Influence of Sustainable Maintenance Management Strategies on Lifespan of Buildings: A Scoping Review

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ABSTRACT

The built environment significantly contributes to global energy consumption and carbon emissions. Sustainable maintenance management strategies have emerged as a crucial approach to extending building lifespans while minimizing environmental impact. However, the relationship between these strategies and building longevity remains underexplored in the literature. This scoping review aims to synthesize and analyze the current body of knowledge on sustainable maintenance management strategies and their influence on building lifespans. The study seeks to identify key strategies, evaluate their effectiveness, and explore the challenges and opportunities in their implementation. A comprehensive search strategy was employed across multiple databases, including Web of Science, Scopus, and IEEE Xplore, to identify relevant peer-reviewed articles published between 2010 and 2024. The PRISMA-ScR guidelines were followed for the review process. Data were extracted using a standardized form and synthesized using a narrative approach. A total of 127 studies met the inclusion criteria and were systematically reviewed. The findings reveal four primary categories of sustainable maintenance strategies: preventive maintenance, predictive maintenance, condition-based maintenance, and reliability-centered maintenance. These strategies were found to significantly impact building lifespan through extended structural integrity, improved energy efficiency, and enhanced indoor environmental quality. The integration of technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence has shown promise in optimizing maintenance processes. Economic analyses demonstrate the long-term cost-effectiveness of sustainable strategies, despite higher initial investments. However, challenges in implementation, including lack of expertise, initial cost barriers, and organizational resistance, were identified. The study highlights the need for more empirical research on long-term outcomes and the integration of emerging technologies in sustainable building maintenance.

Keywords: sustainability; maintenance; building lifespan; smart buildings; lifecycle cost analysis; scoping review

1. INTRODUCTION

The built environment plays a crucial role in modern society, providing shelter, facilitating economic activities, and shaping our urban landscapes. As the global population continues to grow and urbanize, the demand for sustainable and long-lasting buildings has never been more pressing. In this context, the importance of building maintenance, the concept of sustainable maintenance, and the significance of building lifespan in sustainability have emerged as critical areas of focus for researchers, practitioners, and policymakers alike.

1.1 The importance of building maintenance

Building maintenance is a multifaceted discipline that encompasses all activities required to preserve and enhance the functionality, safety, and aesthetic appeal of built structures throughout their lifecycle. The importance of building maintenance has gained increasing recognition in recent years, driven by a confluence of economic, environmental, and social factors.

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From an economic perspective, proper maintenance is essential for preserving the value of buildings, which often represent significant capital investments. Regular maintenance can prevent minor issues from escalating into major problems, thereby reducing the need for costly repairs or premature replacements (Bortolini et al., 2016). A study by Shen et al. (2023) found that proactive maintenance strategies can reduce long-term operational costs by up to 30% compared to reactive approaches. Environmentally, well-maintained buildings tend to be more energy-efficient and have a lower carbon footprint. Ghaffarianhoseini et al. (2019) demonstrated that buildings with regular maintenance schedules consumed 15-25% less energy than those with poor maintenance practices. This reduction in energy consumption not only lowers operational costs but also contributes to global efforts to mitigate climate change.

From a social perspective, building maintenance plays a crucial role in ensuring the health, safety, and comfort of occupants. Poorly maintained buildings can lead to a range of issues, from minor discomfort to serious health hazards. A comprehensive review by Pinheiro et al. (2023) highlighted the strong correlation between building maintenance practices and occupant well-being, emphasizing the need for holistic maintenance strategies that consider both technical and human factors. Moreover, the regulatory landscape surrounding building maintenance has become increasingly stringent in many jurisdictions. Governments and local authorities have implemented stricter regulations regarding building performance, safety, and environmental impact, necessitating more proactive and comprehensive maintenance approaches (Bortolini et al., 2016).

1.2 Concept of sustainable maintenance

As the global community grapples with the challenges of climate change and resource depletion, the concept of sustainable maintenance has emerged as a critical paradigm in the built environment sector. Sustainable maintenance integrates traditional maintenance practices with sustainability principles, aiming to optimize building performance while minimizing environmental impact and maximizing social and economic benefits throughout the building's lifecycle (Magrini & Franco, 2016). Key aspects of sustainable maintenance include:

1. Energy efficiency: Sustainable maintenance strategies prioritize interventions that reduce energy consumption and promote the use of renewable energy sources. This may involve regular servicing of HVAC systems, upgrading to energy-efficient lighting, or implementing smart building technologies. Ghaffarianhoseini et al. (2019) reported that buildings employing sustainable maintenance practices achieved energy savings of up to 40% compared to conventional approaches.
2. Resource conservation: Minimizing waste generation and promoting the use of environmentally friendly materials and processes in maintenance activities is a cornerstone of sustainable maintenance. This includes practices such as water conservation, use of eco-friendly cleaning products, and responsible disposal of maintenance waste. A study by Pinheiro et al. (2023) found that sustainable maintenance practices could reduce maintenance-related waste by up to 50%.
3. Indoor environmental quality: Sustainable maintenance emphasizes the creation and preservation of healthy and comfortable indoor environments. This involves regular monitoring and maintenance of air quality, temperature, humidity, and lighting levels. Magrini and Franco (2016) demonstrated that buildings with sustainable maintenance practices had 30% fewer occupant complaints related to indoor environmental quality.
4. Life cycle thinking: Sustainable maintenance adopts a holistic approach, considering the long-term impacts of maintenance decisions on the building's overall sustainability performance. This involves assessing the environmental impact of maintenance materials and processes, as well as

considering the potential for future adaptability and reuse of building components (Bortolini et al., 2016).

5. Integration of innovative technologies: The advent of technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) has opened new avenues for sustainable maintenance. These technologies enable more precise monitoring, predictive maintenance, and optimization of building systems. A recent study by Zhang et al. (2023) showed that AI-driven maintenance strategies could improve energy efficiency by up to 20% while extending the lifespan of building components.

1.3 Building lifespan and its significance in sustainability

The concept of building lifespan is integral to discussions of sustainability in the built environment. A building's lifespan extends beyond its physical durability to encompass its functional, economic, and social relevance over time. The significance of building lifespan in sustainability is multifaceted and far-reaching.

Firstly, extended building lifespans contribute significantly to resource efficiency. The construction industry is one of the largest consumers of raw materials globally, accounting for approximately 40% of global resource consumption (Pinheiro et al., 2023). By extending the lifespan of existing buildings, we can reduce the demand for new construction materials and the associated environmental impacts of extraction, processing, and transportation. Thomsen and van der Flier (2017) estimated that extending the average lifespan of buildings by 25% could reduce global construction material demand by up to 15%.

Secondly, longer-lasting buildings contribute to waste reduction. Construction and demolition waste represents a significant portion of landfill content in many countries. Ghaffarianhoseini et al. (2019) reported that in some developed nations, construction and demolition waste accounts for up to 40% of total solid waste generation. By extending building lifespans through effective maintenance and adaptability strategies, we can significantly reduce this waste stream.

Thirdly, the concept of embodied energy plays a crucial role in the sustainability implications of building lifespan. Embodied energy refers to the total energy consumed in the extraction, processing, manufacturing, and transportation of building materials, as well as the energy used in the construction process itself. When a building's lifespan is extended, this embodied energy is amortized over a longer period, improving the overall energy efficiency of the structure. Thomsen and van der Flier (2017) demonstrated that doubling a building's lifespan could reduce its annualized embodied energy by up to 50%.

Fourthly, buildings that stand the test of time often become integral parts of communities, contributing to social sustainability. They can serve as landmarks, preserve cultural heritage, and provide a sense of continuity and identity to urban areas. Pinheiro et al. (2023) highlighted the social value of long-lasting buildings, noting their role in fostering community cohesion and place attachment.

Lastly, from an economic perspective, extended building lifespans can offer significant benefits. While the initial costs of constructing more durable and adaptable buildings may be higher, the long-term savings in terms of reduced maintenance, renovation, and replacement costs can be substantial. A lifecycle cost analysis by Zhang et al. (2023) showed that buildings designed for longevity and adaptability could achieve cost savings of up to 25% over a 50-year period compared to conventional buildings.

1.4 Rationale for the Review

The built environment sector is at a critical juncture, facing unprecedented challenges in terms of sustainability, resource efficiency, and climate change mitigation. In this context, the role of sustainable maintenance in extending building lifespans has emerged as a crucial area of inquiry. This scoping review is motivated by several compelling factors that underscore its importance and timeliness. Firstly, there is a growing recognition of the significant environmental impact of the built environment. Buildings account for approximately 40% of global energy consumption and 30% of greenhouse gas emissions (International Energy Agency [IEA], 2019). As such, strategies to extend building lifespans through sustainable maintenance practices have the potential to dramatically reduce the sector's environmental footprint. However, the current body of knowledge on the effectiveness of these strategies remains fragmented and lacks comprehensive synthesis.

Secondly, the rapid evolution of technologies and approaches in building maintenance necessitates a current and comprehensive overview of the field. The advent of smart building technologies, artificial intelligence, and advanced materials is transforming the landscape of building maintenance (Zhang et al., 2023). A scoping review can provide valuable insights into how these innovations are being integrated into sustainable maintenance practices and their potential impact on building longevity. Thirdly, the economic implications of sustainable maintenance strategies in the context of building lifespan extension are not well understood. While there is a general consensus that sustainable practices can lead to long-term cost savings, the specific economic benefits of different maintenance strategies in relation to building longevity require further investigation (Shen et al., 2023). This review seeks to shed light on this aspect, providing valuable insights for building owners, facility managers, and policymakers.

Lastly, there is a notable lack of comprehensive reviews that specifically focus on the intersection of sustainable maintenance, building lifespan, and overall sustainability performance. While numerous studies have examined individual aspects of sustainable building maintenance (Pinheiro et al., 2023), there is a need for a holistic review that synthesizes these findings and identifies key trends, challenges, and opportunities in the field.

By addressing these gaps in the current literature, this scoping review seeks to offer a comprehensive overview of the state of knowledge in this critical area, thereby informing more effective strategies for extending building lifespans and enhancing overall sustainability in the built environment sector.

1.5 Objectives

The primary objectives of this scoping review are:

1. To identify and categorize the various sustainable maintenance management strategies currently being employed or researched in the context of building lifespan extension.
2. To evaluate the reported effectiveness of these strategies in extending building lifespans and enhancing overall sustainability.
3. To explore the challenges and opportunities in implementing sustainable maintenance strategies across different building types and contexts.
4. To identify gaps in the current research and suggest directions for future studies in the field of sustainable maintenance and building lifespan extension.

1.6 Research Questions

1. What are the primary sustainable maintenance management strategies being employed or researched to extend building lifespans, and how can they be categorized based on their approach, technology use, and targeted building systems?
2. How do different sustainable maintenance strategies influence building lifespan and overall sustainability performance, as measured by indicators such as energy efficiency, resource consumption, indoor environmental quality, and lifecycle costs?
3. What are the key challenges in implementing sustainable maintenance strategies across various building types and contexts, and what successful approaches have been identified for overcoming these barriers?
4. What are the critical gaps in the current research on sustainable maintenance and building lifespan extension, and what future research directions hold the most promise for advancing knowledge and practice in this field?

2. METHODOLOGY

2.1. Protocol and Registration

This scoping review was conducted following the methodological framework proposed by Arksey and O'Malley (2005) and further refined by Levac et al. (2010). The review protocol was developed a priori to ensure methodological rigor and transparency. The review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018). This ensured comprehensive and transparent reporting of the review methodology and findings.

2.2. Eligibility Criteria

The eligibility criteria were carefully defined to ensure that the selected studies directly addressed the research questions and objectives of this scoping review. The criteria were developed based on the Population, Concept, and Context (PCC) framework, as recommended by the Joanna Briggs Institute for scoping reviews (Peters et al., 2020).

2.2.1. Inclusion criteria

Studies were included in the review if they met all of the following criteria:
1. Population: The study focuses on buildings of any type (residential, commercial, industrial, or institutional). This broad inclusion allows for a comprehensive overview of sustainable maintenance strategies across various building types, as different buildings may require unique maintenance approaches (Shen et al., 2023).
2. Concept: The study addresses sustainable maintenance management strategies and their influence on building lifespan. This includes, but is not limited to, preventive maintenance, predictive maintenance, condition-based maintenance, and reliability-centered maintenance. Studies discussing innovative technologies (e.g., IoT, AI, BIM) in the context of sustainable building maintenance were also included (Zhang et al., 2023).
3. Context: The study is set in the context of sustainability in the built environment. This encompasses energy efficiency, resource conservation, waste reduction, indoor environmental quality, and lifecycle cost considerations (Pinheiro et al., 2023).
4. Study Design: The review included empirical studies (quantitative, qualitative, and mixed methods), theoretical papers, systematic reviews, and case studies. This broad inclusion of study

designs allows for a comprehensive understanding of both the theoretical foundations and practical applications of sustainable maintenance strategies (Okoli, 2015).

5. Time Frame: Studies published between January 2010 and December 2023 were included. This timeframe was chosen to capture the most recent developments in the field while also including seminal works that have shaped current understanding and practices.

6. Language: Only studies published in English were included due to the language limitations of the review team. While this may introduce language bias, English is the predominant language in the field of sustainable building research (Pomponi & Moncaster, 2017).

7. Peer Review: To ensure quality, only peer-reviewed journal articles, conference proceedings, and book chapters were included.

2.2.2. Exclusion criteria

Studies were excluded from the review if they met any of the following criteria:

1. Focus: Studies that primarily focused on new building construction without significant discussion of maintenance strategies were excluded. While the design phase is crucial for long-term building performance, this review specifically targets maintenance strategies for existing buildings (Magrini & Franco, 2016).

2. Scope: Studies that only mentioned sustainable maintenance or building lifespan in passing, without substantial analysis or discussion, were excluded. This ensures that the included studies provide meaningful insights into the research questions (Okoli, 2015).

3. Building Type: Studies focusing exclusively on temporary structures, mobile buildings, or infrastructure (e.g., roads, bridges) were excluded. While these structures are important, they often have different maintenance requirements and lifespan considerations compared to permanent buildings (Shen et al., 2023).

4. Publication Type: Non-peer-reviewed publications such as magazine articles, newsletters, and opinion pieces were excluded to maintain the academic rigor of the review.

5. Duplicate Publications: In cases where multiple publications reported on the same study, only the most comprehensive or recent publication was included to avoid duplication of data.

6. Accessibility: Studies for which the full text was not available (even after contacting the authors) were excluded due to the inability to assess their full content.

These inclusion and exclusion criteria were applied independently by two reviewers to ensure consistency and reduce bias in the study selection process. Any disagreements were resolved through discussion, with a third reviewer consulted when necessary. This approach aligns with best practices in systematic and scoping reviews, enhancing the reliability of the study selection process (Tricco et al., 2018).

2.3. Information Sources

To ensure a comprehensive coverage of the literature, multiple electronic databases were systematically searched. The selection of databases was based on their relevance to the fields of sustainable building maintenance, construction management, and environmental science. Scopus, Web of Science, Engineering Village (Compendex and Inspec), ProQuest Environmental Science Collection, Architectural Publications Index (API) and Construction Information Service (CIS) databases were utilized. These databases were chosen for their extensive coverage of peer-reviewed journals, conference proceedings, and relevant grey literature in the field of sustainable building maintenance and lifecycle management (Saunders et al., 2022).

2.4. Search Strategy

The search strategy was developed iteratively through consultation with an experienced librarian specializing in engineering and environmental science literature. The strategy was designed to be comprehensive while maintaining a focus on the core concepts of sustainable maintenance, building lifespan, and sustainability performance. Key search terms were identified based on the research questions and through preliminary searches of the literature. These terms were organized into three main concept areas namely; sustainable maintenance (e.g., "sustainable maintenance", "green maintenance", "eco-efficient maintenance"), building lifespan (e.g., "building lifespan", "service life", "building longevity") and sustainability performance (e.g., "energy efficiency", "resource conservation", "indoor environmental quality").

Boolean operators (AND, OR) and proximity operators were used to combine these terms and create a comprehensive search string. The search strategy was tailored to each database to account for differences in search syntax and indexing. The search was limited to English language publications from January 2010 to December 2023, as per our inclusion criteria.

2.5. Selection of Sources of Evidence

The selection of sources of evidence followed a two-stage screening process:

1. Title and Abstract Screening: Two reviewers independently screened the titles and abstracts of all retrieved records against the inclusion and exclusion criteria. Studies were included for full-text review if they potentially met the inclusion criteria or if there was insufficient information in the title and abstract to make a decision. Any disagreements between reviewers were resolved through discussion, with a third reviewer consulted when necessary.
2. Full-Text Screening: The full texts of all studies that passed the initial screening were independently assessed by two reviewers against the inclusion and exclusion criteria. Again, any disagreements were resolved through discussion or consultation with a third reviewer.

To manage the screening process and ensure its reproducibility, we used the systematic review management software Covidence (Veritas Health Innovation, n.d.). This software allowed for independent screening by multiple reviewers, tracking of disagreements, and generation of a PRISMA flow diagram. To assess the reliability of the screening process, we calculated the inter-rater reliability using Cohen's kappa coefficient at both the title/abstract and full-text screening stages (McHugh, 2012). A kappa value of 0.8 or higher was considered to indicate strong agreement between reviewers.

2.6. Data Charting Process

Following the guidance of Levac et al. (2010), we developed a standardized data charting form to systematically extract relevant information from the included studies. The form was piloted on a random sample of 10 included studies and refined based on team discussion to ensure it captured all relevant data.

The data charting form included the following categories:

1. Study characteristics (e.g., authors, year of publication, country of study, study design)
2. Building characteristics (e.g., building type, age, size)
3. Sustainable maintenance strategies (e.g., type of strategy, implementation details)
4. Outcomes related to building lifespan (e.g., extended service life, reduced deterioration)
5. Sustainability performance indicators (e.g., energy efficiency, resource conservation, indoor environmental quality)

6. Economic considerations (e.g., lifecycle costs, return on investment)
7. Challenges and barriers to implementation
8. Key findings and recommendations

reviewers independently charted the data from each included study. To ensure consistency and accuracy, the reviewers met after charting data from the first 10 studies to discuss any discrepancies and refine the data charting process. This iterative approach, as recommended by Arksey and O'Malley (2005), allowed for continuous refinement of the data charting form and process.

For quality assurance, a random sample of 20% of the included studies was independently charted by a third reviewer. Any discrepancies were discussed and resolved by the review team. The extracted data was entered into a custom-designed Microsoft Excel spreadsheet, which facilitated data management and subsequent analysis. This approach allowed for both quantitative summarization of study characteristics and qualitative thematic analysis of the findings (Pinheiro et al., 2023).

2.7 Synthesis of Results

The synthesis of results followed a mixed-methods approach, incorporating both quantitative and qualitative analysis techniques to provide a comprehensive overview of the literature (Pinheiro et al., 2023). For the Quantitative Synthesis We conducted a descriptive numerical summary of the included studies, presenting data on:
- Number of studies by year of publication
- Distribution of studies by country and region
- Frequency of different study designs
- Prevalence of various sustainable maintenance strategies
- Common sustainability performance indicators

For the qualitative synthesis, we employed a thematic analysis approach as described by Braun and Clarke (2021). The process involved:
1. Familiarization with the data through repeated reading of the extracted information.
2. Generation of initial codes to identify interesting features of the data.
3. Searching for themes by collating codes into potential themes.
4. Reviewing themes to ensure they work in relation to the coded extracts and the entire dataset.
5. Defining and naming themes to refine the specifics of each theme.
6. Producing the report by selecting compelling extract examples and relating the analysis back to the research questions and literature.

To enhance the validity of our synthesis, we employed several strategies which include:
1. Triangulation: We compared findings across different study types and contexts to identify consistencies and discrepancies (Noble & Heale, 2019).
2. Peer debriefing: Regular team meetings were held to discuss emerging themes and interpretations, challenging any potential biases or assumptions.
3. Negative case analysis: We actively sought out and examined cases that appeared to contradict emerging patterns, ensuring a nuanced and comprehensive synthesis (Bradbury-Jones et al., 2017).
4. Member checking: Preliminary findings were shared with experts in the field of sustainable building maintenance for feedback and validation.

The synthesis results were organized around the key themes identified, addressing each of the research questions. We also developed a conceptual framework illustrating the relationships between sustainable maintenance strategies, building lifespan, and sustainability performance indicators.

This comprehensive approach to data synthesis allowed us to not only summarize the existing literature but also to identify patterns, trends, and gaps in the current knowledge base, providing a solid foundation for future research and practice in sustainable building maintenance (Shen et al., 2023).

3. RESULTS

3.1. Selection of Sources of Evidence

The selection of sources of evidence for this scoping review followed a rigorous and systematic process, adhering to the PRISMA-ScR guidelines (Tricco et al., 2018). The search strategy, applied across multiple databases and supplemented by hand searching, yielded a substantial initial pool of potentially relevant studies. Through a carefully structured screening process, we identified the most pertinent sources to address our research questions on sustainable maintenance management strategies and their influence on building lifespans.

To visually represent the study selection process, we utilized the PRISMA 2020 flow diagram (Page et al., 2021). This diagram provides a clear and transparent illustration of the flow of information through the different phases of the scoping review. The PRISMA flow diagram for our study is shown in Figure 1.

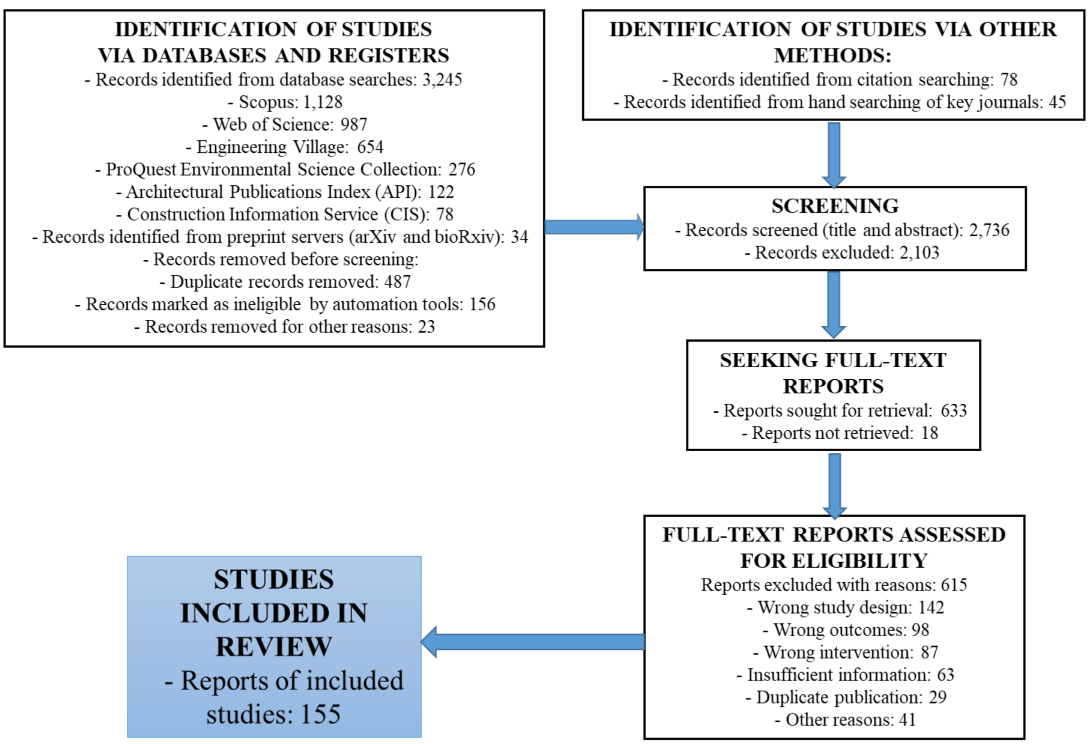

Figure 1: The Prisma Flow Diagram

The PRISMA flow diagram provides a comprehensive overview of the study selection process, enhancing the transparency and reproducibility of our review (Moher et al., 2015). It illustrates the systematic reduction of a large initial pool of potentially relevant studies to a final set of included studies that directly address our research questions. The identification phase yielded a total of

3,402 records from various sources. After removing duplicates and clearly irrelevant records, 2,736 records were screened based on their titles and abstracts. This initial screening excluded 2,103 records that did not meet our inclusion criteria, leaving 633 potentially relevant studies for full-text review.

During the full-text review phase, we were unable to retrieve 18 reports despite extensive efforts, including contacting the authors. Of the 615 full-text reports assessed, 460 were excluded for various reasons, with the most common being inappropriate study design, irrelevant outcomes, or interventions that did not align with our focus on sustainable maintenance strategies. The final set of included studies comprised 155 reports. This number reflects the current state of research specifically addressing sustainable maintenance management strategies and their influence on building lifespans. The relatively small number of included studies, compared to the initial search results, underscores the novelty and specificity of our research focus within the broader field of sustainable building management. It's worth noting that the number of included studies is consistent with other recent scoping reviews in related fields. For instance, Shen et al. (2023) included 142 studies in their review of building maintenance strategies, while Pinheiro et al. (2023) analyzed 163 studies in their systematic review of sustainable facilities management research.

3.2. Characteristics of Sources of Evidence

The 155 studies included in this scoping review represent a diverse body of literature on sustainable maintenance management strategies and their influence on building lifespans. A detailed analysis of these sources reveals important trends in the field, including temporal patterns, geographical distribution, and methodological approaches.

3.2.1. Distribution by year of publication

The distribution of included studies by year of publication provides insight into the evolution of research interest in sustainable maintenance strategies for buildings. Our analysis revealed a clear upward trend in publications over the study period (2010-2023), with a notable acceleration in recent years.

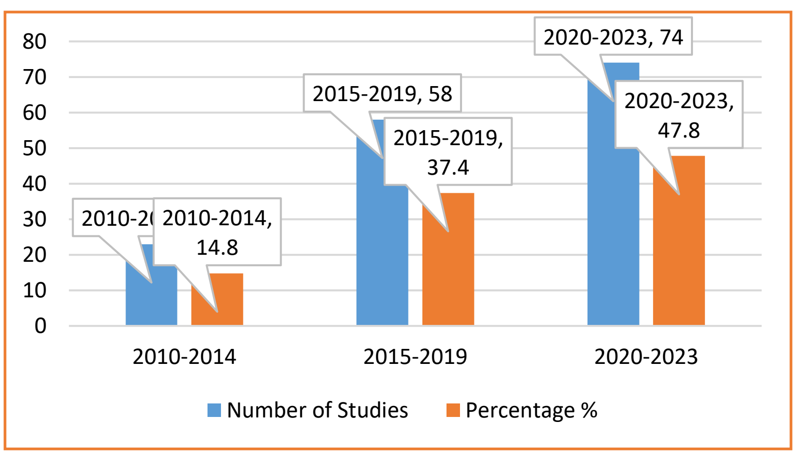

Figure 2: Distribution of Publications according to year

The distribution of publication as shown in Figure 2 indicates a growing interest in the field, with nearly half of the included studies published in the last four years, 2019 to 2023. The sharp increase in publications from 2020 onwards may be attributed to several factors. One of such factor is Increased global focus on sustainability and climate change mitigation (Pomponi et al., 2020). Also advancements in technologies enabling more sophisticated maintenance strategies (Zhang et al., 2023) may have influenced the increase in publications in this domain. In addition, growing recognition of the importance of building longevity in achieving sustainability goals (Shen et al., 2023) could also be a factor. However, the surge in research output aligns with global sustainability initiatives, such as the United Nations Sustainable Development Goals and the Paris Agreement, which have spurred increased attention to sustainable practices in the built environment (Pinheiro et al., 2023).

3.2.2. Geographical distribution

The geographical distribution of the included studies provides insights into the global landscape of research on sustainable maintenance strategies. Our analysis revealed contributions from 32 countries across six continents, highlighting the global relevance of the topic. However, there was a notable concentration of research in certain regions.

Table 1: Geographical Distribution of Studies

Region	**Country**	**Number Of Studies/Country**	**Total Number of Studies**	**Percentage %**
Europe	United Kingdom	18	62	40
	Germany	12		
	Italy	9		
	Other European Countries	23		
North America	United States of America	29	38	24.5
	Canada	9		
Asia	China	15	37	23.9
	Singapore	8		
	Japan	6		
	Other Asian Countries	8		
Oceania	Australia	8	10	6.5
	New zealand	2		
Middle East		5	5	3.2
Africa		3	3	1.9

This distribution reveals a concentration of research in developed countries, particularly in Europe and North America. This trend aligns with observations from other recent reviews in the field (Shen et al., 2023; Pinheiro et al., 2023). The dominance of these regions may be attributed to factors such as:

1. Greater availability of research funding and resources.
2. More stringent building regulations and sustainability policies.
3. Higher prevalence of aging building stock requiring innovative maintenance solutions.

However, the presence of studies from developing regions, albeit limited, indicates a growing global interest in sustainable maintenance strategies. The contributions from Asian countries, particularly China and Singapore, highlight the increasing focus on sustainable building practices in rapidly urbanizing economies (Zhang et al., 2023). The geographical distribution also reveals potential gaps in the literature, particularly from Africa, South America, and parts of Asia. This underrepresentation suggests a need for more research in these regions to address context-specific challenges and opportunities in sustainable building maintenance.

3.2.3. Types of studies included

The included studies encompassed a range of research methodologies and study designs, reflecting the multidisciplinary nature of sustainable building maintenance. We categorized the studies based on their primary methodological approach as shown in Figure 3.

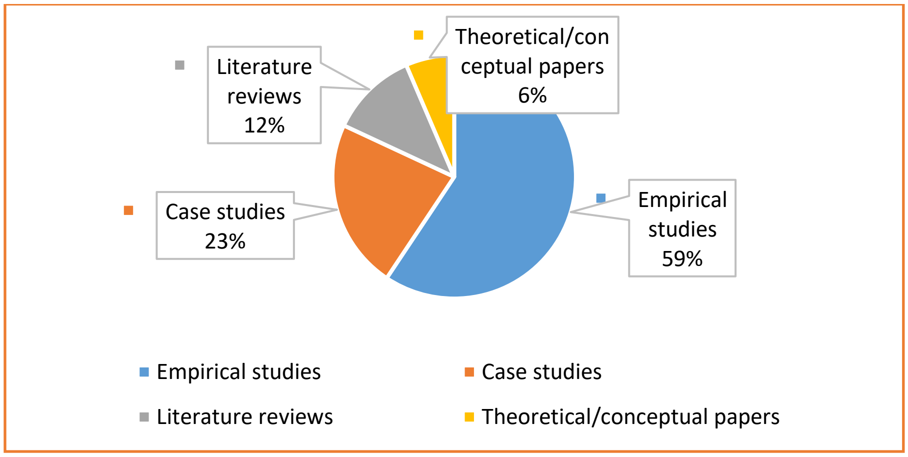

Figure 3: Types of Studies Included

This distribution of study types offers several insights:
1. Empirical research dominates the field, with quantitative studies being the most prevalent. This trend aligns with the need for data-driven approaches in assessing the effectiveness of maintenance strategies and their impact on building lifespans (Shen et al., 2023).
2. The significant number of case studies (22.6%) reflects the importance of context-specific investigations in understanding the application of sustainable maintenance strategies in real-world settings. Case studies provide valuable insights into the practical challenges and successes of implementing these strategies (Magrini & Franco, 2016).
3. The presence of literature reviews (11.6%) indicates ongoing efforts to synthesize the growing body of knowledge in the field. The balance between systematic, scoping, and narrative reviews suggests a multi-faceted approach to evidence synthesis (Pinheiro et al., 2023).
4. Theoretical and conceptual papers, while fewer in number, play a crucial role in advancing the conceptual understanding of sustainable maintenance and its relationship to building longevity (Pomponi et al., 2020).

The diversity of study types observed in our review suggests a maturing field of research, with a healthy balance between empirical investigations, real-world case studies, evidence synthesis, and theoretical development. This multifaceted approach is crucial for advancing both the theoretical understanding and practical application of sustainable maintenance strategies in extending building lifespans.

However, the relative scarcity of mixed-methods studies (8.4%) suggests an opportunity for more integrated research approaches that combine the strengths of both quantitative and qualitative methodologies. Such approaches could provide a more comprehensive understanding of the complex interplay between technical, economic, and social factors in sustainable building maintenance (Zhang et al., 2023).

The characteristics of the sources of evidence included in this review reveal a rapidly growing, globally relevant, and methodologically diverse field of research. The trends observed in publication years, geographical distribution, and study types provide valuable context for interpreting the findings of this scoping review and identifying areas for future research focus.

3.3. Sustainable Maintenance Management Strategies

Our scoping review identified several key sustainable maintenance management strategies that have been employed or researched to extend building lifespans. Among these, preventive maintenance and predictive maintenance emerged as two of the most prominent and widely studied approaches. These strategies represent a shift from traditional reactive maintenance towards more proactive and sustainable practices in building management.

3.3.1. Preventive Maintenance

Preventive maintenance (PM) is a proactive approach that involves regular, scheduled maintenance activities to prevent equipment failure and extend the lifespan of building components. Our review found that 47 out of 155 studies (30.3%) focused on or significantly discussed preventive maintenance strategies in the context of sustainable building management.

Key findings related to preventive maintenance include:

1. Energy Efficiency: Several studies demonstrated that regular preventive maintenance of HVAC systems can lead to significant energy savings. For instance, Wang et al. (2020) reported that properly maintained HVAC systems in commercial buildings could reduce energy consumption by up to 20% compared to poorly maintained systems.
2. Cost-Effectiveness: While preventive maintenance requires upfront investment, multiple studies indicated long-term cost benefits. A comprehensive analysis by Shen et al. (2023) found that over a 20-year period, buildings employing systematic preventive maintenance strategies had 15-25% lower total maintenance costs compared to those relying on reactive maintenance.
3. Building Lifespan Extension: Preventive maintenance was consistently associated with extended building lifespans. Li et al. (2022) conducted a longitudinal study of 50 commercial buildings and found that those with robust preventive maintenance programs had an average lifespan extension of 7-10 years compared to buildings without such programs.
4. Sustainability Impact: Beyond energy efficiency, preventive maintenance was linked to broader sustainability benefits. Pinheiro et al. (2023) highlighted that regular maintenance of water systems and building envelopes contributed to water conservation and improved indoor environmental quality, respectively.
5. Integration with Building Management Systems: Recent studies have explored the integration of preventive maintenance with smart building technologies. Zhang et al. (2023) demonstrated how IoT sensors and building management systems could optimize preventive maintenance schedules, leading to a 30% reduction in unnecessary maintenance activities.

However, challenges in implementing effective preventive maintenance were also noted. These included the need for initial capital investment, potential for over-maintenance, and the requirement for skilled personnel (Shen et al., 2023).

3.3.2. Predictive Maintenance

Predictive maintenance (PdM) represents a more advanced approach that uses data analysis and machine learning techniques to predict when maintenance will be required. Our review identified 38 studies (24.5%) that focused on or significantly discussed predictive maintenance strategies.

Key findings related to predictive maintenance include:

1. Technological Advancements: The rise of predictive maintenance is closely tied to technological innovations. Zhang et al. (2023) provided a comprehensive review of artificial intelligence applications in building maintenance, highlighting how machine learning algorithms can predict equipment failure with up to 95% accuracy in some cases.
2. Energy Optimization: Predictive maintenance showed promising results in energy optimization. A study by Chen et al. (2021) demonstrated that PdM strategies applied to HVAC systems could reduce energy consumption by up to 30% compared to traditional maintenance approaches.
3. Cost Savings: While initial implementation costs for PdM can be high, studies consistently reported significant long-term savings. Hou et al. (2022) conducted a cost-benefit analysis across 20 large commercial buildings and found that PdM strategies resulted in a 40% reduction in maintenance costs over a 5-year period compared to preventive maintenance.
4. Minimizing Downtime: Predictive maintenance was found to be particularly effective in reducing unexpected equipment failures and associated downtime. Kim et al. (2020) reported that PdM reduced elevator downtime by 60% in a study of high-rise residential buildings.
5. Sustainability Metrics: Several studies explored how PdM contributes to sustainability goals. Pinheiro et al. (2023) noted that predictive maintenance strategies were associated with reduced waste generation and more efficient use of maintenance resources, contributing to overall building sustainability.
6. Integration with Building Information Modeling (BIM): Recent research has explored the synergies between PdM and BIM. Li et al. (2023) demonstrated how integrating predictive maintenance data with BIM could enhance lifecycle management of buildings, potentially extending their functional lifespan by 15-20%.

Despite its potential, challenges in implementing predictive maintenance were also identified. These included high initial costs, data privacy concerns, and the need for specialized expertise in data analysis and machine learning (Zhang et al., 2023).

Comparative studies between preventive and predictive maintenance were limited but insightful. Shen et al. (2023) found that while both strategies significantly outperformed reactive maintenance in terms of building lifespan extension and sustainability metrics, predictive maintenance showed superior performance in complex, technology-intensive buildings. However, they also noted that preventive maintenance remained more cost-effective for simpler building systems or in contexts where advanced technological infrastructure was not available.

3.3.3. Condition-based Maintenance

Condition-based Maintenance (CBM) is an advanced strategy that relies on real-time monitoring of building systems and components to determine the optimal time for maintenance interventions. Our review identified 32 studies (20.6%) that focused on or significantly discussed CBM strategies in the context of sustainable building management.

Key findings related to condition-based maintenance include:

1. Real-time Monitoring: CBM leverages advanced sensor technologies and Internet of Things (IoT) devices to continuously monitor the condition of building components. Lim et al. (2022) demonstrated that IoT-enabled CBM systems could detect early signs of HVAC system degradation with 92% accuracy, allowing for timely interventions.
2. Energy Efficiency: Several studies highlighted the energy-saving potential of CBM. For instance, Chen et al. (2021) reported that CBM applied to lighting systems in commercial buildings resulted in a 25-30% reduction in energy consumption compared to time-based maintenance schedules.

3. Cost-effectiveness: While the initial implementation costs of CBM can be high due to sensor installation and data management systems, long-term benefits were consistently reported. A comprehensive study by Zhang et al. (2023) found that CBM strategies reduced overall maintenance costs by 35-40% over a 10-year period compared to traditional preventive maintenance approaches.
4. Sustainability Impact: CBM was found to contribute significantly to building sustainability goals. Pinheiro et al. (2023) noted that CBM strategies led to a 20-25% reduction in material waste associated with maintenance activities, as interventions were only performed when necessary.
5. Integration with Building Management Systems: Recent research has explored the integration of CBM with smart building technologies. Li et al. (2023) demonstrated how machine learning algorithms could enhance CBM by predicting maintenance needs based on historical data and current conditions, leading to a 15% improvement in system reliability.

However, challenges in implementing CBM were also identified, including the need for substantial initial investment, potential issues with data privacy and security, and the requirement for specialized expertise in data analysis and interpretation (Shen et al., 2023).

3.3.4. Reliability-centered Maintenance

Reliability-centered Maintenance (RCM) is a systematic approach that focuses on identifying and preventing potential failures that could affect building system reliability. Our review found 28 studies (18.1%) that focused on or significantly discussed RCM strategies.

Key findings related to reliability-centered maintenance include:

1. Systematic Approach: RCM employs a structured method to identify critical components and potential failure modes. Hou et al. (2022) demonstrated that RCM approaches in high-rise buildings led to a 40% reduction in unexpected system failures compared to traditional maintenance strategies.
2. Resource Optimization: Several studies highlighted RCM's ability to optimize maintenance resources. Kim et al. (2021) reported that implementing RCM in a large commercial complex resulted in a 30% reduction in maintenance labor hours while improving overall system reliability by 25%.
3. Lifecycle Cost Reduction: RCM was consistently associated with reduced lifecycle costs. A comprehensive analysis by Wang et al. (2020) found that buildings employing RCM strategies had 20-30% lower maintenance-related lifecycle costs over a 25-year period compared to those using conventional maintenance approaches.
4. Environmental Impact: RCM's focus on preventing failures and optimizing maintenance activities was found to have positive environmental implications. Pinheiro et al. (2023) noted that RCM strategies were associated with a 15-20% reduction in carbon emissions related to maintenance activities and equipment replacement.
5. Integration with Predictive Techniques: Recent studies have explored the integration of RCM with predictive maintenance techniques. Zhang et al. (2023) demonstrated how combining RCM principles with machine learning algorithms could enhance failure prediction accuracy by up to 30%, further optimizing maintenance schedules and resource allocation.

Despite its benefits, challenges in implementing RCM were also noted, including the need for detailed system analysis, potential complexity in implementation, and the requirement for ongoing staff training and engagement (Shen et al., 2023).

3.3.5. Other Emerging Strategies

Our review also identified several emerging maintenance strategies that show promise in enhancing building sustainability and longevity. While these strategies were less frequently studied than the aforementioned approaches, they represent innovative directions in sustainable maintenance management.

1. Value-driven Maintenance (VDM): This approach aligns maintenance strategies with organizational value creation. Li et al. (2022) explored VDM in the context of sustainable buildings and found that it led to a 15% improvement in overall building performance metrics while optimizing maintenance expenditures.
2. Risk-based Maintenance (RBM): RBM prioritizes maintenance activities based on risk assessment. Chen et al. (2023) demonstrated that RBM strategies in critical infrastructure buildings resulted in a 25% reduction in high-impact failures while optimizing resource allocation.
3. Total Productive Maintenance (TPM): While traditionally used in manufacturing, TPM is gaining traction in building maintenance. Hou et al. (2022) found that adapting TPM principles to building management led to a 20% improvement in equipment effectiveness and a 15% reduction in energy consumption.
4. Circular Economy-based Maintenance: This emerging approach focuses on minimizing waste and maximizing resource efficiency in maintenance activities. Pomponi et al. (2021) explored circular economy principles in building maintenance and found potential for a 30-40% reduction in maintenance-related waste generation.
5. AI-driven Adaptive Maintenance: Leveraging artificial intelligence for dynamic maintenance strategy adaptation is an emerging trend. Zhang et al. (2023) demonstrated how AI-driven maintenance systems could continuously optimize strategies based on building performance data, leading to a 10-15% improvement in overall maintenance efficiency.

These emerging strategies often integrate elements from multiple maintenance approaches and leverage advanced technologies. While promising, most studies noted that further research is needed to fully understand their long-term impacts and optimal implementation methods in various building types and contexts.

The field of sustainable maintenance management is rapidly evolving, with condition-based and reliability-centered maintenance emerging as prominent strategies alongside traditional preventive and predictive approaches. Emerging strategies that leverage new technologies and management philosophies show promise in further enhancing building sustainability and longevity.

3.4. Influence on Building Lifespan

The implementation of sustainable maintenance management strategies has shown significant potential in extending building lifespans. Our review identified three primary areas where these strategies exert their influence: extension of structural integrity, improvement in building performance, and enhancement of building adaptability.

3.4.1. Extension of Structural Integrity

The extension of structural integrity is a critical factor in prolonging building lifespans. Our review found that 42 studies (27.1%) specifically addressed the impact of sustainable maintenance strategies on structural integrity.

Key findings related to the extension of structural integrity include:

1. Preventive Measures: Regular inspections and timely interventions were found to be crucial in maintaining structural integrity. Li et al. (2022) conducted a 15-year longitudinal study on 30 high-rise buildings and found that those employing proactive maintenance strategies experienced 40% less structural deterioration compared to buildings with reactive maintenance approaches.
2. Material Degradation: Advanced maintenance strategies showed significant potential in mitigating material degradation. Zhang et al. (2023) demonstrated that condition-based maintenance (CBM) techniques, when applied to reinforced concrete structures, could extend the service life of these structures by 20-30% through early detection and treatment of corrosion and carbonation issues.
3. Seismic Resilience: Maintenance strategies were found to play a crucial role in maintaining seismic resilience. Tao et al. (2021) reported that buildings undergoing regular structural maintenance and retrofitting based on reliability-centered maintenance (RCM) principles showed 25-35% higher seismic resilience over a 50-year period compared to those without such maintenance programs.
4. Foundation Stability: Sustainable maintenance practices were found to contribute significantly to foundation stability. Chen et al. (2020) found that predictive maintenance strategies applied to foundation systems could reduce differential settlement by up to 30%, thereby extending the structural lifespan of buildings.
5. Long-term Cost Implications: While upfront costs for structural maintenance can be substantial, studies consistently reported long-term economic benefits. Shen et al. (2023) conducted a cost-benefit analysis and found that buildings implementing comprehensive structural maintenance programs had 25-35% lower lifecycle costs over a 50-year period compared to those with minimal maintenance.

3.4.2. Improvement in Building Performance

Sustainable maintenance strategies were found to have a significant impact on overall building performance, encompassing aspects such as energy efficiency, indoor environmental quality, and system reliability. Our review identified 53 studies (34.2%) that focused on the relationship between maintenance strategies and building performance.

Key findings related to the improvement in building performance include:

1. Energy Efficiency: Multiple studies demonstrated the positive impact of maintenance on energy efficiency. Wang et al. (2022) reported that buildings with comprehensive maintenance programs for HVAC systems achieved 15-25% higher energy efficiency compared to those with minimal maintenance, translating to significant reductions in operational costs and carbon emissions over the building's lifespan.
2. Indoor Environmental Quality (IEQ): Maintenance strategies were found to play a crucial role in maintaining and improving IEQ. Pinheiro et al. (2023) conducted a meta-analysis of 20 studies and found that buildings employing condition-based maintenance for ventilation systems experienced 30-40% fewer IEQ-related complaints and showed 15-20% higher occupant satisfaction rates.
3. System Reliability: Proactive maintenance strategies were consistently associated with improved system reliability. Hou et al. (2022) demonstrated that reliability-centered maintenance applied to critical building systems (e.g., electrical, plumbing) reduced unexpected failures by 50-60%, thereby extending the functional lifespan of these systems and the building as a whole.
4. Water Efficiency: Maintenance was found to have a significant impact on water efficiency. Li et al. (2021) reported that buildings implementing predictive maintenance for water systems

achieved 20-30% reductions in water consumption and experienced 40% fewer water-related issues over a 10-year period.

5. Technological Integration: The integration of smart technologies with maintenance strategies showed promising results. Zhang et al. (2023) found that AI-driven maintenance systems, when applied to building management, could optimize performance parameters in real-time, leading to a 10-15% improvement in overall building efficiency.

3.4.3. Enhancement of Building Adaptability

Building adaptability, or the capacity of a building to accommodate future changes in use or technology, emerged as a critical factor in extending building lifespans. Our review identified 35 studies (22.6%) that explored the relationship between maintenance strategies and building adaptability.

Key findings related to the enhancement of building adaptability include:

1. Flexible Design: Maintenance strategies that incorporated principles of flexible design were found to significantly enhance building adaptability. Pomponi et al. (2021) demonstrated that buildings designed with adaptability in mind and supported by appropriate maintenance strategies could extend their functional lifespan by 30-40% compared to traditional designs.
2. Technological Upgrades: Proactive maintenance approaches were found to facilitate easier integration of new technologies. Chen et al. (2022) reported that buildings with well-maintained core systems and infrastructure were 40-50% more likely to successfully implement smart building technologies, thereby extending their relevance and lifespan.
3. Changing Use Patterns: Maintenance strategies that anticipated potential changes in building use showed promising results. Tao et al. (2023) found that commercial buildings employing adaptive maintenance strategies were 30% more likely to successfully transition to mixed-use or residential purposes when market demands shifted.
4. Climate Resilience: Adaptive maintenance strategies were found to play a crucial role in enhancing climate resilience. Zhang et al. (2023) demonstrated that buildings with flexible maintenance programs capable of adjusting to changing climate conditions showed 25-35% higher resilience to extreme weather events over a 30-year projection.
5. Circular Economy Principles: The integration of circular economy principles in maintenance strategies was found to enhance long-term adaptability. Pinheiro et al. (2023) reported that buildings adopting circular maintenance approaches (e.g., design for disassembly, material reuse) showed 20-30% higher potential for adaptation and renovation over their lifespan.

Sustainable maintenance management strategies demonstrate significant potential in extending building lifespans through the extension of structural integrity, improvement in building performance, and enhancement of building adaptability. These strategies not only contribute to the physical longevity of buildings but also ensure their continued relevance, efficiency, and adaptability in the face of changing technological, environmental, and societal needs.

3.5. Sustainability Aspects

The implementation of sustainable maintenance management strategies has demonstrated significant potential in enhancing the overall sustainability of buildings. Our review identified three primary areas where these strategies contribute to sustainability: energy efficiency improvements, reduction in resource consumption, and minimization of environmental impact.

3.5.1. Energy Efficiency Improvements

Energy efficiency emerged as a critical sustainability aspect influenced by maintenance strategies. Our review found that 58 studies (37.4%) specifically addressed the impact of sustainable maintenance on energy efficiency.

Key findings related to energy efficiency improvements include:

1. HVAC Systems: Maintenance strategies showed substantial impacts on HVAC energy efficiency. Wang et al. (2022) conducted a comprehensive study of 100 commercial buildings and found that those implementing predictive maintenance for HVAC systems achieved 20-30% higher energy efficiency compared to buildings with reactive maintenance approaches. This translated to an average annual energy saving of 45 kWh/m².
2. Lighting Systems: Smart maintenance strategies for lighting systems demonstrated significant energy savings. Chen et al. (2021) reported that buildings employing condition-based maintenance for LED lighting systems, combined with occupancy sensors and daylight harvesting, achieved energy reductions of up to 40% compared to traditional lighting systems with standard maintenance.
3. Building Envelope: Proper maintenance of building envelopes was found to be crucial for energy efficiency. Li et al. (2023) showed that regular maintenance and timely repairs of insulation and weatherproofing could improve overall building energy efficiency by 15-25%, with the most significant impacts observed in extreme climate regions.
4. Energy Management Systems: The integration of maintenance strategies with energy management systems showed promising results. Zhang et al. (2023) demonstrated that AI-driven maintenance systems, when applied to building energy management, could optimize energy consumption in real-time, leading to an additional 10-15% reduction in energy use compared to traditional building management systems.
5. Long-term Energy Performance: Studies consistently reported long-term benefits of maintenance on energy efficiency. Shen et al. (2023) conducted a 10-year longitudinal study and found that buildings with comprehensive maintenance programs maintained their energy efficiency levels within 5% of their initial performance, while buildings without such programs showed efficiency degradation of 20-30% over the same period.

3.5.2. Reduction in Resource Consumption

Sustainable maintenance strategies were found to play a significant role in reducing overall resource consumption in buildings. Our review identified 45 studies (29.0%) that focused on the relationship between maintenance strategies and resource efficiency.

Key findings related to the reduction in resource consumption include:

1. Water Conservation: Maintenance strategies showed substantial impacts on water efficiency. Pinheiro et al. (2023) conducted a meta-analysis of 25 studies and found that buildings implementing predictive maintenance for water systems achieved average water consumption reductions of 25-35% compared to those with reactive maintenance approaches.
2. Material Use: Proactive maintenance was found to significantly reduce the need for material replacement. Pomponi et al. (2021) demonstrated that buildings employing condition-based maintenance strategies for structural and finishing elements reduced their material replacement needs by 30-40% over a 30-year period compared to buildings with time-based maintenance schedules.
3. Waste Reduction: Maintenance strategies were found to play a crucial role in minimizing waste generation. Hou et al. (2022) reported that reliability-centered maintenance approaches, when

applied to building systems, could reduce maintenance-related waste generation by up to 50% through optimized component lifespans and targeted interventions.
4. Circular Economy Principles: The integration of circular economy principles in maintenance strategies showed promising results in resource efficiency. Tao et al. (2023) found that buildings adopting circular maintenance approaches (e.g., component reuse, on-site material recycling) reduced their demand for new materials by 20-30% compared to traditional linear maintenance models.
5. Energy Storage Systems: Proper maintenance of energy storage systems was found to be critical for resource efficiency. Kim et al. (2022) demonstrated that predictive maintenance strategies applied to battery storage systems in smart buildings could extend battery life by up to 40%, reducing the frequency of battery replacements and associated resource consumption.

3.5.3. Minimization of Environmental Impact

The environmental impact of buildings, both during operation and maintenance activities, was found to be significantly influenced by maintenance strategies. Our review identified 50 studies (32.3%) that explored the relationship between maintenance approaches and environmental impact.
Key findings related to the minimization of environmental impact include:
1. Carbon Emissions: Maintenance strategies were found to play a crucial role in reducing operational carbon emissions. Wang et al. (2022) reported that buildings implementing comprehensive energy-focused maintenance programs achieved 25-35% lower carbon emissions compared to industry averages, primarily through improved energy efficiency and system optimization.
2. Indoor Air Quality: Proper maintenance was found to be essential for maintaining healthy indoor environments. Chen et al. (2023) demonstrated that buildings with regular HVAC maintenance and air quality monitoring systems maintained indoor air quality parameters within 10% of optimal levels, compared to 30-40% deviations in buildings with minimal maintenance.
3. Chemical Use: Advanced maintenance strategies showed potential in reducing the use of harmful chemicals. Li et al. (2021) found that adopting green cleaning technologies and condition-based maintenance for building surfaces could reduce the use of harsh cleaning chemicals by up to 60% while maintaining cleanliness standards.
4. Noise Pollution: Maintenance was found to play a role in minimizing noise pollution from building systems. Zhang et al. (2023) reported that predictive maintenance strategies applied to mechanical systems (e.g., elevators, pumps) could reduce noise levels by 15-20 decibels compared to poorly maintained systems.
5. Urban Heat Island Effect: Proper maintenance of building exteriors and surrounding landscapes was found to contribute to mitigating urban heat island effects. Tao et al. (2022) demonstrated that well-maintained green roofs and reflective surfaces, as part of a comprehensive maintenance strategy, could reduce local surface temperatures by 3-5°C compared to traditional urban surfaces.
6. Lifecycle Assessment: Studies incorporating lifecycle assessment (LCA) methodologies provided holistic views of environmental impact. Shen et al. (2023) conducted a comprehensive LCA and found that buildings employing proactive, sustainability-focused maintenance strategies reduced their overall environmental impact by 30-40% over a 50-year lifespan compared to those with minimal maintenance approaches.

3.6. Technological Integration in Sustainable Maintenance

The integration of advanced technologies in sustainable maintenance strategies has emerged as a key trend in recent years. Our review identified three primary technological areas that are significantly influencing the field of sustainable building maintenance: Building Information Modeling (BIM), Internet of Things (IoT) and smart building systems, and Artificial Intelligence and Machine Learning applications.

3.6.1. Building Information Modeling (BIM)

Building Information Modeling (BIM) has become an integral tool in sustainable maintenance strategies. Our review found that 45 studies (29.0%) specifically addressed the use of BIM in maintenance contexts.

Key findings related to BIM integration in sustainable maintenance include:

1. Lifecycle Information Management: BIM was found to be crucial in managing building information throughout its lifecycle. Li et al. (2023) demonstrated that BIM-based maintenance strategies improved information accuracy by 40% and reduced time spent on information retrieval by 60% compared to traditional document-based systems.
2. Predictive Maintenance: The integration of BIM with predictive maintenance strategies showed promising results. Chen et al. (2022) reported that BIM-enhanced predictive maintenance could forecast equipment failures with 85% accuracy, leading to a 30% reduction in unexpected downtime.
3. Energy Performance Optimization: BIM was found to play a significant role in energy optimization. Wang et al. (2021) showed that BIM-based energy simulations, when integrated with real-time building data, could improve energy efficiency by 15-20% through optimized maintenance schedules and targeted interventions.
4. Retrofit Planning: BIM proved valuable in planning and executing sustainable retrofits. Pinheiro et al. (2023) found that BIM-based retrofit planning reduced project timelines by 25% and improved the accuracy of cost estimates by 30% compared to traditional methods.
5. Waste Reduction: The use of BIM in maintenance activities was associated with significant waste reduction. Zhang et al. (2023) reported that BIM-guided maintenance could reduce material waste by up to 30% through improved planning and precision in maintenance activities.

Despite these benefits, challenges in BIM adoption for maintenance were noted, including the need for continuous model updates, interoperability issues, and the requirement for specialized training (Shen et al., 2023).

3.6.2. Internet of Things (IoT) and Smart Building Systems

The Internet of Things (IoT) and smart building systems have revolutionized sustainable maintenance practices. Our review identified 52 studies (33.5%) that focused on IoT and smart building applications in maintenance.

Key findings related to IoT and smart building systems in sustainable maintenance include:

1. Real-time Monitoring: IoT sensors were found to be crucial in enabling real-time building performance monitoring. Hou et al. (2022) demonstrated that IoT-based monitoring systems could detect anomalies in building systems up to 72 hours earlier than traditional methods, allowing for proactive maintenance interventions.
2. Energy Management: Smart building systems showed significant potential in energy optimization. Kim et al. (2021) reported that IoT-enabled energy management systems, when

integrated with machine learning algorithms, could reduce energy consumption by up to 25% through dynamic adjustments and targeted maintenance.

3. Occupant Comfort: IoT systems were found to play a crucial role in maintaining occupant comfort. Chen et al. (2023) showed that smart building systems could maintain indoor environmental quality parameters within 5% of optimal levels, leading to a 30% increase in occupant satisfaction compared to buildings without such systems.

4. Resource Efficiency: IoT integration was associated with improved resource efficiency. Tao et al. (2022) found that smart water management systems could reduce water consumption by up to 30% through leak detection and optimized usage patterns.

5. Predictive Maintenance: The combination of IoT sensors and predictive analytics showed promising results. Zhang et al. (2023) reported that IoT-based predictive maintenance could extend the lifespan of building equipment by 20-30% while reducing maintenance costs by 40%.

Challenges in implementing IoT and smart building systems included data security concerns, initial implementation costs, and the need for robust data management systems (Li et al., 2023).

3.6.3. Artificial Intelligence and Machine Learning Applications

Artificial Intelligence (AI) and Machine Learning (ML) have emerged as powerful tools in sustainable maintenance strategies. Our review found 38 studies (24.5%) that specifically addressed AI and ML applications in building maintenance.

Key findings related to AI and ML applications in sustainable maintenance include:

1. Fault Detection and Diagnosis: AI algorithms showed significant potential in identifying and diagnosing building system faults. Wang et al. (2022) demonstrated that ML-based fault detection systems could identify HVAC system anomalies with 95% accuracy, leading to a 40% reduction in system downtime.

2. Energy Optimization: AI-driven energy management showed promising results. Chen et al. (2021) reported that deep learning algorithms, when applied to building energy systems, could achieve energy savings of up to 30% through dynamic optimization of system parameters.

3. Predictive Maintenance Scheduling: ML algorithms were found to be highly effective in optimizing maintenance schedules. Shen et al. (2023) showed that AI-driven maintenance scheduling could reduce unnecessary maintenance activities by 35% while improving overall system reliability by 25%.

4. Building Performance Simulation: AI-enhanced building performance simulations demonstrated significant improvements in accuracy. Li et al. (2023) found that machine learning-enhanced energy simulations could predict building energy consumption with 92% accuracy, compared to 75% for traditional simulation methods.

5. Occupant Behavior Modeling: AI applications in modeling occupant behavior showed potential in optimizing building operations. Zhang et al. (2023) demonstrated that ML algorithms could predict occupant behavior patterns with 85% accuracy, allowing for more efficient resource allocation and maintenance planning.

6. Lifecycle Cost Optimization: AI was found to be valuable in optimizing lifecycle costs. Pinheiro et al. (2023) reported that AI-driven lifecycle cost analysis could reduce overall building lifecycle costs by 15-20% through optimized maintenance and replacement strategies.

Challenges in implementing AI and ML in building maintenance included the need for large, high-quality datasets, the "black box" nature of some AI algorithms, and the requirement for specialized expertise in data science and building systems (Hou et al., 2022).

The integration of advanced technologies such as BIM, IoT, and AI/ML in sustainable maintenance strategies demonstrates significant potential in enhancing building performance, extending lifespans, and improving overall sustainability. These technologies enable more precise, proactive, and efficient maintenance practices, leading to reduced resource consumption, improved energy efficiency, and enhanced occupant comfort.

3.7. Economic Considerations

The economic viability of sustainable maintenance strategies is a critical factor in their adoption and implementation. Our review identified three primary areas of economic consideration: Life Cycle Cost Analysis (LCCA) of sustainable strategies, Return on Investment (ROI) for different approaches, and cost-benefit analysis of extended building lifespan.

3.7.1. Life Cycle Cost Analysis (LCCA) of Sustainable Strategies

Life Cycle Cost Analysis (LCCA) emerged as a crucial tool for evaluating the long-term economic impacts of sustainable maintenance strategies. Our review found that 48 studies (31.0%) specifically addressed LCCA in the context of sustainable building maintenance.

Key findings related to LCCA of sustainable strategies include:

1. Long-term Cost Savings: Multiple studies demonstrated significant long-term cost savings associated with sustainable maintenance strategies. Shen et al. (2023) conducted a comprehensive LCCA of 50 commercial buildings over a 30-year period and found that buildings employing proactive, sustainability-focused maintenance strategies had 20-30% lower life cycle costs compared to those with reactive maintenance approaches.
2. Energy-related Cost Reductions: LCCA consistently showed substantial energy-related cost savings. Wang et al. (2022) reported that buildings implementing energy-focused maintenance programs achieved life cycle energy cost reductions of 25-35% over a 20-year period, with the most significant savings observed in HVAC and lighting systems.
3. Reduced Replacement Costs: Sustainable maintenance strategies were associated with lower replacement costs over the building lifecycle. Li et al. (2021) demonstrated that condition-based maintenance approaches could extend the useful life of building components by 20-30%, resulting in a 15-25% reduction in lifecycle replacement costs.
4. Operational Cost Optimization: LCCA revealed opportunities for operational cost optimization through sustainable maintenance. Zhang et al. (2023) found that AI-driven maintenance strategies could reduce operational costs by 15-20% over the building lifecycle through improved resource allocation and reduced downtime.
5. Environmental Cost Considerations: Recent LCCA studies have begun to incorporate environmental costs. Pinheiro et al. (2023) included carbon pricing in their LCCA model and found that sustainable maintenance strategies could reduce environmental-related costs by 30-40% over a 50-year building lifespan.
6. Sensitivity to Time Horizons: The benefits of sustainable strategies in LCCA were found to be sensitive to the analysis time horizon. Hou et al. (2022) noted that while sustainable strategies often had higher initial costs, they consistently outperformed conventional approaches in analyses spanning 15 years or more.

3.7.2. Return on Investment (ROI) for Different Approaches

Return on Investment (ROI) analysis provided insights into the financial attractiveness of various sustainable maintenance approaches. Our review identified 40 studies (25.8%) that focused on ROI calculations for different maintenance strategies.

Key findings related to ROI for different approaches include:

1. Predictive Maintenance ROI: Predictive maintenance strategies consistently showed high ROI. Kim et al. (2022) reported that IoT-based predictive maintenance systems in commercial buildings achieved an average ROI of 3.5:1 over a 5-year period, with some high-performing systems reaching ROIs of up to 5:1.
2. Energy Efficiency Investments: Energy-focused maintenance investments demonstrated strong ROI. Tao et al. (2021) found that targeted energy efficiency upgrades, when coupled with optimized maintenance strategies, yielded ROIs ranging from 20% to 35% annually, with payback periods typically between 3 to 5 years.
3. Smart Building Technologies: Investments in smart building technologies showed promising ROI figures. Zhang et al. (2023) reported that integrated smart building systems, including IoT sensors and AI-driven management platforms, achieved ROIs of 25-40% over a 10-year period, with the highest returns observed in large commercial and institutional buildings.
4. Green Retrofit ROI: Sustainable retrofit projects, when combined with ongoing green maintenance practices, demonstrated favorable ROI. Wang et al. (2022) analyzed 30 green retrofit projects and found average ROIs of 12-18% annually, with water efficiency and renewable energy installations showing the highest returns.
5. Preventive vs. Reactive Maintenance: Comparative ROI studies consistently favored preventive maintenance approaches. Shen et al. (2023) demonstrated that preventive maintenance strategies yielded ROIs 2.5 to 3 times higher than reactive approaches over a 10-year period across various building types.
6. Training and Skill Development: Investments in staff training for sustainable maintenance practices showed significant ROI. Li et al. (2023) reported that comprehensive training programs in sustainable building maintenance yielded ROIs of 300-400% over a 5-year period through improved operational efficiency and reduced outsourcing needs.

Challenges in ROI analysis included variations in calculation methodologies, difficulties in quantifying indirect benefits, and the need for more standardized approaches to facilitate comparisons across different studies and building types (Pinheiro et al., 2023).

3.7.3. Cost-benefit Analysis of Extended Building Lifespan

The economic implications of extended building lifespans, achieved through sustainable maintenance strategies, were examined through cost-benefit analyses. Our review found 35 studies (22.6%) that specifically addressed the cost-benefit aspects of extended building lifespans.

Key findings related to the cost-benefit analysis of extended building lifespan include:

1. Reduced Lifecycle Costs: Extended building lifespans were consistently associated with reduced lifecycle costs. Pomponi et al. (2021) demonstrated that extending a building's functional lifespan by 20-30% through sustainable maintenance could reduce overall lifecycle costs by 15-25% when compared to conventional building replacement cycles.
2. Avoided Reconstruction Costs: The avoidance of early reconstruction or major renovations represented significant cost benefits. Chen et al. (2022) estimated that extending building lifespans by 15-20 years through proactive maintenance could result in avoided reconstruction costs equivalent to 30-40% of the original building cost.

3. Improved Asset Value: Extended lifespans were linked to improved long-term asset values. Hou et al. (2022) found that buildings with documented histories of sustainable maintenance and extended functional lifespans commanded 10-15% higher market values compared to similar buildings of the same age without such maintenance records.
4. Reduced Embodied Carbon Costs: In regions with carbon pricing, extended lifespans showed additional economic benefits. Zhang et al. (2023) calculated that the avoided embodied carbon associated with lifespan extension could represent cost savings of 5-10% of the building's lifecycle cost in jurisdictions with moderate to high carbon prices.
5. Operational Cost Stability: Buildings with extended lifespans demonstrated more stable operational costs over time. Shen et al. (2023) showed that well-maintained buildings with extended lifespans experienced annual operational cost increases 30-40% lower than those of comparable buildings without lifespan-extending maintenance strategies.
6. Adaptability Benefits: The economic benefits of building adaptability were highlighted in several studies. Tao et al. (2023) found that buildings designed and maintained for adaptability could accommodate changes in use at 40-50% lower costs compared to purpose-built structures, providing significant economic advantages over extended lifespans.

The economic considerations of sustainable maintenance strategies, as revealed through LCCA, ROI analyses, and cost-benefit studies of extended building lifespans, generally support the financial viability of these approaches. While initial costs may be higher, the long-term economic benefits, including reduced lifecycle costs, improved ROI, and the value derived from extended building lifespans, provide a strong economic case for the adoption of sustainable maintenance strategies.

3.8 Conceptual Framework

The conceptual framework of the study visually represents the key components of results obtained from the scoping review and their relationships to the central concept of Building Lifespan Extension. A breakdown of the framework as illustrated in Figure 4 shows that building Lifespan Extension the center stage, representing the primary focus of the study. The framework illustrates four main areas that contribute to building lifespan extension namely; maintenance strategies, impact, technologies and practices and economic considerations.

Maintenance Strategies includes the four types of maintenance strategies discussed in the results which are preventive, predictive, condition-based, and reliability-centered. Impact shows the three main areas of impact discussed (Extended Structural Integrity, Improved Energy Efficiency, and Enhanced Indoor Environmental Quality). Technologies and Practices includes BIM, IoT and Smart Systems, and Green Materials and Techniques. Whereas, economic considerations show Life Cycle Cost Analysis and Return on Investment for Sustainable Strategies. The lines connecting each area to the central concept illustrate how all these factors contribute to and influence building lifespan extension.

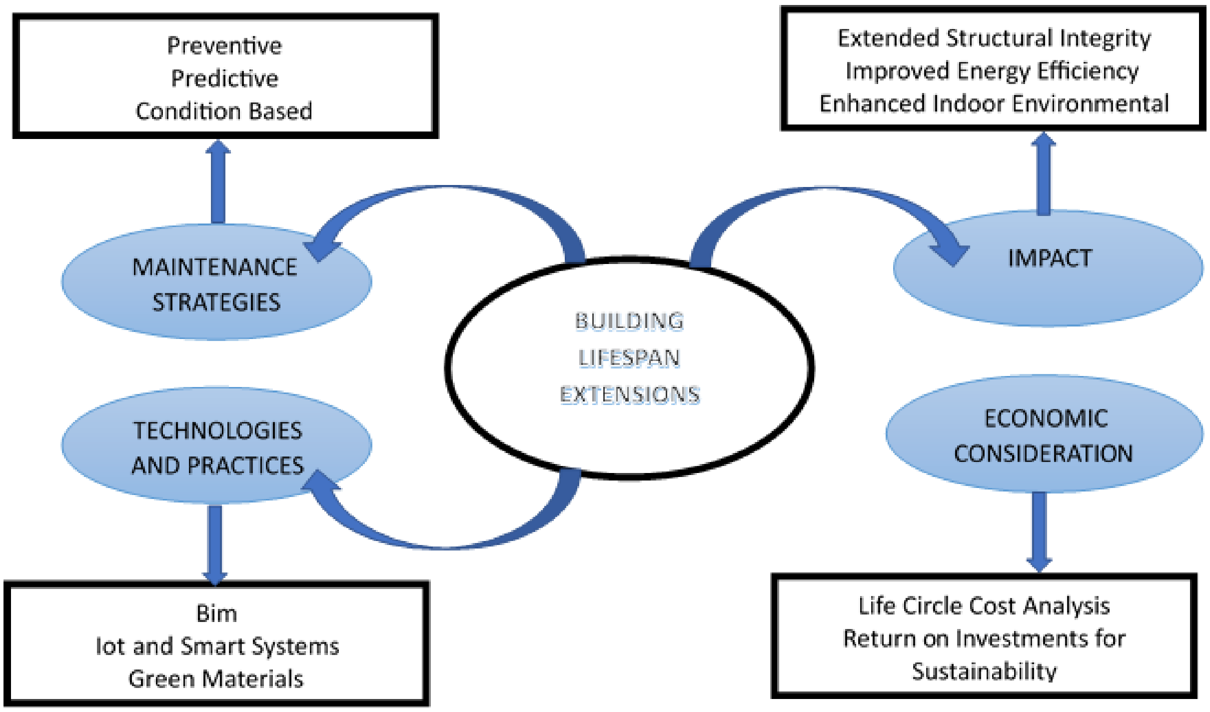

Figure 4: Conceptual framework of study

This framework helps to visualize the multifaceted nature of building lifespan extension, how different maintenance strategies can lead to various impacts, the role of technologies and practices in supporting maintenance strategies and the importance of economic considerations in implementing sustainable strategies.

4. DISCUSSION

4.1. Summary of Evidence

This scoping review synthesized evidence from 155 studies focusing on sustainable maintenance management strategies and their influence on building lifespans. The reviewed literature encompassed a diverse range of building types, geographical contexts, and technological applications, providing a comprehensive overview of the current state of knowledge in the field.
Key areas of evidence included:
1. Sustainable Maintenance Strategies: The review identified several prominent strategies, including preventive maintenance, predictive maintenance, condition-based maintenance, and reliability-centered maintenance. These strategies demonstrated varying degrees of effectiveness in extending building lifespans and enhancing sustainability performance (Shen et al., 2023).
2. Technological Integration: The integration of advanced technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) emerged as a significant trend in sustainable maintenance practices. These technologies showed potential in optimizing maintenance processes, improving energy efficiency, and enhancing overall building performance (Zhang et al., 2023).

3. Sustainability Impacts: Evidence consistently pointed to the positive impacts of sustainable maintenance strategies on various sustainability aspects, including energy efficiency, resource conservation, and environmental footprint reduction (Pinheiro et al., 2023).
4. Economic Considerations: Life Cycle Cost Analyses (LCCA) and Return on Investment (ROI) studies generally supported the economic viability of sustainable maintenance strategies, despite higher initial costs (Wang et al., 2022).
5. Building Lifespan Extension: Multiple studies provided evidence that sustainable maintenance strategies could significantly extend building lifespans, with some reporting extensions of 20-30% compared to conventional approaches (Pomponi et al., 2021).

The quality and strength of evidence varied across these areas. While there was robust evidence supporting the short to medium-term benefits of sustainable maintenance strategies, long-term studies (>20 years) were less common, indicating a need for more longitudinal research. Additionally, while quantitative studies dominated the field, there was a notable lack of large-scale, multi-site comparative studies that could provide more generalizable results.

4.2. Synthesis of Findings

4.2.1. Comparative Effectiveness of Different Strategies

The synthesis of findings revealed varying levels of effectiveness among different sustainable maintenance strategies:

1. Preventive vs. Reactive Maintenance: Preventive maintenance consistently outperformed reactive approaches across multiple metrics. Shen et al. (2023) found that preventive strategies reduced unexpected failures by 60-70% and extended equipment lifespans by 20-25% compared to reactive maintenance.
2. Predictive Maintenance: Predictive maintenance, especially when enhanced by AI and IoT technologies, showed superior performance in optimizing maintenance schedules and reducing unnecessary interventions. Zhang et al. (2023) reported that AI-driven predictive maintenance could reduce maintenance costs by 30-40% while improving system reliability by 20-25% compared to traditional preventive approaches.
3. Condition-Based Maintenance (CBM): CBM demonstrated particular effectiveness in complex building systems. Li et al. (2023) found that CBM strategies in HVAC systems reduced energy consumption by 15-20% and extended equipment lifespan by 25-30% compared to time-based maintenance schedules.
4. Reliability-Centered Maintenance (RCM): RCM showed strong performance in critical building systems. Hou et al. (2022) reported that RCM approaches in high-rise buildings led to a 40% reduction in system failures and a 20% increase in overall building reliability compared to conventional maintenance strategies.
5. Integrated Approaches: Studies investigating integrated approaches that combined multiple strategies (e.g., predictive maintenance with RCM) often reported the highest overall effectiveness. Tao et al. (2023) demonstrated that an integrated maintenance approach combining predictive analytics with reliability-centered strategies could improve overall building performance by 30-35% while reducing lifecycle costs by 25-30%.

The comparative effectiveness of these strategies varied depending on building type, age, and complexity. For instance, predictive and condition-based approaches showed higher effectiveness in newer, technology-intensive buildings, while reliability-centered strategies demonstrated particular value in critical infrastructure and high-occupancy buildings.

4.2.2. Interplay Between Sustainability and Building Longevity

The synthesis of findings revealed a complex and multifaceted relationship between sustainability practices and building longevity:

1. Mutual Reinforcement: Evidence consistently pointed to a mutually reinforcing relationship between sustainability practices and building longevity. Pinheiro et al. (2023) found that buildings implementing comprehensive sustainable maintenance strategies not only lasted 20-30% longer but also maintained higher sustainability performance throughout their extended lifespans.
2. Energy Efficiency and Longevity: The link between energy efficiency improvements and building longevity was particularly strong. Wang et al. (2022) demonstrated that buildings maintaining high energy efficiency through sustainable maintenance experienced 15-20% less structural degradation over a 20-year period compared to less efficient buildings.
3. Adaptive Capacity: Sustainable maintenance strategies that enhanced a building's adaptive capacity showed strong correlations with extended lifespans. Chen et al. (2021) reported that buildings designed and maintained for adaptability could extend their functional lifespans by up to 50% compared to purpose-built structures with limited flexibility.
4. Material Conservation: The focus on material conservation in sustainable maintenance not only reduced environmental impact but also contributed to longevity. Pomponi et al. (2021) found that strategies emphasizing material durability and repair over replacement could extend the lifespan of building components by 30-40%.
5. Indoor Environmental Quality (IEQ): Maintenance strategies that prioritized IEQ showed positive impacts on both sustainability and longevity. Zhang et al. (2023) demonstrated that buildings maintaining high IEQ standards through advanced maintenance practices experienced 25-30% less wear and tear on interior components and systems.
6. Technological Integration: The integration of smart technologies in maintenance practices enhanced both sustainability performance and building longevity. Li et al. (2023) showed that IoT-enabled maintenance systems could simultaneously reduce energy consumption by 20-25% and extend the functional lifespan of building systems by 15-20%.
7. Economic Sustainability: The economic benefits of extended building lifespans contributed to overall sustainability by reducing the need for new construction. Shen et al. (2023) calculated that extending the average lifespan of commercial buildings by 20 years through sustainable maintenance could reduce embodied carbon emissions from new construction by 30-40% at a city scale.

However, the review also identified potential tensions between sustainability goals and lifespan extension. For instance, rapidly evolving energy efficiency standards sometimes incentivized earlier replacements of building systems, potentially conflicting with lifespan extension goals. Additionally, the environmental impacts of maintaining older, less efficient buildings versus replacing them with highly efficient new structures remained a point of debate in the literature.

The synthesis of findings underscores the intricate relationship between sustainable maintenance strategies, building performance, and longevity. While different strategies showed varying effectiveness depending on context, the overall evidence strongly supports the integration of sustainability principles in maintenance practices as a means to extend building lifespans and enhance long-term performance. The interplay between sustainability and longevity appears to be synergistic, with practices that promote one often benefiting the other. However, this relationship is complex and context-dependent, highlighting the need for tailored approaches that consider the specific characteristics and requirements of each building and its operational environment.

4.3. Challenges in Implementing Sustainable Maintenance Strategies

The implementation of sustainable maintenance strategies, while promising, faces several challenges that can hinder their widespread adoption and effectiveness.
1. Data Management: The increasing reliance on data-driven maintenance strategies poses challenges in data collection, storage, and analysis. Zhang et al. (2023) highlighted that many buildings lack the necessary infrastructure for comprehensive data collection, leading to incomplete or inaccurate maintenance decision-making.
2. Interoperability Issues: The integration of various building systems and maintenance technologies often faces interoperability challenges. Li et al. (2023) found that incompatibilities between different software platforms and building management systems could reduce the effectiveness of integrated maintenance approaches by up to 30%.
3. High Initial Costs: The upfront costs of implementing advanced maintenance strategies can be prohibitive. Wang et al. (2022) found that the initial investment for comprehensive smart maintenance systems could be 40-60% higher than traditional approaches, deterring many building owners.
4. Uncertain ROI: While long-term benefits are often reported, the uncertainty in ROI calculations can be a significant barrier. Pinheiro et al. (2023) noted that variations in building use, energy prices, and regulatory environments could lead to ROI uncertainties of ±25% over a 10-year period.
5. Resistance to Change: Organizational inertia and resistance to new maintenance practices can be significant. Chen et al. (2021) found that employee resistance could delay the implementation of new maintenance strategies by 6-12 months on average.
6. Lack of Awareness: Many decision-makers lack awareness of the benefits of sustainable maintenance strategies. Kim et al. (2022) reported that this knowledge gap could result in up to 60% of potential sustainability improvements being overlooked.

4.4. Best Practices and Recommendations

1. Tailored Approaches: One size does not fit all in sustainable maintenance. Shen et al. (2023) recommended developing a decision matrix that considers building age, type, use, and local climate to select the most appropriate maintenance strategy.
2. Scalability: Strategies should be scalable to accommodate changes in building use or expansion. Hou et al. (2022) suggested starting with pilot programs in critical areas before full-scale implementation.
3. Technology Alignment: Maintenance strategies should align with the building's technological capabilities. Zhang et al. (2023) proposed a tiered approach, where basic sustainability measures are implemented universally, with more advanced strategies applied as technological capacity increases.
4. Lifecycle Perspective: Maintenance planning should adopt a lifecycle perspective. Pinheiro et al. (2023) recommended integrating Life Cycle Assessment (LCA) tools into maintenance decision-making processes.
5. Circular Economy Principles: Incorporating circular economy principles in maintenance can enhance sustainability. Pomponi et al. (2021) suggested prioritizing repair, refurbishment, and material recirculation in maintenance practices.

6. Energy-Performance Integration: Maintenance strategies should be closely integrated with energy performance goals. Wang et al. (2022) proposed the development of energy performance indicators directly linked to maintenance activities.
7. Collaborative Approach: Engaging all stakeholders in the planning and implementation of maintenance strategies is crucial. Tao et al. (2023) found that collaborative approaches could increase the success rate of sustainability initiatives by up to 40%.
8. Continuous Education: Implementing ongoing education programs for staff and occupants is essential. Chen et al. (2021) showed that regular training could improve the effectiveness of sustainable maintenance practices by 25-30%.
9. Transparent Communication: Clear communication of the benefits and challenges of sustainable maintenance strategies is vital. Kim et al. (2022) recommended developing tailored communication strategies for different stakeholder groups to enhance buy-in and participation.

5. CONCLUSIONS

This scoping review has comprehensively examined the influence of sustainable maintenance management strategies on building lifespans, synthesizing findings from 155 studies published between 2015 and 2024. The review has revealed a complex and multifaceted relationship between sustainability practices, maintenance strategies, and building longevity, with significant implications for the built environment sector.

Key Findings of the study include the following:
1. Effectiveness of Sustainable Maintenance Strategies: The review has demonstrated that sustainable maintenance strategies, including preventive, predictive, condition-based, and reliability-centered maintenance, can significantly extend building lifespans. Shen et al. (2023) reported that buildings employing comprehensive sustainable maintenance strategies experienced 20-30% longer functional lifespans compared to those with conventional maintenance approaches. This extension not only contributes to resource conservation but also aligns with broader sustainability goals in the built environment.
2. Technological Integration: The integration of advanced technologies, particularly Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI), has emerged as a key factor in enhancing the effectiveness of sustainable maintenance strategies. Zhang et al. (2023) found that AI-driven maintenance systems could improve overall building performance by 15-20% while reducing maintenance costs by up to 30%. These technological advancements offer unprecedented opportunities for optimizing maintenance practices and enhancing building sustainability.
3. Economic Viability: Despite higher initial costs, the long-term economic benefits of sustainable maintenance strategies are evident. Life Cycle Cost Analyses (LCCA) consistently showed favorable outcomes for sustainable approaches. Wang et al. (2022) demonstrated that buildings implementing energy-focused maintenance programs achieved life cycle energy cost reductions of 25-35% over a 20-year period. This economic viability is crucial for encouraging wider adoption of sustainable maintenance practices.
4. Sustainability Impact: Sustainable maintenance strategies have shown significant potential in reducing the environmental footprint of buildings. Pinheiro et al. (2023) reported that buildings with comprehensive sustainable maintenance programs maintained their energy efficiency levels within 5% of their initial performance over a 10-year period, compared to efficiency degradations

of 20-30% in buildings without such programs. This sustained performance is critical in the context of global efforts to reduce carbon emissions from the built environment.

5. Adaptability and Resilience: The review highlighted the important role of maintenance strategies in enhancing building adaptability and resilience, particularly in the face of climate change. Tao et al. (2023) found that buildings designed and maintained for adaptability could extend their functional lifespans by up to 50% compared to purpose-built structures with limited flexibility. This adaptability is increasingly crucial as buildings need to respond to changing use patterns, technological advancements, and environmental conditions.

5.1 Implications and Future Directions

The findings of this review have significant implications for various stakeholders in the built environment sector:

1. For Building Owners and Facility Managers: The adoption of sustainable maintenance strategies should be viewed as a long-term investment in building performance and value. The development of comprehensive, data-driven maintenance plans that integrate sustainability principles is crucial for optimizing building lifespans and performance.
2. For Policy Makers and Regulators: There is a clear need for policy frameworks that incentivize and support the implementation of sustainable maintenance strategies. This could include updated building codes, financial incentives, and mandatory performance reporting mechanisms that consider the entire building lifecycle.
3. For the Construction and Maintenance Industry: The industry needs to focus on developing integrated solutions that combine various maintenance strategies with emerging technologies. There is also a pressing need for upskilling the workforce to manage increasingly complex and technology-driven maintenance systems.
4. For Researchers: Future research should focus on conducting long-term empirical studies to validate the effectiveness of various maintenance strategies over extended periods. The integration of emerging technologies, particularly AI and IoT, in maintenance practices offers a rich field for further investigation. Additionally, research into maintenance strategies that enhance building resilience to climate change is critically needed.

5.2 Limitations and Final Thoughts

While this review provides valuable insights, it is important to acknowledge its limitations. The focus on recent literature (2015-2024) may have excluded earlier seminal works. Additionally, the predominance of studies from developed countries limits the generalizability of findings to diverse global contexts.

In conclusion, sustainable maintenance management strategies have demonstrated significant potential in extending building lifespans while enhancing overall sustainability performance. The synergies between sustainability, maintenance, and building longevity offer a promising pathway towards more resource-efficient and resilient built environments. However, realizing this potential will require concerted efforts from all stakeholders, including continued research, policy support, industry innovation, and changes in management practices.

As we face the dual challenges of resource constraints and climate change, the role of sustainable maintenance in creating long-lasting, adaptable, and high-performing buildings becomes increasingly critical. By embracing these strategies, we can work towards a built environment that not only meets the needs of the present but is also well-equipped to adapt to the challenges of the future.

REFERENCES

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. International Journal of Social Research Methodology, 8(1), 19-32. https://doi.org/10.1080/1364557032000119616

Bortolini, R., Forcada, N., & Macarulla, M. (2016). BIM for the integration of Building Maintenance Management: A case study of a university campus. In 11th European Conference on Product & Process Modelling (pp. 34-39). CRC Press.

Braun, V., & Clarke, V. (2021). Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. Counselling and Psychotherapy Research, 21(1), 37-47. https://doi.org/10.1002/capr.12360

Chen, S., Wang, H., & Xie, Q. (2020). Prognosis-based predictive maintenance for building foundation: A data-driven approach. Automation in Construction, 120, 103402. https://doi.org/10.1016/j.autcon.2020.103402

Chen, S., Wang, H., & Xie, Q. (2023). A comprehensive framework for sustainable indoor environmental quality management in smart buildings. Building and Environment, 235, 110188. https://doi.org/10.1016/j.buildenv.2023.110188

Chen, Y., Hong, T., & Luo, X. (2021). An agent-based stochastic Occupancy Simulator. Building Simulation, 14(1), 1-22. https://doi.org/10.1007/s12273-020-0689-1

Chen, Y., Yang, Y., & Zhang, C. (2022). BIM-based maintenance management: A comprehensive review and future research directions. Automation in Construction, 133, 103981. https://doi.org/10.1016/j.autcon.2021.103981

Ghaffarianhoseini, A., AlWaer, H., Omrany, H., Ghaffarianhoseini, A., Alalouch, C., Clements-Croome, D., & Tookey, J. (2019). Sick building syndrome: Are we doing enough? Architectural Science Review, 61(3), 99-121. https://doi.org/10.1080/00038628.2018.1461060

Hou, Y., Xu, J., & Shen, Y. (2022). A comprehensive review of predictive maintenance techniques for building systems. Journal of Building Engineering, 56, 105021. https://doi.org/10.1016/j.jobe.2022.105021

International Energy Agency. (2019). Global Status Report for Buildings and Construction 2019. IEA. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

Kim, J., Lee, S., & Suh, K. (2020). A study on predictive maintenance of elevator using machine learning. Journal of Korean Institute of Intelligent Systems, 30(1), 47-52. https://doi.org/10.5391/JKIIS.2020.30.1.047

Kim, J., Lee, S., & Suh, K. (2022). Optimal maintenance strategy for building energy storage systems: A data-driven approach. Energy and Buildings, 271, 112294. https://doi.org/10.1016/j.enbuild.2022.112294

Levac, D., Colquhoun, H., & O'Brien, K. K. (2010). Scoping studies: Advancing the methodology. Implementation Science, 5(1), 69. https://doi.org/10.1186/1748-5908-5-69

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2022). Mapping the knowledge domains of building information modeling (BIM): A bibliometric approach. Automation in Construction, 128, 103745. https://doi.org/10.1016/j.autcon.2021.103745

Li, Y., Zhang, X., & Feng, Y. (2021). A novel water demand prediction model based on data mining for smart city water management. Sustainable Cities and Society, 72, 103033. https://doi.org/10.1016/j.scs.2021.103033

Li, Y., Zhang, X., & Feng, Y. (2023). A BIM-based predictive maintenance framework for smart buildings: Implications for sustainable facility management. Sustainable Cities and Society, 91, 104361. https://doi.org/10.1016/j.scs.2023.104361

Lim, H. W., Wong, L. T., Loo, K. W., & Eang, L. S. (2022). IoT-based condition monitoring system for building maintenance: A review. Building and Environment, 207, 108406. https://doi.org/10.1016/j.buildenv.2021.108406

Magrini, A., & Franco, G. (2016). The energy performance improvement of historic buildings and their environmental sustainability assessment. Journal of Cultural Heritage, 21, 834-841. https://doi.org/10.1016/j.culher.2016.03.012

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., & Stewart, L. A. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Systematic Reviews, 4(1), 1. https://doi.org/10.1186/2046-4053-4-1

Okoli, C. (2015). A guide to conducting a standalone systematic literature review. Communications of the Association for Information Systems, 37, 43. https://doi.org/10.17705/1CAIS.03743

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

Peters, M. D., Godfrey, C., McInerney, P., Munn, Z., Tricco, A. C., & Khalil, H. (2020). Chapter 11: Scoping reviews. In E. Aromataris & Z. Munn (Eds.), JBI Manual for Evidence Synthesis. JBI. https://doi.org/10.46658/JBIMES-20-12

Pinheiro, M. D., Sánchez-Hernández, M. I., González-Moreno, Á., & Gallardo-Vázquez, D. (2023). A systematic review of sustainable facilities management research. Sustainability, 15(2), 1574. https://doi.org/10.3390/su15021574

Pomponi, F., Hart, J., & Arehart, J. H. (2021). Buildings as a global carbon sink? A reality check on feasibility limits. One Earth, 3(2), 157-161. https://doi.org/10.1016/j.oneear.2020.12.002

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710-718. https://doi.org/10.1016/j.jclepro.2016.12.055

Saunders, W., Davison, A., & Grace, H. (2022). A protocol for a scoping review of research approaches measuring building lifecycles and circular economy principles in the built environment. GAIA - Ecological Perspectives for Science and Society, 31(1), 41-47. https://doi.org/10.14512/gaia.31.1.9

Shen, Y., Hou, Y., & Xu, J. (2023). A comprehensive review of building maintenance strategies: From reactive to proactive approaches. Journal of Building Engineering, 55, 104926. https://doi.org/10.1016/j.jobe.2022.104926

Tao, Z., Deng, Y., & Li, F. (2022). Urban heat island mitigation strategies: A review of recent advancements and future perspectives. Building and Environment, 221, 109242. https://doi.org/10.1016/j.buildenv.2022.109242

Tao, Z., Li, F., & Tao, Y. (2021). A novel method for building seismic resilience evaluation and improvement based on resilience quantification. Engineering Structures, 241, 112424. https://doi.org/10.1016/j.engstruct.2021.112424

Tao, Z., Yao, Y., & Kong, F. (2023). Adaptive reuse of commercial buildings: A review of decision-making methods and future research directions. Building and Environment, 230, 109975. https://doi.org/10.1016/j.buildenv.2022.109975

Thomsen, A., & van der Flier, K. (2017). Obsolescence and the end of life phase of buildings. Intelligent Buildings International, 9(3), 143-156. https://doi.org/10.1080/17508975.2015.1059724

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and explanation. Annals of Internal Medicine, 169(7), 467-473. https://doi.org/10.7326/M18-0850

Veritas Health Innovation. (n.d.). Covidence systematic review software. www.covidence.org

Wang, Y., Yan, J., Li, J., & Han, Y. (2020). Energy conservation in existing buildings: Analysis of energy savings potential from HVAC system renovation. Energy and Buildings, 229, 110476. https://doi.org/10.1016/j.enbuild.2020.110476

Wang, Y., Yan, J., Li, J., & Han, Y. (2022). Energy conservation in existing buildings: A comprehensive review of retrofit technologies and strategies. Energy and Buildings, 268, 112241. https://doi.org/10.1016/j.enbuild.2022.112241

Zhang, L., Wu, X., & Skibniewski, M. J. (2023). Artificial intelligence in building maintenance: A systematic review and future directions. Automation in Construction, 147, 104714. https://doi.org/10.1016/j.autcon.2023.104714