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Review

Life-Cycle Performance Modeling for Sustainable and Resilient Structures under Structural Degradation: A Systematic Review

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Abstract: The performance of structures degrades during their service life due to deterioration and extreme events, compromising the social development and economic growth of structure and infrastructure systems. Buildings and bridges play a vital role in the socioeconomic development of the built environment. Hence, it is essential to understand existing tools and methodologies to efficiently model the performance of these structures during their life cycle. In this context, this paper aims to explore the existing literature on the life-cycle performance modeling, assessment, enhancement, and decision making of buildings and bridge infrastructure systems under deterioration and extreme events for a sustainable and resilient built environment. The main objectives are to (1) systematically review the existing literature on life-cycle performance modeling of buildings and bridges based on the PRISMA methodology, (2) provide a bibliometric analysis of the systematically assessed journal articles, (3) perform an analysis of the included articles based on the identified components of life-cycle performance modeling, and (4) provide a discussion on the utilized tools, techniques, methodologies, and frameworks for buildings and bridge infrastructure systems in the life-cycle context. The provided systematic literature review and subsequent discussions could provide an overview to the reader regarding the individual components and existing methodologies of life-cycle performance management under deterioration and extreme events.

Keywords: life cycle; performance; reliability; risk; resilience; sustainability; extreme events

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1. Introduction

The sustainable and continued growth of the world economy depends on the performance and proper functioning of the built environment [1]. The built environment comprises components, structures, networks of physical infrastructure, and socioeconomic systems. Physical structures and infrastructure systems are prone to degradation over time due to various degradation mechanisms including environmental deterioration and extreme events. Subsequently, the socioeconomic performance of the built environment can be compromised by deteriorating physical structures and infrastructure systems prone to extreme events [2]. Furthermore, most of the existing structures in the world were built decades ago and have subsequently deteriorated since then due to aging, posing a greater risk to the sustainable socioeconomic development of the built environment [3].

For instance, the ASCE infrastructure report card published in 2021 on a comprehensive assessment of America's infrastructure highlighted that almost 42% of all the existing bridges in the United States are more than 50 years old with 7.5% of the bridges being structurally deficient and requiring maintenance [4]. Additionally, the required infrastructure maintenance investment gap will grow to USD 2.59 trillion over the next decade. This continued under-investment could cost the United States a loss of USD 10 trillion in gross domestic product. Furthermore, according to the World Economic Forum, the infrastructure around the world is failing, and subsequently, the infrastructure investment gap may rise to USD 18 trillion by 2040 [5]. Hence, under budgetary constraints and limited resources, it is essential to understand and adopt the necessary tools, techniques, and methods to efficiently manage the performance of structures during the complete life cycle.

Life-cycle performance management strategies for deteriorating buildings and bridges under extreme events could provide the necessary approaches to assess structural performance and provide tools for planning and executing performance enhancements given budgetary constraints [6]. Furthermore, they could be utilized for decision making in the life-cycle context to select ideal solutions among the range of possible solutions given limited resources, different risk perceptions of decision makers, and uncertainties, and provide overall management of the physical structures and infrastructure systems under degradation mechanisms including deterioration and extreme events [7].

Although numerous studies exist dealing with various aspects of life-cycle performance management given deteriorating mechanisms, no up-to-date systematic review article has been published to address the literature on the life-cycle performance modeling of buildings and bridges under degradation mechanisms [8–12]. Systematic reviews ensure a structured and transparent approach to conducting reviews. It helps in clearly defining eligibility criteria, minimizing selection bias, and ensuring comprehensive literature coverage. Hence, herein, we analyze the existing journal articles based on systematic literature review methodology, i.e., Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [13], perform bibliometric analysis, outline individual components of life-cycle performance modeling, and provide a discussion concerning the included literature related to the components of life-cycle performance management, and the utilized tools, techniques, and methodologies [14–16].

In this context, this paper aims to provide a systematic literature review of the performance modeling of buildings and bridges in the life-cycle context under the degradation mechanisms including environmental deterioration and extreme events. The main contributions of this paper include (1) adopting a PRISMA-based research methodology for the literature search and selection including identification, screening, and eligibility and inclusion criteria, (2) a bibliometric analysis and literature review of the included publications, (3) the identification of individual components of the life-cycle performance modeling of deteriorating buildings and bridges, and (4) providing a discussion on the utilized tools, techniques, methodologies, and frameworks for life-cycle management of deteriorating buildings and bridges.

This paper is divided into seven sections: section (1) provides an introduction, section (2) outlines the adopted PRISMA methodology for the systematic literature review, section (3) discusses research analysis of the systematic literature review, section (4) provides bibliometric analysis of the considered journal articles, section (5) identifies components of the life-cycle performance modeling of buildings and bridges under deterioration and extreme events, section (6) provides discussion on the considered journal articles, and section (7) provides a summary and the conclusions of this paper.

2. Research and Methods

This section provides the methodology for selecting, screening, and extracting relevant research articles for analysis, discussion, and conclusions. A systematic review of the life-cycle performance modeling of buildings and bridge infrastructure systems under degradation mechanisms is performed to identify existing studies that have considered performance assessment, enhancements, and decision-making frameworks, tools, techniques, and strategies in the life-cycle context under degradation mechanisms. A detailed literature review is undertaken to identify the existing studies considering buildings and bridge infrastructure systems. All the papers published from January 2000 to June 2024 are searched and considered for bibliometric analysis. Papers published from January 2015 to June 2024 are included in the state-of-the-art literature review and discussions.

A protocol following the PRISMA flow diagram is developed and adopted before considering the inclusion criteria and conducting the analysis methods. The PRISMA flow diagram consists of four steps, i.e., identification, screening, eligibility, and inclusion. In this paper, the Scopus search engine is selected for searching since it is considered one of the most extensive databases for engineering literature and is considered to perform better than its peers like PubMed, Web of Science, and others [17]. This systematic review was registered with the Open Science Framework (OSF) on 28 August 2024. The registration number is DOI: [10.17605/OSF.IO/7AZFN]. The review objectives and methodology are publicly accessible at https://osf.io/vqtwj (29 August 2024). However, a detailed protocol before the start of the investigation was not established.

The last search was run on the 1 July 2024 on the Scopus search engine and the Google Scholar index. The search is confined to engineering journal articles and the English language is selected for the considered journal articles. The conference papers, book chapters, and others are not considered in this paper. Moreover, the eligibility criteria of the study are limited to the degradation impacts on the structural performance of buildings and bridges with a focus on extreme events, i.e., journal articles focusing on the degradation mechanisms alone are not considered; rather, the effects of degradation mechanisms, particularly extreme events, are considered on the structural performance during the life cycle. Additionally, the effect of degradation mechanisms on the component, structure, and/or system level is explored, and hence, individual non-structural components such as heating, ventilation, and air conditioning components, among others, are not considered.

An overview of the literature search, selection, and subsequent review process is shown in Figure 1. The method consists of three parts including the literature search, literature selection, and review process. In the first step, the total number of publications is identified by utilizing the Scopus search engine and Google Scholar and then screened based on the defined criteria. In the second step, the screened publications are included based on the title and abstracts and then based on the full-text articles for the eligibility criteria. Finally, the included publications are utilized for conducting a relevant literature review and bibliometric analysis. In addition, an overview of life-cycle performance modeling given deteriorating and extreme events is presented and discussed.

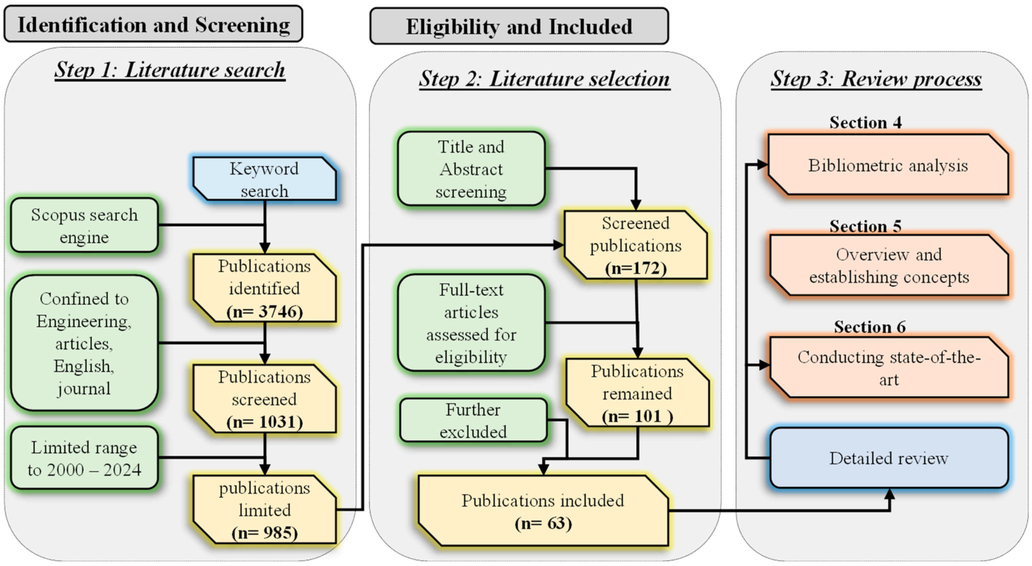

Figure 1. The adopted methodology for the search strategy, literature selection, and review process.

3. Research Analysis

The literature search is carried out under the Scopus field of "article title/abstract/keyword" with the search strings consisting of three parts. The first part consists of "life cycle*" including keywords such as life-cycle performance, life-cycle management, life-cycle cost, life-cycle optimization, or life-cycle decision-making, the second part consists of "reliability" or "risk", or "resilience", and the third part consists of "buildings" and "bridges". The considered three parts ensure that the publications must contain at least one of the keywords from each part in the article title or abstract or keywords such that the considered publication must include the life cycle part, a performance indicator part, and the infrastructure part.

As a result, 3746 publications are retrieved from the Scopus search engine and Google Scholar. The publications are then confined to engineering journal articles ranging from 2000–2024, which resulted in 985 journal article publications. In step 2, the title, keywords, abstract, author name, journal name, and year of publication of the identified records are exported to an MS Excel spreadsheet. The duplicates are removed, and then the titles and abstracts of the resulting publications are screened for relevance to the scope of this research. The articles that lack any one of the aspects including life cycle, degradation, or performance assessment indicators are subsequently excluded.

The screening resulted in 172 publications being assessed based on the exclusion and inclusion criteria and based on full texts of the publications. The full-text articles of the screened publications are carried out in 2 stages. In the first stage, full-text articles are broadly assessed for eligibility based on the developed criteria, resulting in 101 journal article publications. In the second stage, a few of the remaining articles are removed during the comprehensive assessment of the full-text articles for conducting the literature review. The reason for removing additional papers is to make sure that all the papers follow the three highlighted aspects (i.e., life cycle, deterioration, and considered building and bridge infrastructure system) along with a focus on frameworks and methodologies. It is also important to mention that the included articles have several limitations, e.g., time range bias, potentially overlooking earlier or emerging research, a reliance on limited databases, only considering journal articles, among others. Nonetheless, this review paper could serve as an overview of the field and existing methodologies.

Nevertheless, the included journal article publications are comprehensively studied and critically analyzed into three sections: (1) to identify components of life-cycle performance modeling of buildings and bridges under degradation, and (2) to provide a discussion on the components, methodologies, analytical tools, and techniques adopted for life-cycle performance modeling.

4. Bibliography Analysis

The total number of journal articles published in the area confined to engineering is represented in Figure 2 in terms of the total number of journal articles published per year. The content analysis is performed on the retrieved 1031 journal articles extracted as a result of the identification and screening process. The upward trend in the number of citations received and journal articles published each year highlights the increased interest in the life-cycle performance modeling of buildings and bridges under degradation. On average, each year shows a record number of publications and subsequent citations during the investigated time with a major increment in the number of publications observed in the year 2015 and onwards.

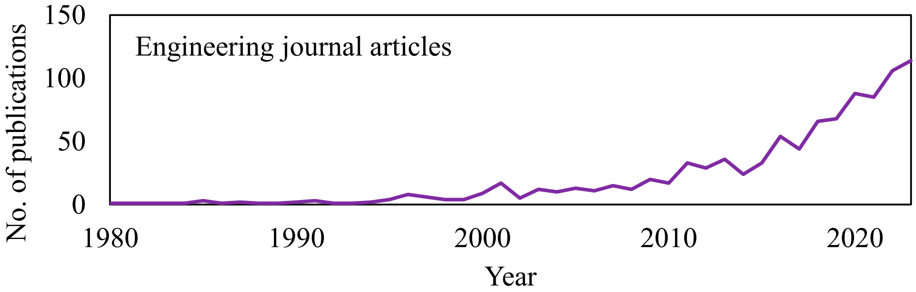

Figure 2. Annual trend in terms of articles published in engineering-related journals.

The highest number of relevant journal articles, e.g., more than half of the publications, are retrieved from the top five journals including *Structure and Infrastructure Engineering*, *Engineering Structures*, *Structural Safety*, *Journal of Bridge Engineering*, *Journal of Structural Engineering*, and *Reliability Engineering and System Safety*. All these journals are reputable, Science Citation Index Expanded indexed, and renowned in the structural engineering field. The top contributing authors in the field include Professor Dan M. Frangopol affiliated with Lehigh University, Professor Dong affiliated with The Hong Kong Polytechnic University, Professor Mitsuyoshi Akiyama affiliated with Waseda University, Professor Paolo Bocchini affiliated with Lehigh University, and Professor Paolo Gardoni affiliated with the University of Illinois Urbana-Champaign. The top 10 contributing universities in the field are shown in Figure 3.

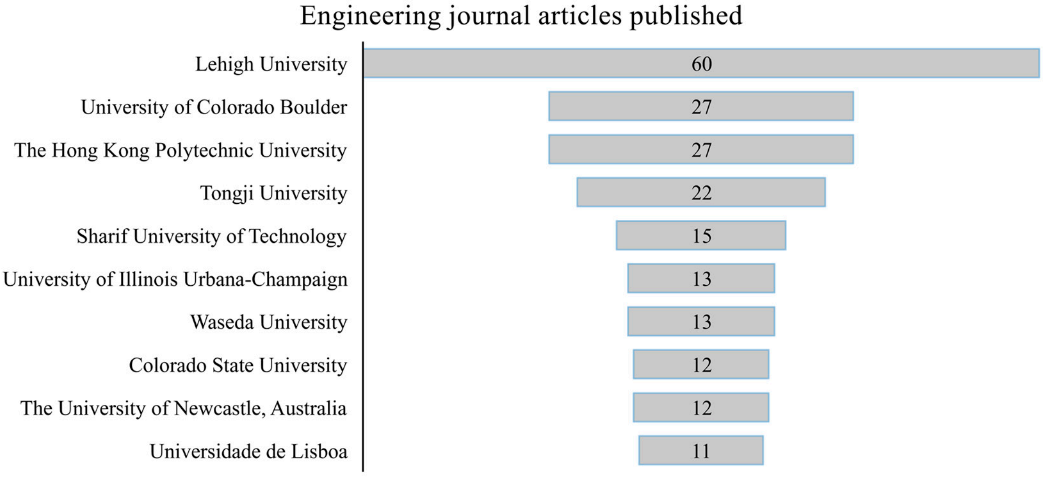

Figure 3. Engineering journal articles published per university affiliations.

Figure 4 shows a co-occurrence network analysis for the keywords of the included publications showing the primary focus area and subsequent relationships between different research topics. The top occurrences of keywords include life cycle, reliability, optimization, maintenance, and decision making, among others. The life cycle is the most prominent keyword indicating its integral role in the proposed research framework. The other important focus areas include reliability, decision making, and optimization with key focus areas of maintenance and inspection. Additionally, uncertainty analysis and stochastic processes show the complexity and probabilistic nature of the life-cycle management of structure and infrastructure systems. The co-occurrence network analysis highlights that most of the studies focus on reliability-related performance indicators with a focus on corrosion-related deterioration mechanisms. Moreover, optimization is the most utilized tool for life-cycle management and is the most occurred keyword in terms of decision-making tools. Furthermore, the most common methodologies and analytical tools include mathematical modeling, finite element methods, and uncertainty analyses.

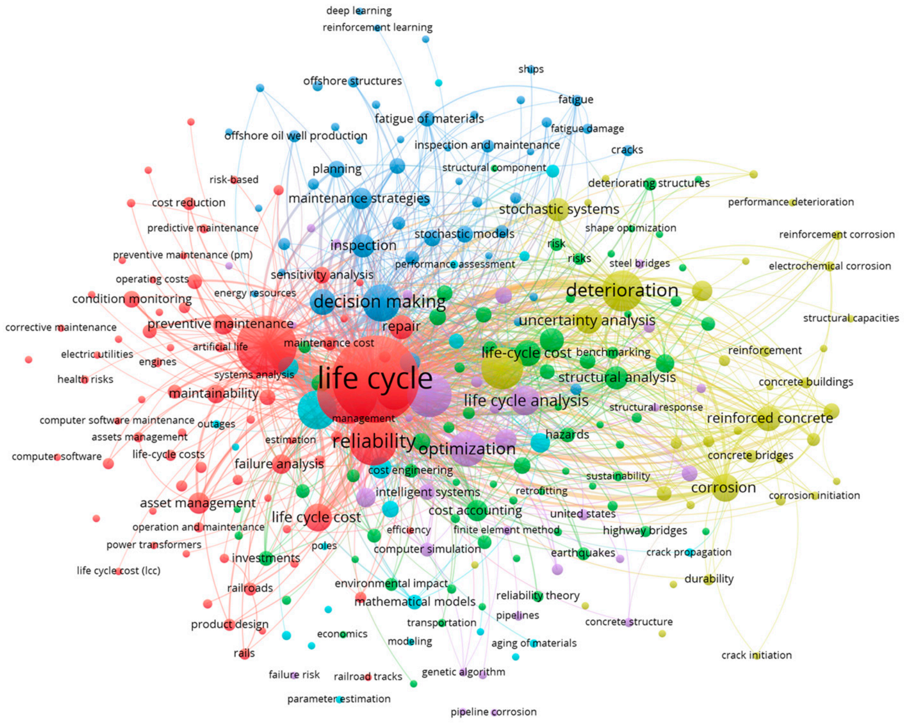

Figure 4. Co-occurrence keyword network analysis of the final included publications.

5. Life-Cycle Performance Modeling

An extensive literature review is conducted to identify individual components of life-cycle performance modeling. The components are divided into categories including mechanisms and indicators. The mechanisms include degradation and intervention mechanisms, and the indicators include reliability, risk, resilience, and sustainability [18–20]. The identified mechanisms alter the performance of structures during the life cycle, which is measured by utilizing performance indicators. The performance indicators could then be employed for subsequent performance assessment, enhancement, optimization, or decision making [21]. Figure 5 illustrates the degradation and intervention mechanisms on the life-cycle performance of structures.

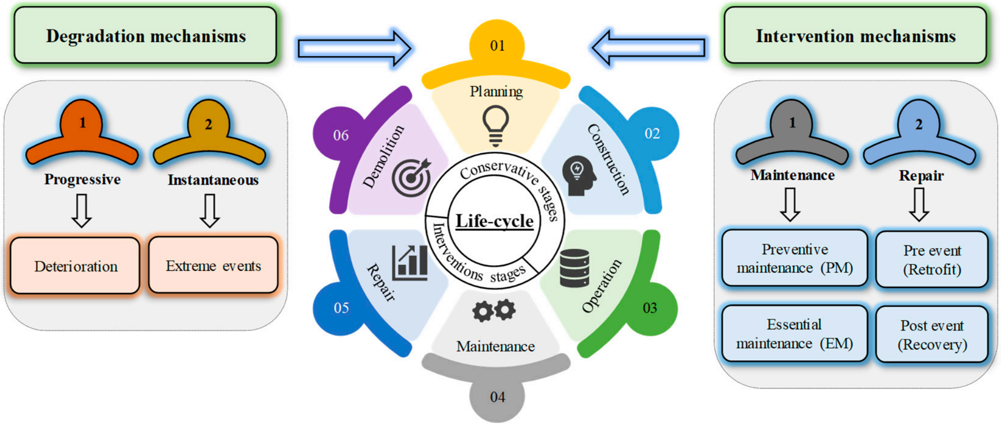

Figure 5. Life-cycle structural performance management framework including life cycle of structures, intervention options, and decision making.

The life cycle of structures is divided into two distinct stages including (1) Conservative stages such as planning, construction, operation, and demolition, and (2) Intervention stages such as maintenance and repair [22]. Subsequently, intervention alternatives could be explored for performance enhancements under limited resources (e.g., intervention costs) under intervention stages. However, intervention planning requires predictions of structural performance given degradation mechanisms and uncertainties during their life cycle. Furthermore, the effects of these interventions on the performance of structures need to be sufficiently understood for the performance enhancements and subsequent performance management-related decision making in a life-cycle context. Subsequently, decision-making strategies including optimization, multi-criteria decision making, utility decision theory, and others could be utilized for intervention planning and execution [23,24].

The degradation mechanisms are the processes that degrade the performance of structures during their life cycle and are divided into (1) progressive degradation mechanisms such as environmental deterioration, and (2) instantaneous degradation mechanisms such as extreme events including earthquakes and flooding, among others [9]. The intervention mechanisms are processes utilized to enhance the performance of structures and are divided into (1) maintenance interventions such as preventive or essential, and (2) repair interventions such as retrofit or recovery. The subsequent sections further discuss the identified degradation mechanisms, intervention mechanisms, and subsequent performance indicators.

5.1. Degradation Mechanisms

The social development and economic growth of the built environment depends on the functioning of physical structures and infrastructure systems. Additionally, these physical structures and infrastructure systems form the backbone for other systems including social and economic systems for the normal functioning of the built environment. However, the performance of physical systems declines due to degradation mechanisms including (1) progressive degradation and (2) instantaneous degradation [25]. These degradation mechanisms may affect the strength, stiffness, and ductility of structures during the life cycle due to age-related deterioration, referred to herein as progressive degradation, and may be sudden such as in the case of extreme events, referred to herein as instantaneous degradation [26].

Progressive deterioration is induced by environmental stressors and/or operating conditions including construction material, loading conditions, geometrical configurations, protection mechanisms, and others [27]. The progressive deterioration-related mechanisms can be grouped into five categories including (1) inception deterioration mechanisms that could be triggered in the first few weeks after construction including concrete bleeding due to inadequate compaction or shrinkage-induced concrete cracking, among others, (2) environmental stressor (e.g., humidity, temperatures, atmospheric carbon dioxide, salts)-induced deterioration such as freeze–thaw-related cracking and surface scaling, carbonation or chloride-induced corrosion, among others, (3) chemical attack-induced deterioration due to alkali–silica reactions, sulfate attacks, corrosion, among others, (4) design- and construction-related deterioration including poor construction materials, improper concrete covers, lack of protection materials, among others, and (5) loading conditions-related deterioration mechanisms including fatigue or creep due to sustained loadings or concrete abrasion, among others [28].

Numerous modeling techniques exist to model these deterioration mechanisms that can generally be categorized into (1) random variable models and (2) stochastic process models depending upon the extent of random variables [29]. Random variable models may include deterioration modeling considering the failure rate, condition index, reliability index, or time-dependent reliability index approach [30]. Conversely, stochastic process models may include Markov Decision Processes or renewal models, among others. The failure rate models account for the uncertainty in the failure of a component or system by utilizing cumulative distribution functions $F(t)$ and probability density functions $f(\mathrm{t})$, mathematically represented as:

$$r(t) = \frac{f(t)}{1 - F(t)},\ t > 0 \tag{1}$$

where *r*(*t*) is the probabilistic failure rate of a component, structure, or system given time *t*. Hence, maintenance decisions can be made by defining a threshold value for the failure rates of each component, structure, or system. The reliability index method is extensively utilized to model deterioration, mathematically represented as:

$$\Pr\{g(\boldsymbol{X}) < 0\} = \int_{x\in\Omega} f_{\boldsymbol{X}}(x_1, \ldots, x_n)dx_1 \ldots dx_n \tag{2}$$

where $\Pr\{g(\boldsymbol{X}) < 0\}$ is the probability of failure, $\Omega = \{\mathbf{x}|\mathrm{g}(\mathrm{x}) < 0\}$ is the failure region, $g(\boldsymbol{X})$ is the limit state function, i.e., the difference between resistance **R** and applied loads **S**, $f_{\boldsymbol{X}}(x)$ is the joint probability density, and $X = (X_1, \ldots, X_n)$ are the n random variables. The probability of failure using the reliability index is difficult to solve analytically, and hence, various methods are developed including the first-order second moment, first-order reliability method, or approximated by utilizing Monte Carlo methods, among others.

The Markov decision processes include defining state spaces and the condition of the structure of components in any of the states. Then, a Markov chain can be formulated as a discrete-time stochastic process $\{X_n, n = 0, 1, 2, \ldots\}$, i.e., future states are independent of the past states but only depend on the transition probabilities. This transition probability of state *i* at time n to move to state j at time n + 1 can be mathematically determined as:

$$P_{ij} = P_r\{X_{n+1} = j|X_0 = i_0, \ldots, X_{n-1} = i_{n-1,} X_n = i\} \tag{3}$$

The transition probabilities given all possible condition state pairs given N states can be mathematically determined as:

$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1N} \\ P_{21} & P_{22} & & P_{2N} \\ & \vdots & \ddots & \vdots \\ P_{N1} & P_{N2} & \cdots & P_{NN} \end{bmatrix} \tag{4}$$

where P is the transition probability matrix such that $\sum_{j=1}^{N} P_{ij} = 1$ for $i = 1, \ldots, N$. Hence, the probability of going from state *i* to state *j* in time steps t can be mathematically represented as:

$$P_{ij}^{t} = \mathrm{P}_r\{X_{n+t} = j|X_n = i\} \tag{5}$$

These transition probabilities for all the states during the investigated time t can then be utilized to determine the deterioration of components, structures, or systems.

The renewal models utilized for the progressive deterioration modeling include the gamma process, which is a continuous time stochastic process $\{X(t), t \geq 0\}$ where X is a random variable having gamma-distribution and its probability density function is mathematically represented as:

$$f(x|v, \mu) = \frac{\mu^{\tau}}{\Gamma(v)} x^{v-1} e^{-\mu x}, \qquad \text{for } x \geq 0 \tag{6}$$

where gamma function is $\Gamma(a) = \int_{t=0}^{\infty} t^{a-1} e^{-t} dt$ for a > 0, and the expectation and variance of the gamma process $\boldsymbol{X}(t)$ can be determined as:

$$E(\boldsymbol{X}(t)) = \frac{v(t)}{\mu}, \quad and \quad V(\boldsymbol{X}(t)) = \frac{v(t)}{\mu^2} \tag{7}$$

Hence, a component, structure, or system fails when the deterioration-related resistance falls below the threshold stress, mathematically represented as

$$R(t) = r_o - \boldsymbol{X}(t) \tag{8}$$

where $R(t)$ is the resistance against deterioration, $\boldsymbol{X}(t)$ is the gamma process, and r_o is the initial resistance of a component, structure, or system.

Instantaneous deterioration may cause a sudden shock to the structures and often results in performance reductions in a relatively short time [31]. Instantaneous deterioration is induced by extreme events and is classified into two major categories, herein including (1) natural hazards such as earthquakes, tsunamis, storms, flooding, landslides, wildfire, and volcanic activity, among others, and (2) man-made disasters such as terrorist attacks or blasts due to exploding gas cylinders, fires due to gas leakage or short circuit, among others. These deterioration mechanisms can reduce the structural performance or increase the probability of the failure of structural members, or may trigger complete structural failure modes including progressive collapse or complete collapse, among others [32,33]. Moreover, this may shorten the service life of a structure and could cause significant social disruptions and economic consequences.

5.2. Intervention Mechanisms

The conservative stages are conventionally a part of the general life-cycle assessment strategies in which the subsequent stage follows once the prior stage is accomplished such as the planning, construction, operation, and end-of-use stage, while intervention stages are introduced to manage the performance of structures against the degradation mechanisms and are further herein classified as the maintenance intervention mechanism and repair intervention mechanism as shown in Figure 6. The maintenance stage includes interventions such as inspections and maintenance actions to enhance the performance of structures burdened by the progressive degradation mechanisms, while the repair stage includes interventions such as inspections, repair, and retrofit actions to enhance the performance of structures burdened by the instantaneous degradation mechanisms [34].

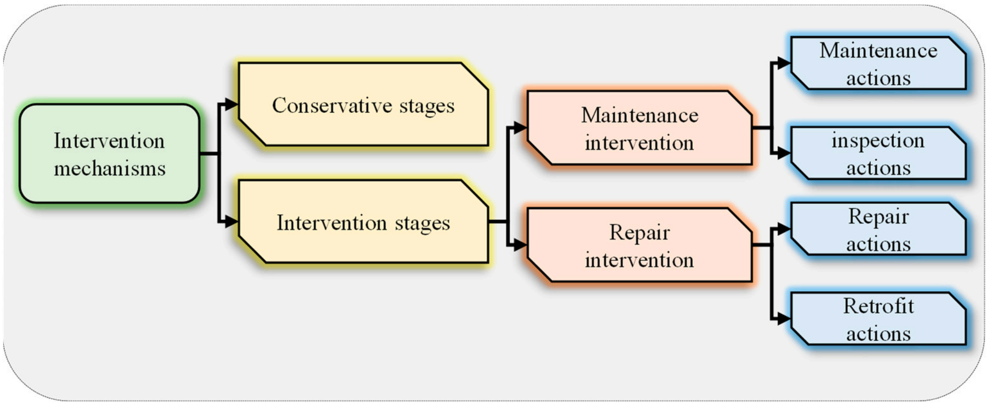

Figure 6. Intervention stages to manage the performance of structures against degradation mechanisms.

The maintenance intervention under progressive degradation can be classified into preventive maintenance strategies and essential maintenance strategies. Preventive maintenance strategies are implemented to slightly enhance the structural performance and the interventions may include repairing cracks, patching concrete, replacing structural members, painting, and cleaning, among others [10]. Conversely, essential maintenance strategies are implemented to significantly enhance the performance of structures and are often considered when the structural performance is reduced to a point that may compromise the safety of a structure (i.e., performance falls below the performance thresholds). The essential maintenance interventions result in significant structural performance enhancements but also at higher maintenance costs. Examples of essential maintenance interventions may include significant structural strengthening, rehabilitation strategies, and the replacement of major structural members, among others [35].

The repair intervention under instantaneous degradation is classified into pre-event intervention strategies and post-event intervention strategies. The pre-extreme event interventions include strategies to enhance the likely performance of structures under probable extreme events [36], e.g., retrofitting structures or altering the built environment to reduce the damage to the structures from the extreme event (e.g., retrofit of the built environment). Examples of retrofitting a structure may include reinforced concrete jacketing, steel jacketing, fiber-reinforced polymer wrapping or jacketing, adding buckling restraint braces, installing base isolators, and many others [37]. Examples of retrofitting a built environment may include constructing flood barriers such as levees, dikes, and seawalls, among others, constructing retaining walls, soil nailing to protect from landslides, and others. The post-event intervention may include adopting and implementing strategies that would result in faster recovery from extreme events such as enhancing the resilience of the structure and/or the built environment [38].

As an illustration, Figure 7 shows the structural performance during the investigated time under progressive and instantaneous degradation mechanisms and subsequent intervention strategies given the intervention costs. As shown, the structural performance is measured by performance indicators or indexes, and after the construction of a structure and during its life, the deterioration initiation could take place with some rate of deterioration given the environmental conditions and construction materials. This slow and gradual reduction in structural performance due to structural degradation is referred to herein as progressive deterioration. The structural performance is reduced during the investigated time, and subsequently, necessary maintenance interventions may be required to enhance the performance. Additionally, the structural performance can be abruptly reduced due to extreme events during the service life of a structure, referred to herein as instantaneous deterioration, and subsequently, repairs may be required to enhance the performance to specified levels such as to pre-extreme event levels or build back better levels.

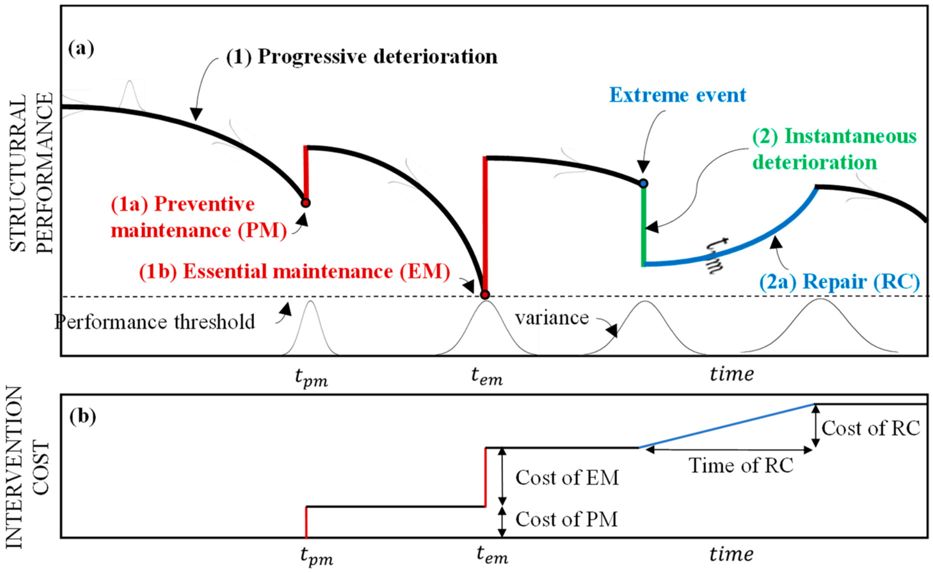

Figure 7. The effects of deteriorating mechanisms of physical structure and infrastructure systems on the (**a**) structural performance and (**b**) intervention costs.

Structural performance can be enhanced by implementing performance enhancement strategies, referred to herein as intervention stages. It is worth noting that these intervention stages are burdened by the intervention costs, and different intervention stages have varying structural performance enhancements and corresponding intervention costs that need to be considered. The intervention stages are broadly classified as maintenance intervention strategies and repair intervention strategies. As discussed, maintenance intervention strategies are utilized to enhance the structural performance against progressive deterioration, and repair intervention strategies are utilized to enhance the performance against instantaneous deterioration. However, the probable scenarios need to be considered, and subsequently, intervention strategies need to be implemented. Hence, a life-cycle performance management framework is required to efficiently manage the structures and/or built environment against these degradation mechanisms [39].

5.3. Performance Indicators

The performance of structures could be determined at a cross-section, member, structure, system, or network of systems and is generally measured in terms of performance indicators. Commonly, structural performance is evaluated in terms of reliability-based performance indicators that consider uncertainties in the load and resistance of structural members, the entire structure, or at a system level. These uncertainties provide the probability of a component or a system failure in terms of loading demands exceeding the resistance capacities [40]. The commonly utilized reliability performance indicator referred to as the reliability index can be mathematically expressed as:

$$\beta(t) = \phi^{-1}(1 - \rho_F(t)) \tag{9}$$

where $\beta(t)$ is the reliability index, $\phi(.)$ is the standard normal cumulative distribution function (CDF), and $\rho_F(t)$ is the time-varying probability of failure determined as:

$$\rho_F(t) = \int_0^{\infty} (\int_0^{s} f_{R,S}(t) dr) ds \tag{10}$$

where $f_{R,S}(t)$ is the joint probability density function (PDF) of random variables (i.e., resistance $R(t)$ and loadings $S(t)$). The reliability index is a robust performance indicator to measure the performance of structures given the loading conditions in terms of the probability of failure only. However, in a possible event of structural failure, the reliability performance indicator cannot provide information related to the consequences occurring as a result of failure. Moreover, the reliability performance indicator cannot efficiently consider instantaneous degradation mechanisms. Conversely, the risk performance indicator is utilized to evaluate the consequences of structural failure or damage to the structures under extreme events. Increasingly, the consequences are being determined in terms of social, economic, and/or environmental consequences as compared to conventionally considered Engineering Demand Parameters because the consequences provide a more meaningful interpretation of performance as compared to conventionally considered decision variables [41]. For instance, risk in terms of repair time and/or repair cost can be mathematically determined as follows:

$$l_{L_{T|IM}} = l_{L_{R|IM,NC}} \left(1 - p_{C|IM}\right) + l_{L_{C|C}} p_{C|IM} \tag{11}$$

where $l_{L_{T|IM}}$ is the risk in terms of cost or time given the Intensity Measure (IM); $l_{L_{R|IM,NC}}$ is the risk in terms of repair cost or time conditioned on non-collapse probability; $l_{L_{C|C}}$ is the risk given the probability of collapse; and $p_{C|IM}$ is the probability of collapse of a building given the IM.

Recent hazard assessment studies have highlighted additional consequences during the recovery from extreme events. Subsequently, the resilience performance indicator has gained interest in the research community concerning additional consequences due to the non-functionality or reduced functionality of structures. The resilience performance indicator accounts for the structural performance during the investigated time after an extreme event and is generally measured in terms of functionality reduction and subsequent functionality recovery as a result of repair efforts [42]. Nonetheless, the resilience performance indicator has three dimensions including the ability to prepare for extreme events, the ability to adapt to changing conditions, and the ability to recover from extreme events efficiently and rapidly. Resilience can be mathematically represented as:

$$R = \int_{t_0}^{t_0+t_r} \frac{Q(t)dt}{t_r} \tag{12}$$

where R is the resilience metric; $Q(t)$ is the functionality; t_r is the resilience time interval (e.g., days); and t_0 is the time of the hazard event.

Another important performance indicator related to the integration of social, economic, and environmental aspects considering future generations is referred to as the sustainability performance indicator [43]. Furthermore, the reliability, risk, and resilience-related performance of structures can be sustained for longer time horizons only if the sustainability performance indicator is considered, and hence, it is also of interest to the decision makers and stakeholders. Additionally, these performance indicators could conflict with each other, i.e., enhancing one performance indicator may reduce the performance of other indicators. Hence, these performance indicators could be considered individually or combined into performance optimization, multi-attribute utility, and/or multi-criteria decision-making, and other decision-making models [44,45].

Overall, life-cycle performance modeling could serve as an effective tool to maintain the performance of structures above the threshold levels cost-effectively by providing planned and scheduled interventions under the deteriorating mechanisms. This could lead to enhanced structural performance and safety, a decreased probability of structural failure, and the increased service life of structures. In this context, an overview of life-cycle performance management is provided along with its components including the life-cycle concept, intervention alternatives, performance indicators, and the decision making considering the intervention options. The next section provides a discussion related to the state-of-the-art on the life-cycle performance management of structures and infrastructure systems given deterioration mechanisms based on the 43 included articles.

6. Discussion

Most of the articles related to life-cycle performance modeling investigate progressive degradation mechanisms. For instance, Chen, et al. [46] proposed an approach for the maintenance planning of deteriorating oil pipes. The authors integrated dynamic programming with particle swarm optimization to determine the optimum maintenance plan for the deteriorating pipes. A total life-cycle cost-based objective function was selected for optimization and was compared with conventional genetic algorithms. Nielsen and Sørensen [47] applied a computational framework for risk-based planning of inspections, maintenance activities, and condition monitoring and implemented it on offshore wind turbine components. The proposed risk-based planning was based on dynamic Bayesian networks utilized for deterioration modeling and was later implemented for the life-cycle cost assessments. Esteva et al. [48] investigated the life-cycle seismic performance of multi-story buildings by evaluating the influence of damage accumulation on the seismic vulnerability of these buildings under instantaneous deterioration.

Several articles also discussed life-cycle performance management under deterioration for infrastructure systems. For instance, Yang and Frangopol [49] proposed risk-based inspection planning to optimize life-cycle costs while preserving safety margins. Three specific planning methods were discussed including Monte Carlo simulation-based, Bayesian network-based, and partially observable Markov decision processes. In addition, Yang and Frangopol [50] proposed the life-cycle management of deteriorating civil infrastructure systems by considering the resilience performance indicator. The resilience to lifetime hazards performance indicator was assessed by utilizing the renewal–rewards process. Ellingwood and Lee [51] provide a discussion on the life-cycle reliability assessment of civil infrastructures that have a considerably longer service life. The authors provide risk-informed decision making by considering time-dependent reliability assessment and performance limits for civil infrastructures.

The following sub-sections provide a discussion on identified components of life-cycle performance modeling including degradation mechanisms, intervention mechanisms, performance indicators, and utilized tools and methodologies.

6.1. Degradation Mechanisms

Most of the studies on progressive degradation mechanisms include corrosion, carbonation, chloride-induced deterioration, fatigue, and fracture, among others. For instance, Han et al. [52] investigated the corrosion-related deterioration of steel bridges. A risk-based life-cycle optimization methodology was proposed to investigate the corrosion mechanisms and, subsequently, corrosion-resistant steel was utilized to reduce the high maintenance costs associated with the corrosion-related deterioration mechanisms. Cadenazzi et al. [53] evaluated life-cycle costs for concrete bridges exposed to chlorides and, subsequently, utilized fiber-reinforced polymers as an effective non-corrosive alternative to reduce chloride-induced deterioration. Stipanovic et al. [54] proposed a reliability-based whole life-cycle model for steel bridges subjected to fatigue-induced deterioration. The reliability model included the assessment of critical limit states, probabilistic fatigue analysis, and finite element modeling. Four different scenarios were investigated considering both direct and indirect costs to investigate the impacts of different maintenance strategies. Cheng et al. [55] provide a bridge inspection and maintenance methodology focusing on invisible deterioration-related aspects such as resistance to scouring. Hence, a risk-based evaluation model was developed for risk factors from component deterioration, scouring, and earthquakes to minimize the life-cycle costs of bridges.

Most of the studies related to instantaneous degradation mechanisms also consider progressive deterioration in a life-cycle context. Few researchers solely considered instantaneous degradation in a life-cycle context, for instance, Wanniarachchi et al. [56] provide a methodology for instantaneous degradation mechanisms including earthquake-induced damages to bridges. Moreover, a decision framework was developed to evaluate the life-cycle performance of enhanced bridges by utilizing novel technologies of performance enhancement. This study aimed to provide informed decision making under dynamic conditions.

Han and Frangopol [57] studied the structural performance of multiple degradation mechanisms including progressive and instantaneous. The authors provided a life-cycle risk-based optimal management strategy for bridge networks considering corrosion-related deterioration and seismic hazard scenarios. Li et al. [58] and Katikala et al. [59] investigated corrosion and seismic scenarios in a life-cycle context for life-cycle performance assessment and management of structures. Dong and Frangopol [60] provide a life-cycle assessment of the resilience of bridges considering multiple degradation scenarios including earthquake scenarios, flood scenarios, and flood-induced scour, along with progressive degradation and impacts of climate change. Bisadi and Padgett [61] provide a time-dependent multi-hazard cost-based methodology for bridge structures to provide an optimum design under seismic hazards and progressive deterioration. Anwar [35] investigated the life-cycle performance enhancement of deteriorating buildings considering the combined effect of degradation mechanisms including deterioration and seismic hazards.

In summary, chloride-induced corrosion and fatigue has been extensively studied under progressive degradation mechanisms, and seismic hazards have been studied extensively under instantaneous degradation mechanisms. Additionally, there has been an increasing trend to consider the combined effect of progressive degradation mechanisms with instantaneous degradation mechanisms.

6.2. Intervention Mechanisms

Interventions are required during the life cycle of physical infrastructure systems to enhance the performance against degradation mechanisms. As highlighted, the intervention mechanisms can be broadly classified as maintenance interventions and repair interventions depending upon the nature of the degradation mechanisms. For instance, Han et al. [62] provided optimal life-cycle management strategies under corrosion-related progressive deterioration mechanisms that include repainting steel girders at time intervals of 25 years and 15 years, along with considering girder replacement using girder replacements. Cadenazzi, Lee, Suraneni, Nolan, and Nanni [53] evaluated life-cycle cost analyses for a fiber-reinforced polymer-retrofitted Reinforced Concrete bridge compared with a conventional reinforced concrete/prestressed concrete bridge. Anwar [35] utilized conventional retrofit methods including reinforced concrete jacketing, steel jacketing, and fiber-reinforced polymers to enhance the performance against degradation mechanisms.

Wanniarachchi, Prabatha, Karunathilake, Zhang, Hewage, and Shahria Alam [56] considered bridge repair activities under the operation and maintenance stage given seismic hazard scenarios that include pothole filling every 5 years, shallow deck overlay every 15 years, and deck replacement every 30 years. Moreover, the authors considered the post-earthquake repair stage, which includes a repair mechanism depending upon the damage state after an earthquake event. In the case of slight damage to the bridges such as minor cracking of the bridge deck or minor spalling from the pier, the repair intervention mechanism includes adjusting and patching by utilizing epoxy injections. For moderate repairable damages such as shear cracking or rebar yielding, the repair would include installing a steel tube jacketing. For extensive damages that are irreparable but without collapse, the repair intervention includes rebuilding the damaged component, and for the complete collapse such as the crushing of core concrete, the repair would include replacing the bridge entirely [63].

In summary, intervention mechanisms are utilized to alter the performance of structures and include maintenance interventions for progressive deterioration mechanisms and repair interventions for instantaneous deterioration mechanisms.

6.3. Performance Indicators

The reliability-based performance indicator is found to be the most widely utilized indicator in the included articles. Among the reliability-based methods, the most utilized is the reliability index β, which considers the load and resistance distribution given time and evaluates the probability of failure. For instance, Ghodoosi et al. [64] consider the reliability index at a system level for decision making regarding maintenance interventions. The deterioration model was based on system reliability presenting deterioration prediction curves based on the reliability indexes. Saad et al. [65] provided a reliability-based optimization framework for the life-cycle cost of reinforced concrete bridge elements given fatigue and corrosion-related degradation mechanisms. García-Segura et al. [66] proposed a lifetime reliability-based optimization framework for box girder post-tensioned bridges. The lifetime reliability was evaluated by utilizing reliability indices determined from the first-order second-moment method.

Risk-based performance indicators were also extensively utilized in several studies in the included articles. Risk-based performance indicators are generally utilized for instantaneous degradation mechanisms and are defined as socioeconomic or environmental consequences resulting from direct damage to the physical infrastructure systems. For instance, Han and Frangopol [57] proposed a risk-based optimal maintenance strategy for bridge networks. The life-cycle risk was assessed based on both the direct and indirect failure consequences associated with the damage states of the bridge. Subsequently, the annual network risk was evaluated in US dollars. In the case of progressive degradation mechanisms, the risk could be assessed in terms of life-cycle maintenance costs. Life-cycle maintenance costs are commonly utilized in numerous retrieved articles and are often combined with other performance indicators. For instance, Shen et al. [67] provided a probabilistic framework for the life-cycle cost analysis of bridge decks designed with various reinforcement alternatives, and Jia and Gardoni [68] provided life-cycle cost analysis considering various deterioration processes, among others [69–71].

Few studies have also investigated resilience and sustainability-related performance indicators. For instance, Dong and Frangopol [60] proposed a framework for the risk and resilience assessment of highway bridges under time-dependent and multiple hazards including earthquakes and floods. The resilience performance indicator was assessed in terms of functionality loss and recovery during the investigated time after a hazard event. The functionality loss and recovery were then translated into annual resilience given time in years. Yang and Frangopol [50] measured the performance level of civil infrastructure by assessing resilience loss given both the progressive and instantaneous degradation mechanisms.

Allah Bukhsh et al. [72] proposed network-level bridge maintenance planning by utilizing the multi-attribute utility theory. The authors utilized environmental costs as a sustainability performance indicator along with other performance objectives for the maintenance planning. Wanniarachchi et al. [56] conducted a life-cycle environmental impact assessment including ozone depletion, acidification, eutrophication, human toxicity, ecotoxicity, and depletion, among many others.

In summary, the reliability performance indicator is the most widely utilized, while other performance indicators are mostly utilized for instantaneous degradation mechanisms. A few studies have also investigated multiple performance indicators under instantaneous degradation mechanisms. Most recently, resilience performance indicators have gained popularity along with sustainability assessments.

6.4. Performance Levels

Performance can be assessed, prioritized, and/or managed at various levels. In this paper, the included articles were investigated for these levels including component, structure, and or system [73]. Few studies have investigated the performance at a component level. For instance, Setunge et al. [74] proposed an integrated approach to assess the failure risk of deteriorated bridges by utilizing the fault-tree model. The reliability and probability of failure were assessed at a component level, i.e., bridge headstocks, columns, and pile caps. Yanaka et al. [75] provide reliability-based and life-cycle cost-based recommendations for bridge girder components of prestressed concrete.

However, most of the studies in the included articles focus on structure-level performance. For instance, Chen et al. [76] proposed an engineering reliability-based approach to assess reinforcement corrosion at a bridge level. Gui et al. [77] proposed a technique for bridge maintenance-related decision making in which a comprehensive state index model, target-based reliability model, degradation rate model, life-cycle costs, and maintenance time models were considered at a bridge structure level. Cheng et al. [78] investigated time preference and risk perception effects on the life-cycle management at a structure level, among others [79–81].

Few of the studies also focus on performance at the network level. For instance, Lei et al. [82] proposed a deep reinforcement learning-based methodology for the life-cycle maintenance planning of deteriorating bridges at a regional level. Hadjidemetriou et al. [83] proposed a predictive maintenance prioritization framework for bridges at a network level, among others. In summary, three performance levels are identified in the literature including component, structure, and system, and various studies investigate the performance of structures given these performance levels.

6.5. Tools and Methodologies

Different tools, techniques, and methodologies are utilized for the life-cycle performance management of structures and infrastructure systems. Among these techniques, optimization is observed as a widely utilized tool for various purposes within life-cycle performance management [84]. For instance, Han and Frangopol [57] utilized an optimization technique for cost optimization, among others, Lei, Xia, Deng, and Sun [82] utilized optimization for maintenance planning and optimization, among others, Saad, Aissani, Chateauneuf, and Raphael [65] utilized optimization for the optimal bridge design considering life-cycle cost as a performance objective, García-Segura, Yepes, Frangopol, and Yang [66] utilized an optimization technique for the lifetime reliability assessment of post-tensioned box girder bridges, and Kim and Frangopol [85] considered multi-objective optimization for the optimum monitoring planning for fatigue damage detection.

Other widely utilized tools include life-cycle assessment, life-cycle impact assessment, and life-cycle cost assessments, among others [86]. In the case of progressive deterioration modeling, Markov models have been extensively utilized. For instance, Hadjidemetriou, Herrera, and Parlikad [83] utilized Markov chains for the deterioration modeling of individual components for maintenance prioritization, Asghari et al. [87] utilized Markovian deterioration models along with deep neural networks to reduce the computational times of the considered mathematical algorithms, and Yang and Frangopol [50] utilized Markov models for the inspection planning of deteriorating structures, among others. The network-level life-cycle performance was assessed by utilizing network models from the graph theory.

Artificial intelligence, machine learning, and deep learning algorithms were also employed for the life-cycle performance management of structures and infrastructures. Gui, Zhang, Lei, Hou, Zhang, and Qian [77] adopted probabilistic neural networks for bridge maintenance-related decision making, Cheng, Chiu, Chiu, Prayogo, Wu, Hsu, and Lin [55] utilized support vector machines for providing a life-cycle maintenance strategy for deteriorating bridges, and Asghari, Hsu, and Wei [87] investigated the life-cycle cost analysis of infrastructure systems by utilizing deep neural networks.

For decision making, various multi-criteria decision-making models were utilized. For instance, Allah Bukhsh, Stipanovic, Klanker, O'Connor, and Doree [72] provided a bridge maintenance planning-related decision-making tool by utilizing multi-attribute utility theory. Kim and Frangopol [85] also utilized a multi-attribute utility theory-based approach for decision making giving multiple objectives. Setunge, Zhu, Gravina, and Gamage [74] introduced a fault-tree-based integrated approach for the decision making of deteriorated reinforced concrete bridges. Cheng, Yang, and Frangopol [78] consider decision-making tools to investigate the effects of time preference and risk perceptions on life-cycle performance management. Other techniques utilized in the included articles consider copula-based multivariate renewal models for investigating higher order moments, renewal–reward processes for life-cycle management, stochastic models, and renewal theory for modeling deterioration processes and uncertainties, dynamic programming, particle swarm optimization, and genetic algorithms for maintenance planning, Monte Carlo methods for incorporating uncertainties, and sensitivity modeling, among others [88–90].

7. Conclusions

This paper examined the literature on the life-cycle performance modeling of deteriorating buildings and bridge infrastructure systems under extreme events. For that purpose, a systematic literature review was performed based on the PRISMA methodology to systematically identify relevant journal articles. The Scopus search engine was utilized for the literature review with the aid of Google Scholar. The objectives were to provide an overview of life-cycle performance modeling in terms of its components and utilized tools, technologies, and methods available in the literature. In this context, the following conclusions could be made.

1. The content analysis shows that the life-cycle performance modeling of buildings and bridge infrastructure systems has received increased attention over the years and the research interest in the field is growing due to the increased vulnerability of the built environment against the degradation mechanisms.
2. It was noted that most of the included articles focus on reliability performance indicators with progressive degradation mechanisms indicating reliability under aging structures being extensively investigated. Conversely, risk and resilience performance indicators are also explored but mostly for instantaneous degradation mechanisms. This could be due to the higher consideration of the low probability of failure and need to consider uncertainties in reliability assessment more frequently as opposed to

risk or resilience performance indicators. Moreover, reliability is arguably an older concept than the risk or, more prominently, resilience in the engineering context.

3. A review of life-cycle performance modeling was provided in terms of its components including degradation mechanisms, intervention mechanisms, life-cycle performance stages, and performance indicators. Then, a discussion on the included journal articles was provided in terms of the identified components of life-cycle performance modeling. This way of identifying individual components, mechanisms, and performance indicators is particularly useful for readers interested in understanding the life-cycle performance management of structure and infrastructure systems.
4. Additionally, the adopted tools, techniques, and methodologies that were utilized for the performance management of buildings and bridges under degradation mechanisms during their life cycle were highlighted. The prominent methodologies include optimization, life-cycle assessments, stochastic models, artificial intelligence, machine learning, and decision-making tools, among others.

In summary, while reliability is extensively explored under progressive deterioration, there is still a need to explore the risk and resilience performance of structure and infrastructure systems, particularly for the combined progressive and instantaneous degradation mechanisms. Furthermore, there is a need to integrate advanced technologies in a multi-hazard context including artificial intelligence, machine learning, and real-time monitoring systems, among others. Nonetheless, these gaps highlight opportunities for future research, particularly in integrating modern technologies and exploring combined degradation mechanisms for more resilient and sustainable infrastructure management.

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