. IES-VE uses multiple weather sources, allowing users to choose based on the model location. The results are presented in three simulation tools, and the Sustainable Development Goals (SDG) are expressed in each software. The study also discusses the application of life cycle assessment to demonstrate sustainability and select suitable materials for restoring historical fabrics. Sefaira helps assess building energy performance in early design stages; Green Building Studio allows users to create and analyze models; IES-VE is a comprehensive simulation tool for analyzing energy and environmental performance; and Revit Insight 360 uses Revit's analytical energy model to track carbon reduction strategies. A comparative overview of the capabilities of the three mentioned building energy simulation tools is provided in Fig. 7.

2.3. Results and discussion

The findings of this study underscore the value of a data-driven approach, presenting substantial benefits when contrasted with conventional restoration methods. These traditional practices frequently depend on the subjective judgments of experts or are constrained by a narrow focus on singular, often competing, metrics like historical authenticity versus cost. The integrated framework proposed herein is engineered to surmount these deficiencies in three principal ways. Firstly, it instills objectivity and quantification into the process by supplanting purely qualitative evaluations with scientific, standardized metrics

derived from Life Cycle Assessment (LCA). This elevates the discussion from ambiguous concepts of "green materials" to tangible data on specific impacts, such as Global Warming Potential. Secondly, it facilitates comprehensive and transparent decision-making via the COPRAS method. This offers a structured framework to systematically assess the trade-offs across a diverse spectrum of criteria, including environmental performance, cost, and historical authenticity. Thirdly, BIM serves as the central digital repository for all project data, thereby superseding the fragmented, paper-based documentation inherent in traditional workflows and establishing a unified, data-rich platform for managing information throughout the building's lifecycle.

The Revit model was used to simulate a single-family house in Shiraz to address safety, welfare, and urban environment challenges, as shown in Fig. 8. The software pinpointed the optimal sustainable materials for various aspects such as insulation, flooring, structural systems, wall construction, facade beautification, and floor coverings. The study used BIM technology to evaluate the efficiency and effectiveness of the sustainable development model in reconstructing worn-out buildings. The simulations were conducted in three stages: creating a test project, comparing results, and relating results to Sustainable Development Goals (SDG). The study also applied a life cycle assessment to demonstrate sustainability and select the most suitable materials for restoring historical fabrics.

The revitalization project in Shiraz aims to minimize the environmental impact of the built environment, reduce resource consumption, lower greenhouse gas emissions, protect biodiversity, improve the quality of life for residents, enhance health and comfort, increase social interaction, improve access to services, contribute to economic growth, create job opportunities, increase property values, attract investment and tourism, preserve cultural heritage, integrate new and old elements harmoniously, and adaptively reuse historic buildings. A multifaceted approach involving sustainable material selection, energy-efficient building design, water conservation measures, community engagement, innovative technologies, and effective project management and governance is suggested to achieve these goals. Success can be evaluated based on environmental performance, social impact, economic viability, and cultural preservation.

The "Photovoltaic Analysis" feature incorporates a payback period calculation, enabling users to tailor solar panel configurations according to a desired return on investment, which offers a transparent evaluation for project stakeholders. However, a critical caveat is necessary to contextualize this analysis. The calculated payback period is not presented as a definitive financial forecast; instead, it functions as a comparative decision-support metric intended for preliminary design phases. Within the simulation, the objective is to provide a relative benchmark of economic viability when comparing various material and energy scenarios under a standardized set of assumptions. Actual payback periods are subject to numerous volatile factors that lie outside the simulation's scope, such as fluctuating energy tariffs, governmental incentives, inflation, and maintenance expenditures. Consequently, this metric must be interpreted as an instrument for relative comparison rather than one of absolute prediction. Ultimately, integrating renewable energy into buildings not only curtails energy expenditures but also serves to optimize the design and accelerate the return on investment.

The simulation results demonstrate the significant advantages of using optimized, sustainable materials, particularly in reduced energy consumption and operational costs. Comparative analysis between conventional materials and the proposed sustainable alternatives showed a reduction of approximately 25 % in annual energy usage and 30 % in carbon emissions, highlighting the practical benefits of this methodological approach. Further information regarding the obtained results is provided in Tables 7-9, as well as Figs. 9-16.

To bridge the results of this simulation-based study with real-world scenarios, it is crucial to place the technical analysis within a broader implementation context. The ranked list of sustainable material alterna-

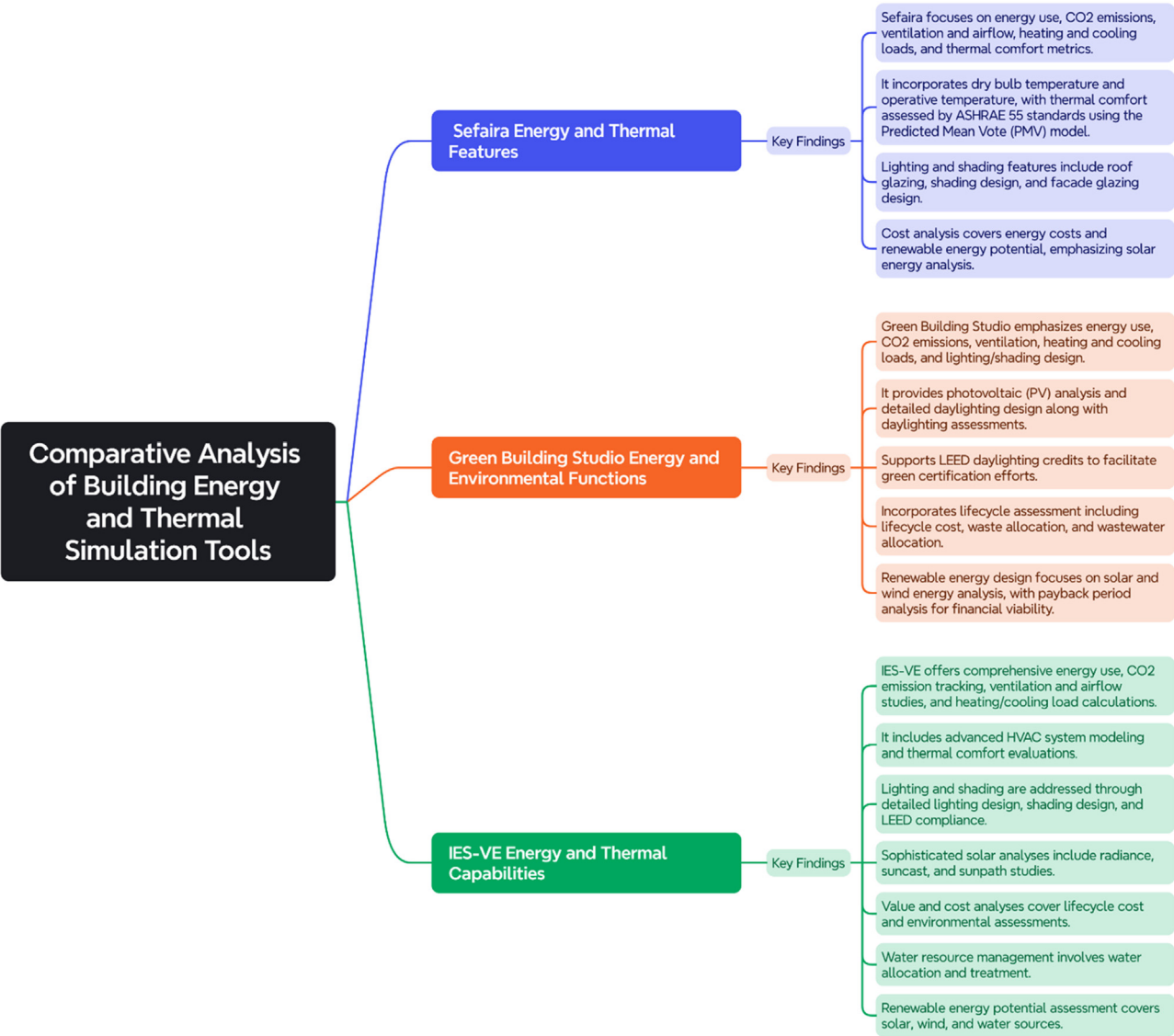


Fig. 7. A comparative overview of the capabilities of three building simulation tools.

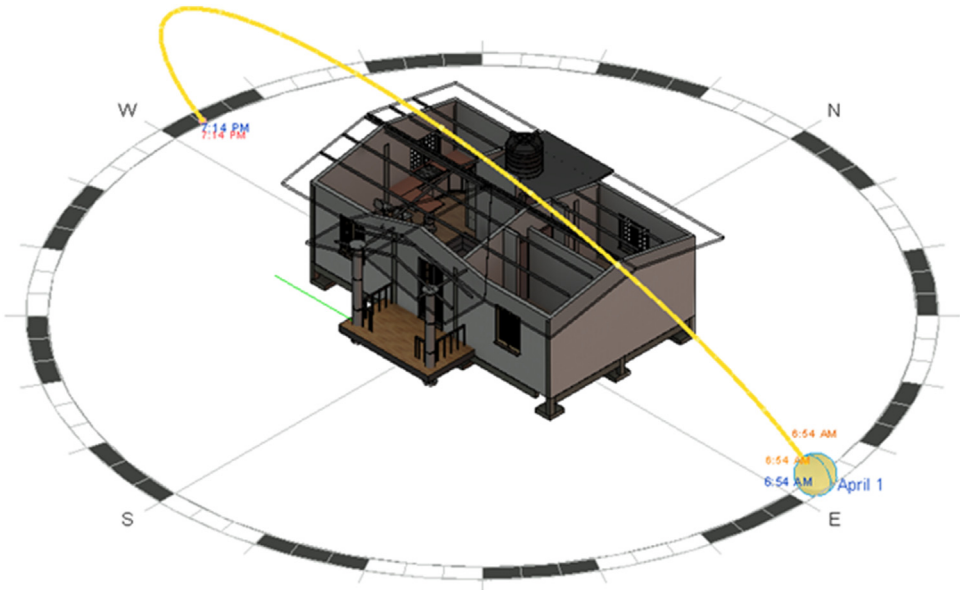


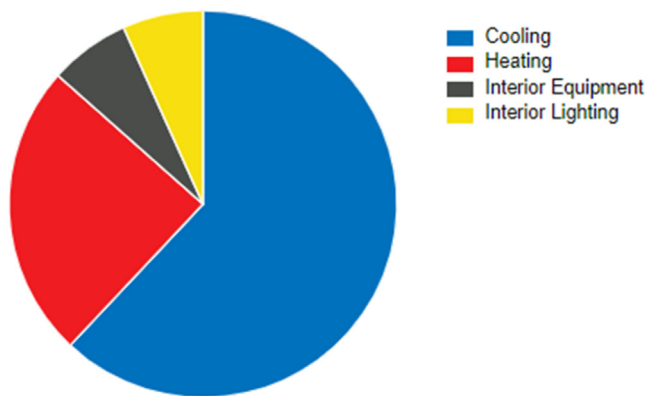
Fig. 8. Solar geometry and sun path analysis for the building model.

Table 7

Disaggregation of the peak cooling load by source and type.

Type		Instant Sensible [W]	Delayed Sensible [W]	Latent [W]	Total [W]	Percent of Total [%]
Envelope	Roof	–	1561	–	1561	64.4
	Other - Roof	–	0	–	0	0.0
	Ceiling	–	0	–	0	0.0
	Glass - Conduction	0	–	–	0	0.0
	Glass - Solar	–	0	–	0	0.0
	Door	–	64	–	64	2.6
	Wall	–	628	–	628	26.0
	Below-grade Wall	–	0	–	0	0.0
	Partition	–	–202	–	–202	–8.4
	Other - Wall	–	0	–	0	0.0
	Exterior Floor	–	0	–	0	0.0
	Interior Floor	–	0	–	0	0.0
	Slab	–	–110	–	–110	–4.5
	Other - Floor	–	0	–	0	0.0
	Infiltration	46	–	–7	40	1.6
	Subtotal	46	1941	–7	1980	81.9
Internal Gains	People	51	14	59	124	5.1
	Lights	120	0	–	120	5.0
	Return Air – Lights	0	–	–	0	0.0
	Equipment	120	0	0	120	5.0
	Subtotal	292	14	59	364	15.1
Systems	Zone Ventilation	85	–	–12	0	3.0
	Transfer Air	0	–	0	0	0.0
	DOAS Direct to Zone	0	–	0	0	0.0
	Return Air – Other	0	–	–	0	0.0
	Power Generation	0	0	–	0	0.0
	Equipment	0	–	0	0	0.0
	Refrigeration	0	–	0	0	0.0
	Water Use	0	–	0	0	0.0
	Equipment	0	0	–	0	0.0
	HVAC Equipment	0	0	–	0	0.0
	Loss	85	0	–12	73	3.0
	Subtotal	85	0	–12	73	3.0
Total	Sizing Factor	0	–	–	0	0.0
	Adjustment	–	0	–	0	0.0
	Time Delay	–	0	–	0	0.0
Grand Total		423	1954	40	2418	100.0

Annual Overview

[End Use - view table](#)
**Fig. 9.** Breakdown of total annual energy consumption by end use for the case study building.**Table 8**

Disaggregation of the peak cooling load by source and type.

Category		Value
Energy, Carbon, and Cost Summary	Annual Energy Cost	\$1513
	Lifecycle Cost	\$20,608
Annual CO ₂ Emissions	Electric	5.0 Mg
	Onsite Fuel	2.7 Mg
Annual Energy	Large SUV Equivalent	0.8 SUVs / Year
	Energy Use Intensity (EUI)	2015 MJ/m ² /year
	Electric	8777 kWh
	Fuel	54,067 MJ
Lifecycle Energy	Annual Peak Demand	3.8 kW
	Electric	263,317 kWh
	Fuel	1622,005 MJ

tives generated by the BIM-LCA-COPRAS model is not an endpoint, but rather a critical input for a practical, iterative, and multi-stakeholder decision-making process. Fig. 17 presents a conceptual framework that illustrates how the technical outputs of this research can be operationalized in heritage restoration projects.

As conceptualized in this framework, the technical analysis furnishes an objective, data-driven basis for stakeholder discourse. This is succeeded by a critical consultation phase, during which qualitative expertise and community values are integrated into the decision-making process. A subsequent analysis of constraints ensures that the ultimately chosen strategy is not merely technically optimal but also economically feasible and pragmatically attainable in the local context. This model

Table 9
Feasibility analysis of renewable energy and passive design strategies.

Category		Details
Photovoltaic Potential	Annual Energy Savings	10,625 kWh
	Total Installed Panel Cost	\$49,275
	Nominal Rated Power	6 kW
	Total Panel Area	45 m ²
	Maximum Payback Period	31 years @ \$0.11 / kWh
Wind Energy Potential	Annual Electric Generation	887 kWh
Natural Ventilation Potential	Total Hours Mechanical Cooling Required	5211 H
	Possible Natural Ventilation Hours	1095 H
	Possible Annual Electric Energy Savings	583 kWh
	Possible Annual Electric Cost Savings	\$65
	Net Hours Mechanical Cooling Required	4116 H

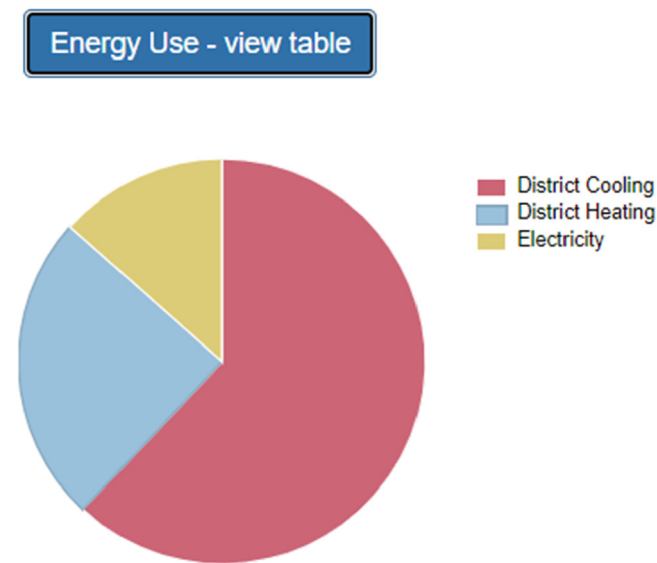


Fig. 10. Distribution of annual energy use by utility source for the case study building.

exemplifies how academic research can be generalized and operationalized, thus amplifying the practical impact of the study.

3. Policy and practical implications

While the technical framework presented in this study shows significant potential for improving the sustainability of heritage restoration, its successful adoption in the resource-constrained contexts of developing countries hinges on addressing formidable financial, regulatory, and socio-economic barriers. This section discusses these challenges and proposes a set of actionable strategies to ensure the framework’s realistic and equitable implementation.

3.1. Overcoming financial and regulatory barriers

A primary obstacle is the often-higher initial cost associated with sustainable materials and the expertise required for advanced digital analysis. To overcome this, a multi-pronged approach is essential. Governments and international development bodies should consider creating targeted financial mechanisms, such as tax credits for heritage rehabilitation, grants for using certified sustainable materials, and low-interest heritage loans. For larger-scale urban regeneration, innovative

models like Public-Private Partnerships (PPPs) can leverage private investment. On the regulatory front, heritage protection agencies should work to streamline bureaucratic approval processes for projects that use validated, data-driven frameworks like the one we propose. This could involve a shift from purely prescriptive regulations (e.g., mandating specific materials) to more flexible performance-based heritage codes that permit innovative yet compatible materials that enhance sustainability without compromising core heritage values.

3.2. Mitigating socio-economic risks: gentrification and community displacement

It is a well-documented paradox that successful, high-quality heritage-led regeneration can unintentionally increase property values and living costs, creating economic pressures that risk the displacement of long-term, low-income residents and local businesses. Therefore, the implementation of our technical framework must be proactively coupled with robust social and economic policies designed to ensure equitable development. Drawing inspiration from established anti-displacement strategies, municipal authorities should consider a suite of interventions. These include inclusive housing policies such as rent stabilization, inclusionary zoning (requiring a percentage of renovated units to be dedicated to affordable housing), and supporting the development of Community Land Trusts (CLTs) to preserve long-term housing affordability. Furthermore, meaningful community engagement must be integrated from a project’s inception to ensure residents and business owners are active participants in the planning process. Finally, policies should actively support the local economic fabric by providing affordable commercial spaces or grants to help small, local businesses, often a key part of a neighborhood’s intangible heritage, to remain and thrive. The mentioned integrated strategies are summarized in the [Table 10](#). This framework outlines key challenges in sustainably reconstructing cultural heritage sites and proposes targeted strategies to address them.

4. Strengths, limitations, and conclusion

This research comprehensively analyzes sustainable reconstruction within Shiraz’s historical fabric, utilizing Building Information Modeling (BIM) and Life Cycle Assessment (LCA) as core methodologies. This integrated approach provides a holistic understanding of the intricate challenges and opportunities in harmonizing preservation efforts with contemporary urban demands.

4.1. Strengths of the research

The study’s primary strength lies in its holistic approach, which integrates environmental, social, and economic factors to formulate a sustainable and balanced reconstruction strategy. By addressing multiple dimensions of urban revitalization, the research moves beyond conventional restoration methods, providing a robust framework for sustainable development. A key strength is leveraging advanced technology, particularly BIM and LCA. BIM facilitates precise simulations across various project phases, optimizing design efficiency and construction processes. At the same time, LCA enables the evaluation of environmental impacts, ensuring material selection and energy use align with sustainability principles.

Furthermore, the study offers actionable insights, presenting practical recommendations for transforming deteriorated historical areas into dynamic, livable urban spaces without compromising cultural and architectural integrity. By preserving cultural heritage, the research underscores the importance of maintaining Shiraz’s unique historical identity, advocating for restoration methods that prioritize authenticity while integrating modern innovations. Additionally, this study makes a significant scientific contribution by enriching the academic discourse on sustainable reconstruction, offering a global methodological blueprint applicable to similar projects. Through its interdisciplinary

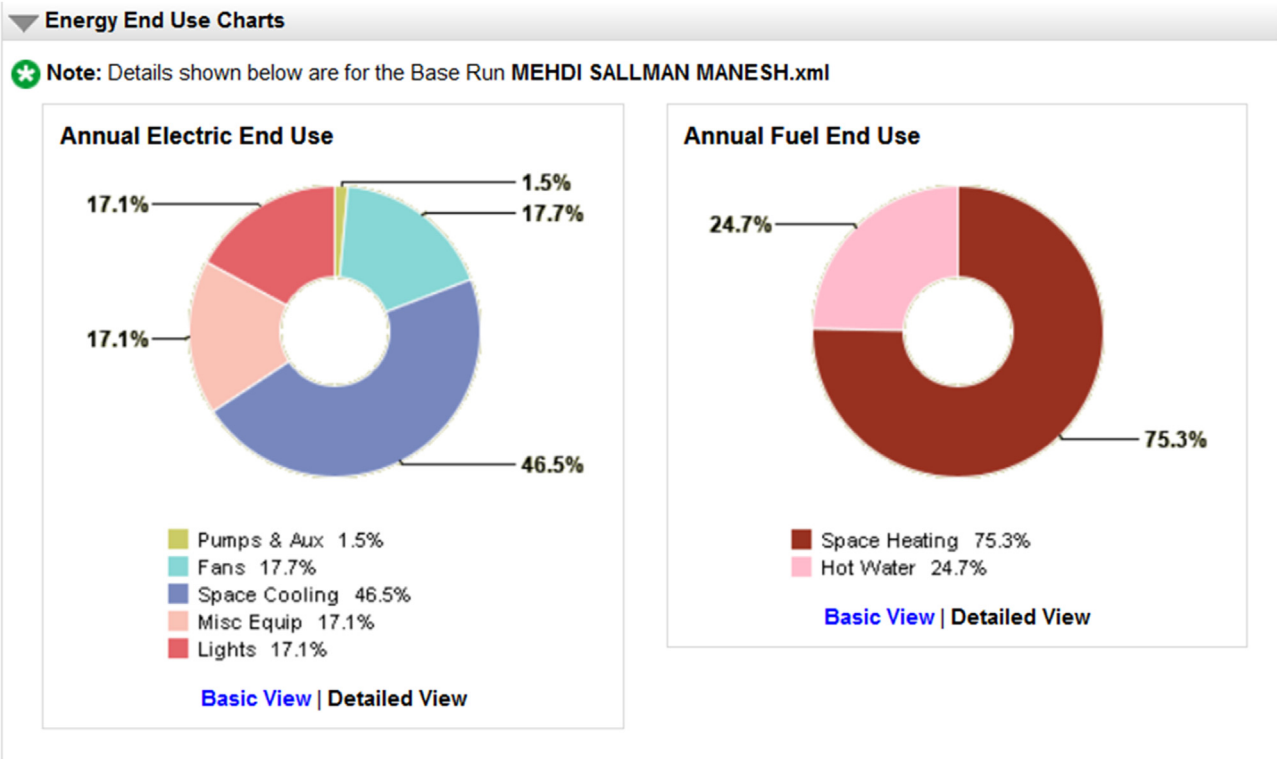


Fig. 11. Breakdown of annual energy consumption for the baseline model, disaggregated by energy carrier.

Monthly Overview

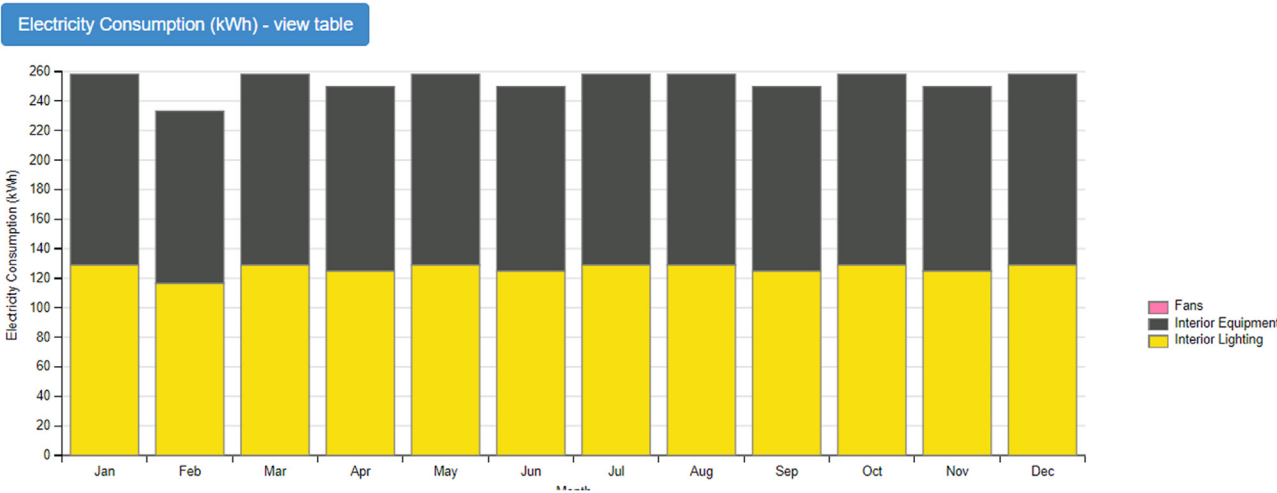


Fig. 12. Monthly profile of the building's baseload electricity consumption.

and technology-driven approach, the research provides valuable insights for policymakers, architects, and conservationists striving to balance urban development with heritage preservation.

4.2. Limitations and further considerations

Despite its valuable contributions, this research faces several limitations that warrant acknowledgment. Financial constraints pose a significant challenge, as securing adequate funding for sustainable projects in historical contexts remains difficult. Exploring innovative funding mechanisms and conducting economic feasibility studies could offer potential solutions. Another major limitation is community engagement,

as resistance from local communities may hinder progress. Ensuring active participation and fostering a sense of ownership among residents through participatory approaches is essential for project success. Regulatory hurdles further complicate the reconstruction process; complex legal frameworks and bureaucratic procedures often cause delays. A more detailed analysis of regulatory requirements and potential policy reforms could help streamline approvals and facilitate smoother implementation.

Preserving authenticity in historical reconstruction presents a considerable challenge, as striking a balance between modernization and heritage conservation requires meticulous attention to detail. The study could benefit from a deeper exploration of specific restoration tech-

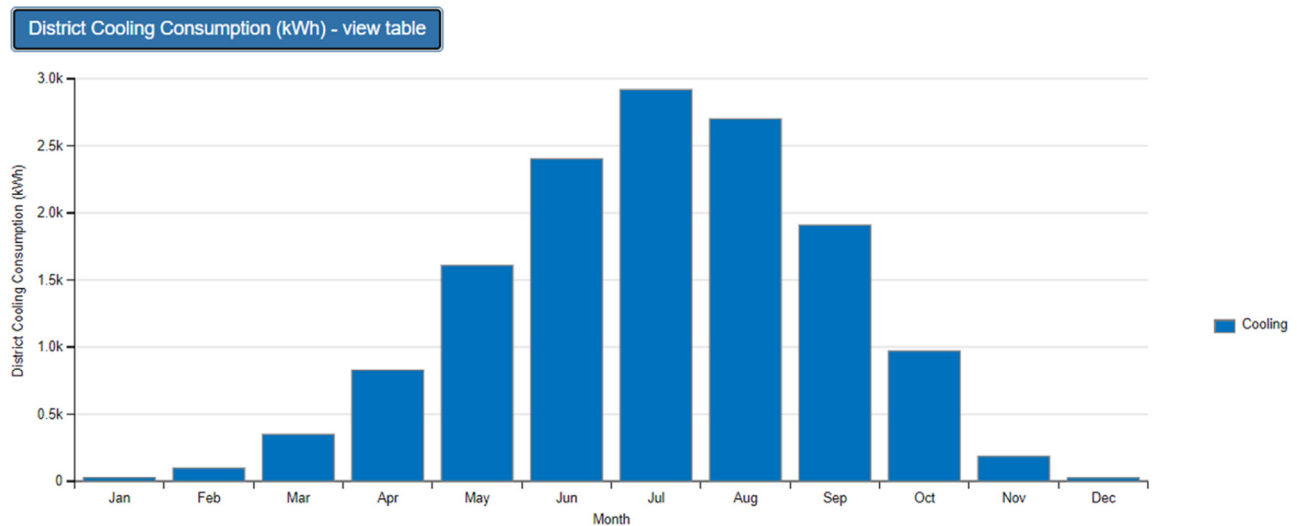


Fig. 13. The seasonal profile of district cooling consumption for the baseline model.

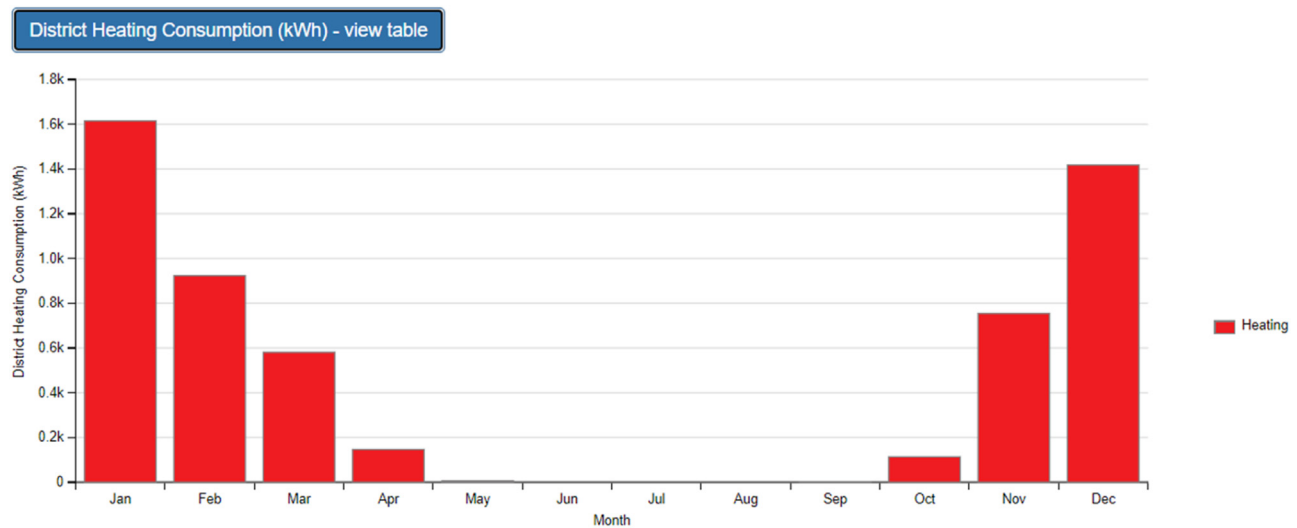


Fig. 14. Monthly district heating energy consumption (kWh) for the case study building.

Table 10

Mitigation policies and strategies for sustainable cultural heritage reconstruction.

Challenge / Risk	Proposed Strategy / Mechanism	Key Stakeholders	Desired Outcome
High Upfront Costs of sustainable materials and analysis.	• Federal/municipal tax credits for heritage revitalization. • Grants and low-interest loans for sustainable retrofits. • Public-Private Partnerships (PPPs) for large projects.	• National/municipal governments • Financial institutions • International development banks	Increased private investment in sustainable heritage conservation; reduced financial barriers for owners.
Complex and Slow Regulatory Barriers	• Streamlined approval processes for projects using certified sustainable frameworks. • Development of performance-based heritage codes instead of purely prescriptive ones.	• Heritage preservation agencies • Urban planning departments	Faster project approvals; incentivizing innovative yet compatible materials and techniques.
Risk of Gentrification and resident displacement.	• Inclusionary zoning policies. • Rent stabilization measures. • Support for Community Land Trusts (CLTs) and housing cooperatives.	• Urban planners • Housing authorities • Community-Based Organizations (CBOs), NGOs	Preservation of affordable housing stock; equitable development and community stability.
Loss of Intangible Heritage and local identity.	• Mandatory participatory planning processes. • Financial support for local businesses and cultural institutions. • Development of community-based heritage tourism.	• Municipal governments • Community organizations • Local business associations	Preservation of neighborhood identity and social fabric; empowerment of local communities.
Lack of Technical Expertise in developing nations.	• Capacity-building and training for local professionals. • Creation of open-access databases for local sustainable materials. • International knowledge-sharing partnerships.	• Universities & research institutions • Professional associations • NGOs, UNESCO, ICCROM	Increased local capacity to implement advanced conservation techniques; greater self-sufficiency.

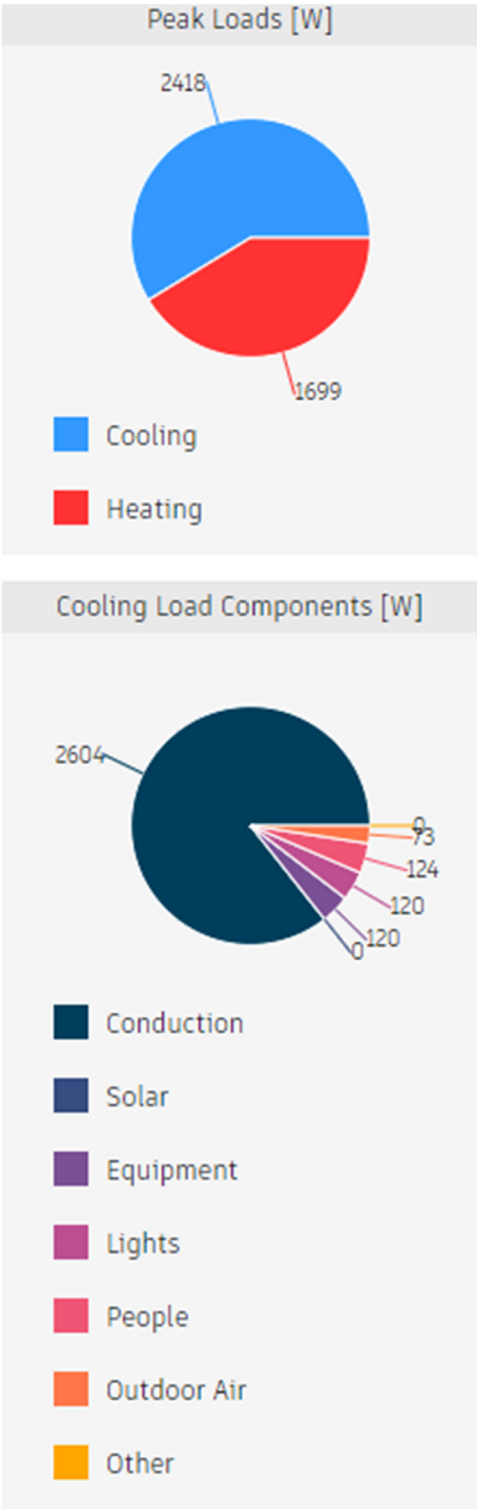


Fig. 15. Peak thermal load comparison and cooling load disaggregation.

niques and material selection strategies to maintain historical integrity while incorporating sustainable innovations; however, although advanced digital modeling is successfully integrated with sustainability assessment techniques, other limitations persist, including limited data availability on sustainable materials within the Iranian market. Addressing these limitations through strategic planning, policy adjustments, and enhanced stakeholder collaboration would strengthen the study's impact and applicability in real-world restoration projects.

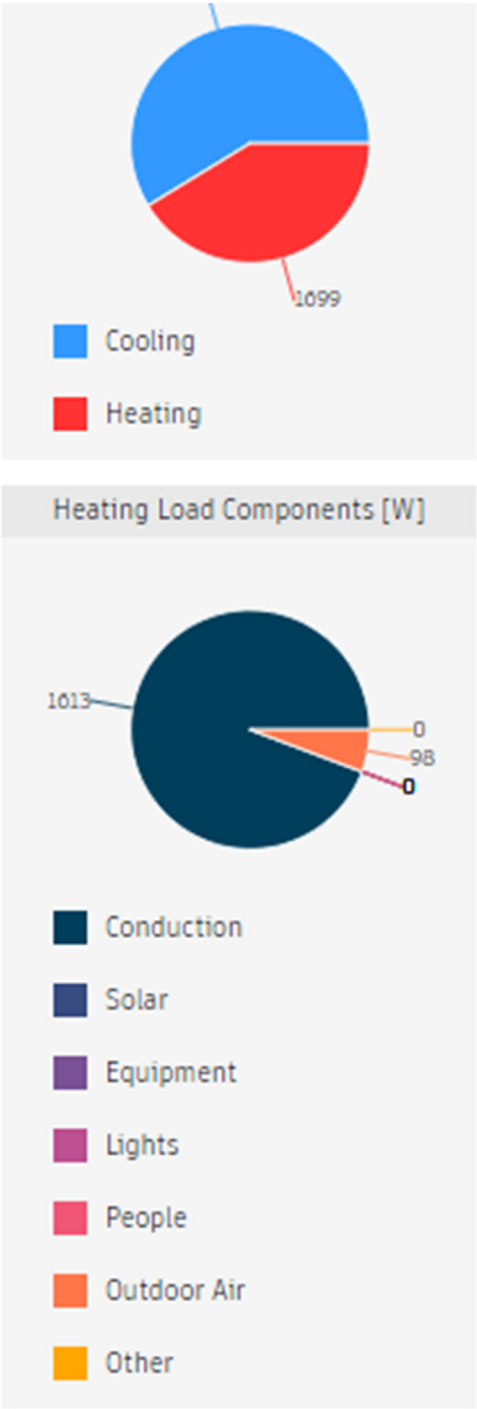


Fig. 16. Peak thermal load comparison and heating load disaggregation.

While the research highlights advanced tools like Revit, Sefaira, and IES-VE, a more detailed analysis of their specific limitations in this context (as shown in Fig. 18) would enhance methodological rigor. Additionally, exploring potential unintended consequences, such as gentrification or community displacement, is crucial to present a balanced perspective on the long-term impacts of such projects.

4.2.1. Data uncertainty in heritage building information modeling (HBIM)

A fundamental challenge inherent in any HBIM-based study is the management of data uncertainty. Unlike new constructions, historic buildings often suffer from incomplete, inconsistent, or inaccurate documentation, making the creation of a perfectly accurate 'as-is' BIM model

Integrating Simulation with Heritage Reconstruction

Fig. 17. Integrating simulation with heritage reconstruction.

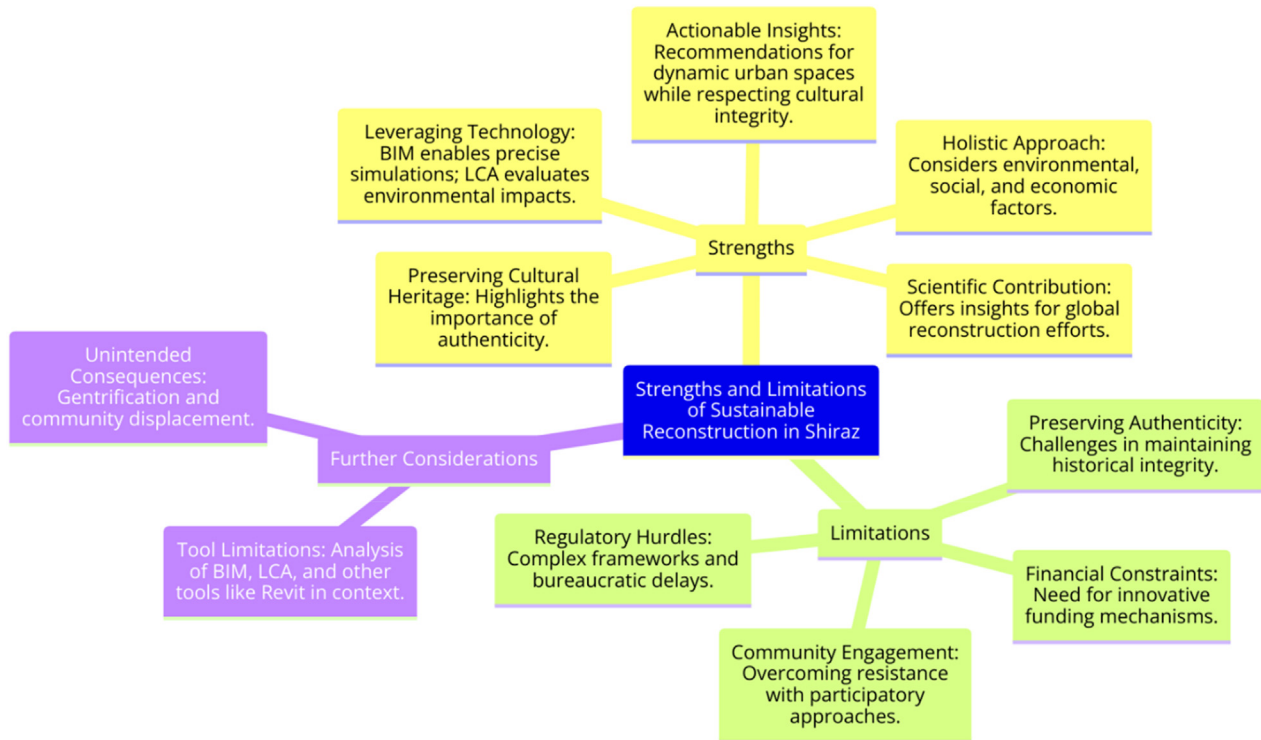
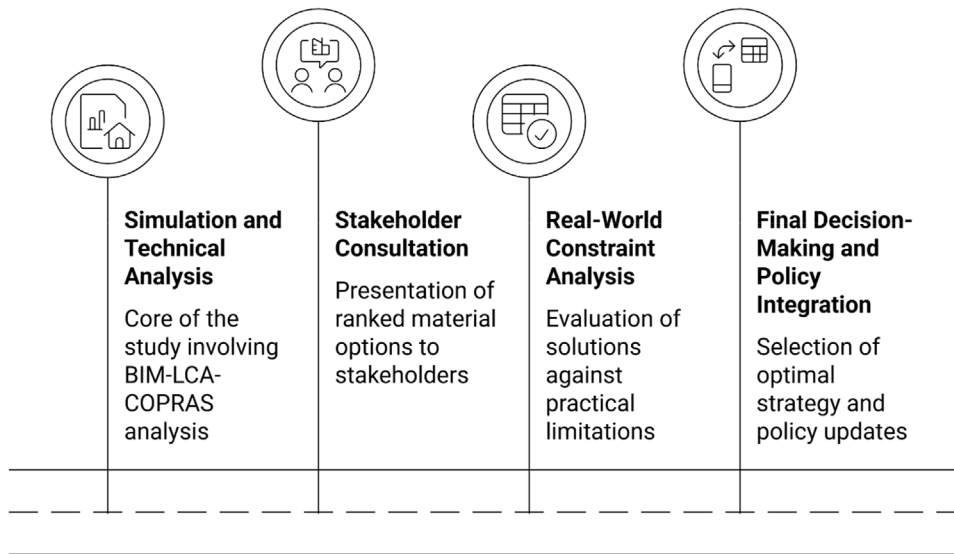


Fig. 18. A synthesis of the strengths and limitations of sustainable reconstruction, based on the case of Shiraz.

a significant hurdle. For this study, where primary data on factors such as precise wall compositions or material thermal properties were unavailable, assumptions were made based on expert consultation and typological data from similar historic structures in the region. This, while necessary for the simulation, introduces a degree of uncertainty.

Future research should seek to manage this uncertainty more formally. Advanced approaches could include: (1) Sensitivity Analysis, wherein uncertain input parameters (such as U-values, air infiltration rates) are systematically varied to understand their impact on the final energy and LCA outcomes, thereby identifying the most critical data points for precise measurement; and (2) The implementation of a Level

of Confidence (LoC) or Level of Accuracy (LoA) attribute for elements within the BIM model. This practice, which is emerging in advanced HBIM literature, allows users to transparently distinguish between data verified through field surveys, data from archival documents, and assumed data, providing a clear record of data provenance and quality.

4.3. Conclusion and recommendations

This study successfully developed and validated a systematic, integrated framework for sustainable material selection in the restoration of historic urban fabrics, addressing a critical need at the intersection

of heritage conservation and sustainable development. Through a case study in Shiraz, the application of a hybrid BIM-LCA-COPRAS methodology demonstrated that a data-driven approach can lead to significant gains in environmental performance—achieving approximately a 25 % reduction in annual energy consumption and a 30 % reduction in carbon emissions—while rigorously and transparently balancing these objectives with the imperative of maintaining historical authenticity.

The broader implication of this research extends beyond these quantitative findings. The study substantiates the value of a systematic, multi-objective approach in a field often guided by qualitative or single-criterion decision-making. By providing a repeatable workflow, this research offers a powerful tool for transitioning heritage conservation from a purely preservationist practice to an active contributor to the sustainable development goals of cities, particularly in the developing world.

Based on these findings, we offer the following recommendations for policy and practice:

- **For Policymakers and Urban Planners:** We strongly recommend the integration of BIM-LCA frameworks into urban heritage management plans and building codes. To facilitate this, governments should develop targeted financial incentives, such as tax credits and grants, to offset the initial costs of sustainable materials and advanced analyses, as detailed in Section 3.
- **For Heritage Professionals and Architects:** We advocate for the adoption of MCDM tools like COPRAS to structure and document the complex decision-making process in material selection. This not only leads to better outcomes but also establishes a more transparent and defensible rationale for interventions in sensitive heritage contexts.

Finally, by bridging the gap between advanced digital tools and the nuanced requirements of historical preservation, this research offers a practical and adaptable framework that can guide stakeholders toward more informed, efficient, and sustainable restoration practices. Future research should focus on extending the application of this framework to diverse climatic and cultural contexts and further developing methods for the formal management of data uncertainty in HBIM to enhance the reliability and generalizability of this critical approach.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr Amirhossein Balali, the corresponding author, is a Member of Early Career Editorial Board of Sustainable Cities and Society Advances.

CRedit authorship contribution statement

Alireza Valipour: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mehdi Salman Manesh:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amirhossein Balali:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

Data will be made available on request.

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