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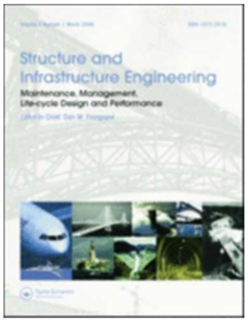

Bridge life-cycle performance and cost: Analysis, prediction, optimization and decision making

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Bridge life-cycle performance and cost: Analysis, prediction, optimization and decision making*

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Abstract

The development of a generalized framework for assessing bridge life-cycle performance and cost, with emphasis on analysis, prediction, optimization, and decision making under uncertainty, is briefly addressed. The central issue underlying the importance of the life-cycle approach to bridge engineering is the need for a rational basis for making informed decisions regarding design, construction, inspection, monitoring, maintenance, repair, rehabilitation, replacement, and management of bridges under uncertainty which is carried out by using multi-objective optimization procedures that balance conflicting criteria such as performance and cost. A number of significant developments are summarized, including time-variant reliability, risk, resilience, and sustainability of bridges, bridge transportation networks, and interdependent infrastructure systems. Furthermore, the effects of climate change on the probabilistic life-cycle performance assessment of highway bridges are addressed. Moreover, integration of structural health monitoring and updating in bridge management and probabilistic life-cycle optimization considering multi-attribute utility and risk attitudes are presented.

Keywords: Life-cycle management, risk, resilience, sustainability, utility, decision making.

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1. Introduction

The condition of civil infrastructure systems around the world is degrading due to a variety of deteriorating mechanisms, including aging, environmental stressors, man-made hazards (e.g., blasts and fires) and natural hazards (e.g., earthquakes and hurricanes), among others. Consequently, improving the overall condition and safety of deteriorating infrastructure systems is a key concern worldwide. For example, in 2013, the American Society of Civil Engineers reported, within the 2013 Report Card for America's Infrastructure, that the average age of the United States' 607,380 bridges was 42 years (ASCE 2013). Additionally, nearly a quarter of these highway bridges were classified as either structurally deficient or functionally obsolete (FHWA 2013). Therefore, it is crucial to implement rational management strategies that maintain performance of highway bridges within acceptable levels through their life-cycle. Life-cycle management is widely recognized as an effective tool for maximizing the cost-effectiveness of implementing intervention actions that improve condition and safety, and extend the service life of deteriorating infrastructure systems.

In order to predict performance of structural systems during their life-cycle under uncertainty, deterioration mechanisms for the investigated systems (e.g., corrosion and fatigue) must be carefully considered. Aggressive environmental conditions and natural aging processes facilitate a gradual reduction in the performance (e.g., system reliability) of existing structures. Alternatively, there are extreme events that cause an abrupt reduction of the functionality of structures such as blasts, fires, earthquakes, hurricanes, and terrorist attacks. During their life-cycle, bridges can be subjected to multiple hazards. Thus, it is necessary to consider the performance of bridges under multiple hazards in the hazard assessment and mitigation procedure, all in a life-cycle context. Life-cycle assessment of deteriorating highway bridges includes aleatory and epistemic uncertainties associated with natural randomness and inaccuracies in the prediction or estimation of reality, respectively (Ang and Tang 2007). These are present within modeling the structural resistance (e.g., material properties and geometrical characteristics), the occurrence and magnitude of hazards that may impact the structure (e.g., corrosion, fatigue, earthquakes, floods, and hurricanes), operating conditions, and loading cases, among others; uncertainties are also associated with the interventions performed during the service life of structures (e.g., inspection, maintenance, monitoring, repair, and replacement) and their costs. Due to these uncertainties, it is imperative for structural engineers to accurately model and assess the structural performance and expected total cost within a probabilistic life-cycle context. Furthermore, the effects of maintenance, repair, and rehabilitation on structural life-cycle performance must be well understood. The influence of maintenance and repairs on structural performance can be incorporated in a generalized framework for multi-criteria optimization of the life-cycle management of infrastructure systems (Frangopol and Liu 2007, Frangopol 2011, Frangopol and Soliman 2016). Within the last two decades, several studies introduced probabilistic techniques which can assist the bridge management process (Frangopol *et al.* 1997, Stewart and Rosowsky 1998, Enright and Frangopol 1999a, b, Miyamoto *et al*. 2000, Estes and Frangopol 2001, Frangopol *et al.* 2001, Kong *et al*. 2002, Kong and Frangopol 2003, Frangopol *et al.* 2004, Morcous and Lounis 2005, Neves *et al*. 2006, Frangopol and Liu 2007, Biondini *et al*. 2008, Frangopol and Okasha 2009, Okasha and Frangopol 2010a, b, Frangopol and Kim 2011, Biondini *et al*. 2014, and Frangopol and Soliman 2016, among others).

The effects of maintenance on the probabilistic performance profile (such as reliability index) and cost are depicted in Figure 1. Within this figure, the probabilistic aspect of performance prediction is illustrated by the probability density functions (PDFs) of the initial performance index, deterioration initiation, rate of deterioration, and service life (a) without maintenance, (b) with preventive maintenance (PM) only, and (c) with both preventive and essential maintenance (EM). In general, preventive maintenance is applied to slightly improve the performance or delay the deteriorating process of a bridge in order to keep the bridge above the required level of structural performance. Preventive maintenance actions for a deteriorating bridge includes replacing small parts, patching concrete, repairing cracks, changing lubricants, and cleaning and painting exposed parts, among others. On the other hand, essential maintenance is typically a performance-based intervention. As depicted in Figure 1(a), essential maintenance is applied when the bridge performance level reaches a predefined threshold. Essential maintenance actions lead to much higher levels of bridge performance than preventive maintenance actions, but they typically cost more. Strengthening and replacement of bridge components are examples of essential maintenance actions. Furthermore, the effects of maintenance on the total cost of bridge management must be considered, Figure 1(b) shows the cumulative maintenance cost as a function of time for preventive and essential maintenance interventions.

Performance of bridge systems may be represented by a variety of indicators. Approaches for the life-cycle management of bridges involving reliability performance indicators consider uncertainties associated with loads and resistance, but are not able to account for the consequences incurred from bridge failure. Risk-based indicators provide the means to combine the probability of structural failure with the consequences associated with this event (Ellingwood 1998, Ang and De Leon 2005, Ellingwood 2005, 2006, Saydam *et al.* 2013, Zhu and Frangopol 2013b, Saydam and Frangopol 2014). Within this paper, approaches which incorporate risk within a generalized life-cycle management framework are presented. Furthermore, methodologies considering sustainability as a performance indicator are discussed. The incorporation of sustainability in the life-cycle performance assessment and management procedures allows for the effective integration of economic, social, and environmental aspects. A sustainability performance metric may be established considering multi-attribute utility theory, which facilitates the combination of several risks while incorporating the risk attitude of the decision maker (Jiménez *et al.* 2003). This particular sustainability performance indicator has been applied to the life-cycle management of bridges (Sabatino *et al.* 2015a, b) and bridge networks (Dong *et al*. 2015). Additionally, risk and sustainability concepts may be successfully integrated within optimal bridge management planning. A general flowchart outlining the use of reliability, risk, multi-attribute utility, and sustainability concepts within a robust decision making process regarding bridge management is shown in Figure 2. The goals of implementing optimal bridge management plans are to improve the performance and functionality of bridges, mitigate detrimental consequences, and minimize costs. These ultimate aims are satisfied with a comprehensive life-cycle framework, like the one shown in Figure 2.

Resilience is another structural performance indicator that accounts for structural performance, along with recovery patterns under hazard effects (Bruneau *et al.* 2013). Presidential Policy Directive (PPD 2013) defined resilience as “the ability to prepare for and adapt to changing conditions and withstand and recover from disruptions”. Considering the effects of uncertainties, it is crucial for the quantification of seismic resilience at the holistic level to be processed through a probabilistic framework. Several deterministic and few probabilistic studies have been reported in the literature to analyse the resilience of individual bridges and bridge networks (Bocchini and Frangopol 2012, Decò and Frangopol 2013, Decò *et al* 2013, Dong and Frangopol 2015, 2016b).

The main effects of climate change on the performance prediction of bridges are investigated and summarized herein. Measurements taken over the last decades indicate that the sea level, global temperature, and ocean temperature are all rising at elevated rates (Church and White 2006, Allison *et al.* 2009, Levitus *et al.* 2009, Peterson and Baringer 2009, Church and White 2011). Additionally, a significant increase of carbon dioxide (CO_2) concentration in the atmosphere has been observed (IPCC 2007). Since these trends will continue within the near future, it is crucial to determine the effects of climate change on the performance and life-cycle assessment of deteriorating infrastructure systems.

This paper presents an overview of life-cycle management concepts for bridge systems under uncertainty and the application of such concepts in bridge sustainability considering the risk attitude of the decision maker. Risk- and sustainability-informed management of bridges under the effects of both gradual and sudden deteriorations is investigated. Quantifying the life-cycle performance, risk, and sustainability of bridges at the component and network levels is also addressed. Additionally, the effect of climate change on probabilistic performance is examined herein. Moreover, bridge management planning and optimization under a constrictive budget and performance constraints are presented through a probabilistic management framework. This framework can serve as a useful tool in risk mitigation and, in general, decision-making associated with bridges. The approach presented can provide optimal intervention strategies to the decision maker that will allow for risk- and sustainability-informed decisions regarding maintenance of individual bridges, bridge networks, and interdependent infrastructure systems during their lifetime.

2. Performance Evaluation and Prediction

Performance of bridge structures can be quantified at the cross-section, component, whole structure (system), group of structures (network), and network of networks levels. In most of the current bridge design and assessment codes, performance requirements are based on component strength. Typically, performance assessment activities associated with bridge components rely on visual inspections results. For bridges, visual inspection results are usually employed to establish a condition rating index to indicate the bridge’s remaining load-carrying capacity. The bridges in the United States are rated using two different methods based on visual inspection. The first method uses the National Bridge Inventory (NBI) condition rating system (FHWA 2013). According to the NBI condition rating system, the condition evaluation corresponds to the physical state of the deck, superstructure, and substructure components of a bridge. The second method uses the element-level condition rating method to represent the conditions of bridge components. Generally, bridge management systems characterize the performance of structural elements by discrete condition states which incorporate predefined degrees of damage (Hawk and Small 1998, Thompson *et al.* 1998). Based on the identified condition states, maintenance interventions may be prioritized among all inspected structural components.

The Pontis (Thompson *et al*. 1998) and another bridge management system BRIDGIT (Hawk and Small 1998) consider discrete condition states and Markovian deterioration modeling. Research efforts have integrated these discrete condition states within the life-cycle management and intervention optimization associated with deteriorating infrastructure systems. Most of these approaches incorporate Markov chain models to depict the structural deterioration process. The main element of a Markov chain model is the transition matrix that specifies the probability that the state of a component changes to another state within a specified period of time. Note that the condition index is a subjective measure which may not realistically reflect the true load-carrying capacity of structural members (Liu and Frangopol 2006b, Saydam *et al.* 2013).

Although such an approach may ensure an adequate level of safety of components, it does not provide information about the interaction between the components and overall performance of the whole structure (Saydam and Frangopol 2011). Accordingly, other performance indicators capable of properly modeling the structural performance, while considering various uncertainties associated with resistance and load effects, have been developed and adopted in the life-cycle management of deteriorating infrastructure systems. Structural reliability theory offers a rational framework for quantification of system performance by including both aleatory and epistemic uncertainties, and correlations among random variables.

2.1 Reliability

Structural reliability can be defined as the probability that a component or a system will adequately perform its specified purpose for a prescribed period of time under particular conditions (Paliou *et al.* 1990, Leemis 1995). Component, as well as system reliability can be computed for the investigated infrastructure considering that failure of a single component or a combination of individual components may initiate the failure of the system. For instance, if R and S represent the resistance and the load effect, respectively, the probability density functions (PDFs) f_R and f_S, characterizing these respective random variables may be established. The probability that S will not exceed R, $P(R > S)$, represents the reliability. As a general case, the time-variant probability of failure $p_F(t)$ can be expressed in terms of joint PDF of the random variables $R(t)$ and $S(t)$, $f_{R,S}(t)$, as:

$$p_F(t) = \int_0^{\infty}\left(\int_0^{s} f_{R,S}(t)\,dr\right)ds \qquad (1)$$

Furthermore, the reliability index can be expressed as:

$$\beta(t) = \Phi^{-1}(1 - p_F(t)) \tag{2}$$

where $\Phi^{-1}(\cdot)$ is the inverse of the standard normal cumulative distribution function (CDF). In addition to evaluating the probability of structural failure at a given point in time, it is also possible to consider various functionality aspects that affect infrastructure systems such as serviceability limit states.

In general, bridge performance can be evaluated by modeling the bridge system as series or parallel or series-parallel combination of bridge components (Hendawi and Frangopol 1994). It is possible to evaluate the reliability of entire bridge structural system by making appropriate assumptions (e.g., series, parallel, or series-parallel assumptions) (Ditlevsen and Bjerager 1986, Thoft-Christensen and Murotsu 1986, Rashedi and Moses 1988) regarding the interaction among individual components. Another approach for reliability assessment of bridges makes use of finite element (FE) analysis, if the overall non-linear system behavior is of interest. A proper statistical distribution for the output of FE analysis (e.g., stress, displacement, bending moment) can be obtained by repeating the analysis for a large number of samples of the random variables associated with the structure. However, for complex structures, the time required to repeat FE analysis many times may be impractical. In such cases, Response Surface Methods (RSMs) can be used to approximate the relation between the desired output of FE analysis and random variables by performing analyses for only a significantly less number of samples. The RSM has also been implemented in system reliability of bridge superstructures (Liu *et al*. 2001), substructures (Ghosn and Moses 1998), and bridge systems (Yang *et al*. 2004, Okasha and Frangopol 2010a). Additionally, Enright and Frangopol (1999a, b) used the failure path method to compute the reliability function of a general (i.e., series-parallel) system and developed the computer program RELTSYS for this purpose (Enright and Frangopol 2000). Lifetime functions (Leemis 1995) are adopted for the time-dependent reliability approach, and have been utilized for the life-cycle performance prediction of bridge structures (Barone and Frangopol 2013a, b, 2104a, b). Establishing the lifetime function system reliability may be carried out utilizing various methods such as the minimal path and cut sets approaches (Hoyland and Rausand 1994, Leemis 1995).

2.2 Life-Cycle Cost

One of the most important measures in the evaluation of bridge performance is life-cycle cost. The proper allocation of resources can be achieved by minimizing the total cost while keeping structural safety at a desired level. The expected total cost during the lifetime of a bridge structure can be expressed as (Frangopol *et al*. 1997)

$$C_{ET} = C_T + C_{PM} + C_{INS} + C_{REP} + C_F \tag{3}$$

where C_T is the initial cost, C_{PM} is the expected cost of routine maintenance cost, C_{INS} is the expected cost of inspections, C_{REP} is the expected cost of repair, and C_F is expected failure cost. Assuming the occurrence of the hazard (e.g., earthquake, flood) as a Poisson process, the total life-cycle failure loss of a bridge during the time interval [0, t_{int}] can be computed (Dong and Frangopol 2016b)

$$C_F(t_{\mathrm{int}}) = \sum_{i=1}^{N(t_{\mathrm{int}})} l(t_k) \cdot e^{-\gamma t_k} \tag{4}$$

where t_{int} is investigated time interval; $N(t_{int})$ is the number of hazard events that occur during the time interval; $l(t_k)$ is the expected annual hazard loss at time t_k given the occurrence of the hazard; and γ is the monetary discount rate. Based on Yeo and Cornell (2005), given the Poisson model with mean rate equal to λ_f, the time t_k follows a uniform distribution over the interval [0, t_{int}].

Given $N\ (t_{int}) = \lambda_f \times t_{int}$, the total expected failure loss under hazard effects can be computed (Ross 2000, Yeo and Cornell 2005)

$$E[C_F(t_{\text{int}})] = \frac{\lambda_f \cdot E(l)}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\text{int}}}) \tag{5}$$

where $E(l)$ and $\sigma(l)$ are the expected value and standard deviation of annual loss l of bridge given a hazard event, respectively. The expected total loss under different hazard scenarios in a life-cycle context is shown in Figure 3. As indicated, various hazard scenarios may dominate the expected total loss at different time intervals during a structure's life-cycle. Numerous research efforts have focused on balancing cost and performance to determine optimum planning for life-cycle management of civil infrastructure systems (Chang and Shinozuka 1996, Frangopol *et al*. 1997, Frangopol and Furuta 2001, Frangopol *et al*. 2001, Estes *et al*. 2004, Ang and De Leon 2005, Estes and Frangopol 2005, Okasha and Frangopol 2010a).

2.3 Risk

Risk is quantified by combining the probability of occurrence and the consequences of events generated by hazards. In general, the instantaneous total risk R of a structural system can be formulated as (CIB 2001)

$$R = \iint \cdots \int \kappa(x_1, x_2, \ldots, x_m) \\ f_{\mathbf{X}}(x_1, x_2, \ldots, x_m) \cdot dx_1 \cdot dx_2 \cdots dx_m \tag{6}$$

where $\kappa(\mathbf{x})$ denotes the consequences associated with events resulting from hazards and $f_{\mathbf{X}}(\mathbf{x})$ is the joint PDF of the random variables involved. The m-fold integral in Eq. (6) is difficult to assess and often cannot be solved. Therefore, assumptions are established in order to obtain a simpler expression for total risk. A simplistic approach for calculating instantaneous total risk R is (Ellingwood 2005)

$$RISK(t) = \sum_{i=1}^{n} C_m(t) \cdot P_{F|H_i} \cdot P(H_i) \tag{7}$$

where C_m represents the consequences of failure, $P(H_i)$ describes the probability of occurrence of a hazard, $P_{F|Hi}(t)$ is the conditional failure probability given the occurrence of a hazard, and n is the total number of hazards considered within the analysis.

Several research efforts have been conducted on the risk assessment of bridge structures. Cesare *et al*. (1993) calculated the total risk associated with a bridge using the reliability and consequences of closure of the bridge. Stein *et al*. (1999) used risk concepts for prioritizing scour-vulnerable bridges. Adey *et al.* (2003) focused on the risk assessment of bridges affected by multiple hazards. Lounis (2004) presented a multi-criteria approach regarding bridge structural assessment with emphasis on risk. Similarly, Stein and Sedmera (2006) proposed a risk-based approach for bridges performance evaluation in the absence of information on bridge foundations. Ang (2011) focused on life-cycle considerations in risk-informed decision making for the design of civil infrastructure. Decò and Frangopol (2011) developed a rational framework for the quantitative risk assessment of highway bridges under multiple hazards. Saydam *et al.* (2013) presented an illustrative example for the time-variant expected losses associated with the flexural failure of girders; a risk-based robustness index was calculated for an existing bridge. Furthermore, risk analysis was utilized to assess the performance of networks of infrastructure systems (Frangopol and Bocchini 2012, occhini and Frangopol 2012, Bocchini and Frangopol 2013, Dong *et al.* 2014a). For example, the time-dependent expected losses of deteriorated highway bridge networks were investigated by Saydam *et al*. (2013). Additionally, Decò and

Frangopol (2011, 2013) and Dong *et al*. (2014a, b) proposed a computational framework for the quantitative assessment of life-cycle risk of multiple bridges within a transportation network including the effects of seismic and abnormal traffic hazards. Overall, risk, as a performance indicator, can offer valuable information regarding the performance of individual structures or spatially distributed systems, such as buildings, bridges, and bridge networks.

2.4 Sustainability

Within the field of life-cycle engineering, two definitions of sustainability are usually referred to when developing appropriate sustainability metrics. The first defines it as: "meeting the needs of the present without comprising the ability of future generations to meet their own needs" (Adams 2006). The second definition complements the first one by emphasizing that economic, environmental, and social objectives must be simultaneously satisfied within a sustainable design or plan (Elkington 2004). It is important to quantify the performance of bridges and networks of structural systems whose functionality is vital for economic and social purposes. Generally, sustainability should be quantified in terms of economic, social, and environmental metrics as indicated in Figure 4.

Recent research efforts have considered a wide variety of risks in order to effectively quantify sustainability. For instance, Dong *et al.* (2013) presented a framework for assessing the time-variant sustainability of bridges associated with multiple hazards considering the effects of structural deterioration. Their approach was illustrated on a reinforced concrete (RC) bridge and the consequences considered within the risk assessment were the expected downtime and number of fatalities, expected energy waste and carbon dioxide emissions, and the expected loss. Overall, the inclusions of societal and environmental impacts along with economic consequences effectively encompass the concept of sustainability within the risk analysis framework.

Combining the economic, societal, and environmental risk metrics allows engineers and decision makers to make informed decisions based on sustainability by providing them with a complete picture of system performance (Lundie *et al*. 2004, Shinozuka 2008).

Generally, a structure is more sustainable if its life-cycle cost (i.e., construction, inspection, maintenance, repair, failure, and replacement costs) is low and energy waste, carbon dioxide emissions, and user delays arising from its maintenance and repair are low. The social metrics can include downtime and fatalities. The downtime due to detour associated with bridge failure can be computed as (Stein *et al.* 1999)

$$DT = d \cdot ADT \cdot \frac{D}{S} \tag{8}$$

where d is the duration of the detour (days), ADT is the average daily traffic to follow detour, D is the detour length (km), and S is the detour speed (km/h). Here, the downtime can be referred to as the social metric of sustainability. The environmental metric includes the energy consumption, global warming potential, and air pollutant emission, among others. Commonly considered environmental metrics including energy waste and carbon dioxide emissions are emphasized herein. The environmental metric associated with traffic detour is expressed as (Kendall *et al.* 2008)

$$EN_{DT} = ADT \cdot D \cdot d \cdot \left[Enp_{car} \cdot \left(1 - \frac{T}{100}\right) + Enp_{truck} \cdot \frac{T}{100} \right] \tag{9}$$

where Enp_{car} and Enp_{truck} are environmental metric per unit distance for cars and trucks (e.g., carbon dioxide kg/km) and T is daily truck traffic ratio (i.e., percentage of average daily total traffic). The environmental metric associated with the repair action is computed as

$$EN_{RE} = \left(Enp_{steel} \cdot V_{steel} + Enp_{conc} \cdot V_{conc} \right) \cdot RCR \tag{10}$$

where Enp_{steel} and Enp_{conc} are environmental metric per unit volume for steel and concrete, respectively (e.g., carbon dioxide emissions kg/m^3), V_{steel} and V_{conc} are the volume of steel and concrete, respectively (m^3), and RCR is the repair cost ratio associated with a certain damage state. The fatalities associated with the failure of a highway bridge can also be computed considering its damage states. The time-variant sustainability of a bridge under a given hazard in terms of economic, social, and environmental metrics is qualitatively shown in Figure 5 (Dong *et al.* 2014a). In this figure, the social and environmental metrics are measured in monetary units and compared with the economic loss.

2.5 Utility

Utility theory is utilized in order to depict the relative desirability of maintenance strategies to the decision maker. In general, utility is defined as a measure of value to the decision maker. Utility theory provides a framework that can measure, combine, and consistently compare these relative values (Ang and Tang 1984). Multi-attribute utility theory may be used to transfer the marginal utility of each attribute involved in the performance assessment (e.g., economic, social, and environmental risks) into one utility value that effectively combines the effects of all risks investigated as shown in Figure 6 (Dong *et al.* 2015, Sabatino *et al.* 2015a). Next, all possible solution alternatives are identified and the uncertainties associated with the investigated decision making problem are accounted for by using a probabilistic approach. Since technical and economic uncertainties are both expected and unavoidable in the life-cycle assessment of bridges, decisions regarding life-cycle management must consider all relevant uncertainties associated with failure and its corresponding consequences. In this process, it is usually assumed that there is a single decision maker who possesses a predetermined risk attitude with respect to a specific system.

Utility theory is employed herein in order to effectively capture the sustainability performance of highway bridges and bridge networks and impact of the decision maker's risk attitude. Once the utility function associated with each attribute of sustainability is appropriately established, a multi-attribute utility that effectively represents all aspects of sustainability can be obtained by combining the utility functions associated with each attribute (Sabatino *et al.* 2015b). Within the additive formulation for the multi-attribute utility function, utility values associated with each attribute are multiplied by weighting factors and summed over all attributes involved. The multi-attribute utility associated with a structural system can be computed as (Jiménez *et al.* 2003)

$$u_S = k_{Eco} u_{Eco} + k_{Soc} u_{Soc} + k_{Env} u_{Env} \tag{11}$$

where k_{Eco}, k_{Soc}, and k_{Env} are the weighting factors corresponding to each sustainability metric and u_{Eco}, u_{Soc}, and u_{Env} are the marginal utilities for the economic, social, and environmental attributes, respectively. Overall, the proposed global strategy may be adopted for a variety of applications, including but not limited to bridges, buildings, and infrastructure networks.

3. Consideration of Hazards within a Life-cycle Context

3.1 Live Load and Corrosion

The structural performance associated with a specific bridge limit state varies with respect to time due to the increasing live load effects (e.g., by the growing demand of increasing traffic volume) and the progressive deterioration of the mechanical properties (e.g., due to corrosion). The investigated flexural and shear failure modes are those related to the bridge superstructure members (e.g., deck and girders). The deterioration of the flexural and shear capacities over time is induced by corrosion. Several researchers have studied probabilistic models for predicting the time-dependent deterioration of structural members due to corrosion (Val *et al*. 1998, Vu and Stewart 2000, Budelmann and Hariri 2006, Marsh and Frangopol 2008, Akiyama *et al.* 2012, Stewart 2012, Val and Chernin 2012, Cavaco *et al*. 2013, Budelmann *et al*. 2014).

AASHTO (2015) specifications are adopted for the estimation of the load effects and capacities at each critical section. Additionally, the increase over time of the live load moments is predicted considering traffic data, such as the average daily truck traffic, and by applying the statistics of extremes (Cohen *et al*. 2003, Akgül 2004a, b, O'Connor and O'Brien 2005).

System reliability and redundancy have been extensively studied. Such studies include time-invariant measures (Moses 1982, Frangopol and Curley 1987, Paliou *et al*. 1990, Frangopol and Nakib 1991, Mori and Ellingwood 1993, Frangopol 1997, Ghosn and Moses 1998, Bertero and Bertero 1999, Frangopol *et al*. 2001, Liu *et al*. 2001, Imai and Frangopol 2002, Ghosn *et al.* 2003, Ghosn and Frangopol 2007, Biondini *et al*. 2008) and time-variant measures (Ellingwood and Mori 1993, Enright and Frangopol 1999a, b, Estes and Frangopol 1999, 2001, Akgül and Frangopol 2004a, b, Yang *et al.* 2004, Estes and Frangopol 2005, Yang *et al.* 2006a, b, Okasha and Frangopol 2010a).

3.2 Fatigue and Fracture

Application of loads on structural components may produce fracture and cause failure if the load is applied cyclically a large number of times. Fatigue failure is due to the progressive propagation of flaws in structural materials under cyclic loading. Fatigue failure is particularly common at the stress concentration at the tip of cracks. These stress concentrations may occur in the component due to discontinuities in the material itself and are not serious when a ductile material like steel is subjected to a static load, as the stresses redistribute themselves to other adjacent elements within the structure.

Fatigue failure involves four stages (Sumi 1998): (1) crack initiation at points of stress concentration, (2) crack growth, (3) crack propagation, and (4) rupture. Generally, fatigue failures are classified into two categories: low-cycle and high-cycle failures, depending upon the number of cycles. Low-cycle fatigue failure occurs under high stress/strain ranges. On the other hand, high-cycle fatigue failure requires very large number of cycles. The most common form of fatigue damage is evaluated using the S-N curve, where the total cyclic stress (S) is plotted against the number of cycles to failure (N) in a logarithmic scale as shown in codes and standards. To carry out fatigue life predictions, a linear fatigue damage model is used in conjunction with relevant S-N curves. Kwon and Frangopol (2010) investigated the bridge fatigue reliability assessment using PDFs of equivalent stress range based on field monitoring data. Newhook and Edalatmanesh (2013) integrated reliability and structural health monitoring in the fatigue assessment of concrete bridge decks. Stamatopoulos (2013) proposed a general approach to consider the fatigue assessment and strengthening measures of a steel railway bridge. Maekawa and Fujiyama (2013) investigated crack- water interaction and fatigue life assessment of RC bridge decks. Nagy *et al.* (2013) presented an approach to improve the fatigue life of orthotropic bridge decks based on fracture mechanics. Pipinato (2014) investigated the high-cycle fatigue behavior of riveted connections for railway metal bridges. Furthermore, the fatigue damage deterioration has been investigated by Garbatov and Guedes Soares (2001), Bastidas-Arteaga *et al.* (2009), Kim and Frangopol (2011a), and Kwon and Frangopol (2011).

3.3 Extreme Events

The United Nations Office for Disaster Risk Reduction (UNISDR) reported that, in 2011, natural disasters (e.g., earthquakes, floods, and tsunamis) resulted in $366 billion of direct economic losses and 29,782 fatalities worldwide (Ferris and Petz 2011). These staggering statistics highlight the need for effective hazard recovery strategies associated with urban structural systems. Within the last few decades, the occurrence of disruptive, low-probability, high-consequences extreme events across the globe has shifted the focus of scientific communities and decision makers to develop approaches which can improve the resilience of infrastructure to disasters. In general, earthquake resilience in civil engineering can be defined as (Bruneau *et al.* 2003) “the ability of social units (e.g., organizations and communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes”. The most widely adopted approach to quantify the resilience of an individual structure, a group of structures, or a network of interrelated structures is to compute the resilience as the integration over time of the functionality (Cimellaro *et al.* 2010, Frangopol and Bocchini 2011, Bocchini *et al.* 2014)

$$RE = \frac{1}{t_r} \int_{t_0}^{t_0+t_r} Q(t)dt \tag{12}$$

in which $Q(t)$ is the functionality, t_o is the occurrence time of the extreme event, and t_r is the investigated time horizon. The resilience, as computed by Eq. (12), can be illustrated graphically as shown in Figure 7 for multiple extreme events during the life-cycle of a system (Dong *et al.* 2014c). Regarding the seismic performance analysis, the first step in seismic vulnerability assessment is to identify the seismic intensity associated with the location of the structural system under investigation (Dong and Frangopol 2015). A number of seismic scenarios should be generated within the region of interest. The generated scenarios should be able to approximate the actual seismic activity of the geographical area. Subsequently, an attenuation equation is used to predict the ground-motion intensity at a certain location (Campbell and Bozorgnia 2008).

Fragility curves are commonly used to predict structural performance under seismic hazard. Due to time effects, the fragility curves should be evaluated throughout the lifetime of a structure. The time-variant fragility curves can be computed as

$$P_{S\geq DS_i|IM}(t)=\Phi\left(\frac{\ln(IM)-\ln(m_i(t))}{\beta_i(t)}\right) \tag{13}$$

where Φ(.) is the standard normal cumulative distribution function, *IM* is the seismic intensity measure (e.g., peak ground acceleration), $\beta_i(t)$ is the standard deviation of the damage state *i* of the structural fragility at time *t*, and m_i is the median value of ground motion intensity associated with damage state *i*. For a given ground motion intensity, the probability of a bridge being in a damage state *i* is given by the difference between the probabilities of exceedance of damage states *i* and *i+1*, where damage state *i+1* is more severe than damage state *i*. These conditional probabilities can be mapped to the bridge damage index (*BDI*) value (Shiraki *et al.* 2007). *BDI* can be evaluated by mapping the bridge damage states given the ground acceleration based on realization of a value between 0 and 1. A *BDI* of 1.0 indicates collapse and 0 corresponds to no damage following an earthquake. The expected *BDI* can be obtained by multiplying the probability of being in each damage state with the corresponding damage factor. Accordingly, the time-variant expected *BDI* of a bridge with four damage states DS_i for a certain ground motion intensity *IM* is

$$\begin{aligned}BDI(t)&=BDI_1\cdot P_{DS_1|IM}(t)+BDI_2\cdot P_{DS_2|IM}(t)\\&+BDI_3\cdot P_{DS_3|IM}(t)+BDI_4\cdot P_{DS_4|IM}(t)\end{aligned} \tag{14}$$

where BDI_i is the bridge damage index for the respective damage state *i*.

A transportation network is defined in terms of nodes and links. A link is considered to be a single element connecting the nodes of a network. Bridges are typically the most vulnerable structures in a network and should be specially considered (Liu and Frangopol 2005a). Following an earthquake, the damaged bridges can be open, closed, or partially open within a bridge network. Consequently, traffic flow in the links can be different and speed limits might be reduced for various damage conditions of the link. As there may be several bridges located on the link, the damage state of each bridge can affect the functionality of the investigated link. The performance of a link after an earthquake can be expressed in terms of link damage index (*LDI*) which depends on the *BDI*s of the bridges on the link. Due to the fact that the seismic vulnerability of a bridge deteriorates with time, *LDI* should also be updated during the investigated time horizon of the transportation networks. The time-variant *LDI* can be expressed as (Chang *et al.* 2000)

$$LDI(t) = \sqrt{\sum_{j=1}^{n} (BDI_j(t))^2} \quad (15)$$

where n is the number of the bridges located in the link, and BDI_j is the expected damage index for bridge j. The level of link traffic flow capacity and flow speed for a damaged link depends on *LDI*. The intact, slight, moderate, and major damage states are associated with $LDI \leq 0.5$, $0.5 < LDI \leq 1.0$, $1.0 < LDI \leq 1.5$, and $LDI > 1.5$, respectively (Chang *et al.* 2000). The increase in the damage state of the link will reduce the link traffic capacity and speed limit

Strong earthquakes can destroy infrastructure systems and cause injuries and/or fatalities. Therefore, it is important to investigate the seismic performance of interdependent healthcare – bridge network systems to guarantee immediate medical treatment after earthquakes. The assessment of healthcare – bridge network system performance depends on the seismic vulnerability of a hospital and bridges located in a surrounding bridge network, in addition to the ground motion intensity. After a destructive earthquake, the functionality of a highway network can be affected significantly; this, in turn, may hinder emergency management. Additional travel time would result due to the damaged bridges and links; consequently, injured persons may not receive treatment in time. Thus, it is important to account for the effects of damage condition associated with highway bridge networks on the healthcare system performance. Myrtle *et al.* (2005) carried out a series of surveys on performance of hospitals during several earthquakes to identify the important components; Yavari *et al*. (2010) investigated performance levels for interacting components (i.e., structural, nonstructural, lifeline, and personnel) using data from past earthquakes; Achour *et al.* (2011) investigated the physical damage of structural and non-structural components of a hospital under seismic hazard; and Cimellaro *et al.* (2011) introduced a model to describe the hospital performance under earthquake considering waiting time. Dong and Frangopol (2016c) investigated the functionality of healthcare system considering the damage conditions associated with bridge networks and the correlation effects. The flowchart used to compute the performance of interdependent healthcare-bridge network is shown in Figure 8.

The damage of electric power, telecommunications, transportation, and water systems due to hazard effects can cause enormous social disruption. Therefore, it is of vital importance to investigate the performance of these interdependent networks subjected to hazard effects considering interdependencies in a large scale. Modeling the interaction between component and system is also important for assessing the risk and resilience of infrastructure systems. In order to understand the behavior of these essential networks (e.g., power, communication, transportation, and water systems), their properties in terms of global connectivity, local clustering, and overall shape should be evaluated considering the failure modes associated with both individual components and the interdependent systems. Then, methods and metrics to assess the performance of infrastructure networks, the evolution of their performance over time, and the interdependencies among different networks should be developed. This will contribute to the improvement of the performance-based design and management methods of interdependent infrastructure systems at the community level considering the interdependency among these infrastructure systems. (Duenas-Osorio *et al.* 2007, Franchin 2014, Ghosn *et al.* 2016).

The consequences associated with the structural damage/failure under natural hazards (e.g., seismic events) include both direct and indirect consequences (Ellingwood 2006), and can be expressed in terms of economic, social, and environmental metrics. Earthquakes can disrupt traffic flow and affect emergency responses and recovery operations which may yield much higher consequences than the repair or rebuilding costs of a damaged infrastructure system. For the proper sustainability and risk analyses, the consequences associated with structural failures should include the economic, social and environmental metrics, including rebuilding, running, time loss, and environmental costs, among others. The uncertainty in the parameters associated with the consequence evaluation should be incorporated within the assessment process. The probability density functions of the repair loss with and without considering the correlation effects are qualitatively shown in Figure 9 (Dong *et al.* 2014a). As indicated, the correlation effects have a large effect on the dispersion of the repair loss.

Bridges also suffer exposure of their pier foundations under scour, which significantly reduces the foundation bearing capacity and can cause structural damage or even collapse during floods (Dong and Frangopol 2016b). Scour is one of the main bridge failure causes in the United States accounting for about 58% of all failures (Briaud *et al.* 2004). It is of vital importance to evaluate the performance of bridges under flood. Generally, there are three types of scour: long-term aggradation and degradation, contraction scour, and local scour (Lagasse *et al.* 2009).

As bridges are subjected to the exposure of pier foundations under flood-induced scour, bearing capacities of their foundations can be reduced significantly causing bridge damage or even collapse. Extensive research has been conducted on the prediction of local scour depth and a number of predictive methods have been proposed (Melville 1997, Briaud *et al.* 1999, Richardson and Davis 2001, Briaud *et al.* 2004). Given the flood intensity and occurrence probability, the bridge vulnerability under flood can be analyzed considering both vertical and lateral failure modes (Dong and Frangopol 2016b). The load capacity of a bridge pile is directly related to the interaction between the piles and the surrounding soil. A lack of lateral confinement could result in lateral failure of the pile under flow-induced load and the axial load arising from the weight of the superstructure (Zhang *et al*. 2005). Vertical failure refers to the bridge failure in the vertical direction, which can be caused by inadequate soil support or pile instability.

During their life-cycle, bridges can be subjected to multiple hazards. Thus, it is necessary to consider the performance of bridges under multiple hazards in the hazard assessment and mitigation procedure, all in a life-cycle context. For example, the flood-induced scour can reduce lateral support of a bridge at foundation and has a major effect on the seismic bridge vulnerability as indicated in Figure 10. The local scour induces the erosion of the soil around the pier and reduce the capacity of the foundation. Although the joint probability of occurrence of multiple hazards is small, past experience shows that successive occurrences of extreme events happen. Due to the effects of global warming and climate change, the frequency, intensity, and magnitude of the hazards are increasing. Hence, it is required to consider the effects of flood-induced scour in the seismic loss assessment, especially for bridges located in seismically flood-prone zones. Additionally, for bridges that span rivers, traffic loading and scour are the two primary causes of failure and lane closure (Zhu and Frangopol 2016a, b). Therefore, these two hazards need to be considered in the risk assessment process. An efficient approach for assessing time-variant risks associated with the closure of bridge lanes due to traffic loading and scour is needed. The effects of hazards on bridges have been investigated including, scour (Stein *et al.* 1999, Zhu and Frangopol 2016a, b), airborne chlorides (Akiyama *et al.* 2012, Titi *et al.* 2014, 2015), tsunami (Akiyama *et al*. 2013) and a combination of hazards (Akiyama *et al.* 2011, Decò and Frangopol 2011, Dong *et al.* 2013, and Zhu and Frangopol 2013b, 2016a, b).

3.4 Climate Change

According to the Intergovernmental Panel on Climate Change, the "scientific evidence for warming of the climate system is unequivocal (NASA 2015)." Measurements taken over the last decades indicate that the sea level, global temperature, and ocean temperature are all rising at elevated rates (Allison *et al.* 2009, Church and White 2006, 2011, Levitus *et al.* 2009, Peterson and Baringer 2009). Additionally, the sea ice in the artic region is rapidly melting and glaciers are retreating almost everywhere around the world (Kwok and Rothrock 2009, Polyak *et al.* 2010). Moreover, a significant increase of carbon dioxide (CO_2) concentration in the atmosphere has been observed (IPCC 2007). Since these trends are projected to continue within the near future, it is crucial to determine the effects of climate change on the performance and life-cycle assessment of deteriorating infrastructure systems. The United States Global Change Research Program (USGCRP 2008) reported that the average precipitation has increased 5% during a 50 years interval; consequently, the frequency of hazards (e.g., flood) has increased as well as they have become more intense. In general, climate change and increase in hazard intensity contribute to an increase in the probability of bridge failure due to hazard effects. Accordingly, the effects of climate change on the loss of bridges under hazard effects in a life-cycle context is qualitatively shown in Figure 11. Understanding how climate change affects the life-cycle performance of bridges can lead to improved preparedness prior to extreme disasters.

Although scientists agree that the climate is, in general, changing, there is a significant uncertainty associated with identifying the location, timing, and magnitude of changes over the lifetime of bridges and other infrastructure systems. In order to account for the uncertainties associated with the performance assessment of highway bridges considering climate change, it is crucial to utilize risk methodologies to incorporate detrimental consequences of structural failure and identify the critical infrastructure that is most threatened by change climate in a given region (Committee on Adaptation to a Changing Climate 2015).

One of the greatest concerns regarding climate change of highway bridges is the rising global temperature. If bridges are subjected to more days with sustained air temperature above 32°C, the integrity of the pavement may suffer and deterioration in roadway and bridge expansion joints may occur (Schwartz *et al*. 2014). Furthermore, the construction productivity and costs of management activities, such as repair and rehabilitation interventions, maybe adversely affected by forcing shortened workdays or overnight work periods (TRB 2014). In conjunction to rising temperature, the effect of increased levels of atmospheric CO_2 on highway bridges is significant. Stewart *et al.* (2011) illustrated that the increase in air temperature and CO_2 levels associated with climate change will increase the likelihood and rate of carbonation-induced corrosion. They also presented an approach that predicts the probability of corrosion initiation and damage for concrete infrastructure subjected to carbonation and chloride-induced corrosion resulting from elevated CO_2 levels and temperatures. The effects of increases in the rate and occurrence of carbonation-induced corrosion on the performance of concrete bridges are significant and cannot be ignored. Carbonation-induced damage risks may increase by more than

16%, which indicates that one in six structures may be subjected to additional corrosion damage by 2100 (Stewart *et al*. 2012).

In addition to rising temperatures and CO_2 in the atmosphere, climate predictions indicate that the frequency of heavy precipitation events may increase over time. For highway bridges, an increased amount of precipitation may cause increases in soil erosion rates and soil moisture levels, causing road washouts and damage to foundations of roads, bridges, and other transportation infrastructure systems (TRB 2008). Overall, bridge failure due to scour during a heavy precipitation event is an extremely significant concern.

Moreover, bridges located in coastal regions are the most vulnerable to adverse climate change effects. Rising sea levels, combined with potentially more intense storm events and regional subsidence pose great threats to coastal deteriorating infrastructure systems (Schwartz *et al*. 2014, TRB 2014). Storm surge paired with increased wave action can lead to bridge scour and increased erosion of roads, supporting structures, and foundations (TRB 2008). The rising sea levels can facilitate saltwater intrusion that accelerates corrosion and ultimately causes a reduction of predicted service-life, an increase in maintenance costs, and an increase in probability of structural failure during extreme events (TRB 2014).

Due to its significant effects on the global temperature, atmospheric CO_2 measurements, and sea levels, climate change must be considered within the life-cycle performance assessment of deteriorating civil infrastructure. By accounting for the uncertainties associated with rising temperature, increased amounts of atmospheric CO_2, and rising sea levels, the effects of climate change on the life-cycle performance evaluation of highway bridges may be properly and accurately carried out.

4. Integration of SHM and Updating in Bridge Management

Structural health monitoring (SHM), inspection, and updating provide a powerful method to reduce uncertainty, calibrate, and improve structural assessment and performance prediction models (Onoufriou and Frangopol 2002, Bucher and Frangopol 2006, Klinzmann *et al*. 2006, Frangopol and Messervey 2007, Catbas *et al.* 2008, Frangopol *et al*. 2008, Frangopol and Messervey 2008, Gul and Catbas 2011, Frangopol and Kim 2014b). Life-cycle management approaches offer bridge managers a practical predictive view of cost, safety, and condition, but in many regards lack knowledge of actual structural performance. In contrast, SHM techniques effectively capture structural behavior and the demands on a structure, but are not as effective in translating this information into actionable data for bridge managers. Consequently, it is of vital importance to incorporate SHM and updating in the life-cycle management framework.

Monitoring can provide data to confirm or improve existing load factors, resistance factors, and load combinations for extreme events. In the past, many studies have been undertaken to model the performance of in-service bridges over time (Liu *et al.* 1997, Ghosn and Moses 1998, Enright and Frangopol 1999a, b, Ghosn 2000, Ghosn *et al*. 2003, Glaser *et al.* 2007, Frangopol *et al*. 2008). Bush *et al*. (2013) presented an innovative approach to bridge management that provides guidance on the type of data to collect, the accuracy and precision required in the data collection process, the frequency of inspections, and the recommended SHM techniques to be used. Similarly, Sousa *et al*. (2013) discussed the application of a SHM system to an RC bridge. The extraction of useful information from SHM data from highway bridges was reviewed by Westgate *et al*. (2013). A novel SHM data processing technique, denoted as singular spectrum analysis, was utilised by Chao and Loh (2013) and applied to a bridge foundation to determine scour and pier settlement. Additionally, Huston *et al*. (2011) studied the non-destructive evaluation of a bridge by comparing five different methods: (a) visual inspection and photographic recording, (b) half-cell electrochemical potential, (c) impulse type multipoint scanning ground penetrating radar, (d) chain drag, and (e) impact echo. Ko *et al*. (2013) aimed to enhance facility management efficiency using radio frequency identification technology.

Information associated with inspection events can be used to update deterioration models of a structural system to reduce uncertainty. The structural details associated with a given system are correlated due to common parameters associated with materials, design, fabrication, loading, and operational conditions. Based on these correlations, the inspection information of one particular component can be used to update deterioration performance of others uninspected components. Probabilistic models have been used to evaluate and update the fatigue reliability using inspection information and are emphasized herein. These models can be used to determine the optimal number of inspected details to make the inspection strategies efficient and economic. Moan and Song (2000) investigated reliability-based fatigue damage assessment and updating details in parallel/series systems. Chen *et al*. (2003) proposed a methodology for inspection planning on the basis on Palmgren-Miner's rule. Huang *et al*. (2013) computed the reliability index of a complex welded structure as a series model under multiple cracks. Maljaars and Vrouwenvelder (2014) presented a reliability-based updating considering multiple critical locations of a bridge. Based on the bridge component/system reliability and risk, the inspection planning and repair priority among the investigated sensitive systems can be identified. In turn, the inspection results can be used to update risk and the timing for the following inspection and management plans based on risk. In this paper, the updating associated with fatigue sensitive details is illustrated. Generally, if no fatigue crack is detected, the updating can be performed within the original fatigue limit state. If repair actions are conducted, the physical changes need to be considered in the estimation of limit state function. The updated probability of failure of the *i*th component under fatigue damage given inspection event *j* can be formulated as follows (Moan and Song 2000)

$$P_{\mathrm{i,\,up}} = P[M_i(t) \le 0 \,|\, IE_j(t_{IE})] = \frac{P[(M_i(t) \le 0) \cap IE_j(t_{IE})]}{P[IE_j(t_{IE})]} \tag{16}$$

where M_i is limit state function associated with detail i, IE_j is the inspection event j, and t_{IE} is the inspection time. The results of inspection are utilized for reliability and risk ranking updating associated with inspected and uninspected sensitive details. The updated reliability of the fatigue detail with and without using inspection information is qualitatively shown in Figure 12 (Dong and Frangopol 2016a). As indicated, given that a crack is detected, the reliability of the inspected detail decreases significantly without repair, in turn the risk associated with the detected detail would increase profoundly.

5. Probabilistic Life-Cycle Optimization

Life-cycle optimization is an essential task within the life-cycle management (LCM) framework (Chang and Shinozuka 1996, Frangopol 1998, Estes and Frangopol 1999, Frangopol 1999, Wen and Kang 2001, Ang and De Leon 2005, Kong and Frangopol 2005, Yang *et al*. 2006b, Okasha and Frangopol 2009, Soliman *et al*. 2013, Soliman and Frangopol 2014, Sabatino *et al*. 2015a, Frangopol and Soliman 2016). This process is performed using a probabilistic platform considering various uncertainties associated with LCM as shown in Figure 13. A maintenance optimization formulation requires one or more life-cycle performance indicators (Frangopol and Saydam 2014), such as system reliability, redundancy, and cost indicators (Augusti *et al.* 1998, Estes and Frangopol 1999, Yang *et al.* 2006b, Marsh and Frangopol 2007, Okasha and Frangopol 2009, Morcous *et al*. 2010, Okasha and Frangopol 2010a, Frangopol and Kim 2014a), condition indicators (Neves *et al*. 2004, Liu and Frangopol 2005b, Neves and Frangopol 2005, Liu and Frangopol 2006a, b, Frangopol and Liu 2007), probabilistic damage detection delay indicators (Kim and Frangopol 2011a, b, Soliman *et al.* 2013), and risk and sustainability-informed performance indicators (Zhu and Frangopol 2013a, Dong *et al.* 2014b, Sabatino *et al*. 2015a, b). Powerful optimization algorithms are also needed (e.g., Goldberg 1989, Deb 2001, Deb *et al.* 2002, Frangopol and Soliman 2013, 2015).

Planning retrofit actions on bridge networks under tight budget constraints were investigated by Dong *et al.* (2014b). They presented a probabilistic methodology to establish optimum pre-earthquake retrofit plans for bridge networks based on sustainability. A multi-criteria optimization problem was formulated to find the optimum timing of retrofit actions for bridges within a network. The role of optimization is to identify the most effective retrofit strategy in terms of which bridges to be retrofitted and the optimal times for retrofit actions.

Utility-informed decision making is necessary for optimum allocation of limited resources. In general, utility-informed decision making may be divided into five separate stages (Keeney and Raiffa 1993): the pre-analysis, problem set-up, uncertainty quantification, utility assignment, and optimization as shown in Figure 14. The application of utility-informed decision making in the optimal lifetime intervention on bridges is a topic of paramount importance and is experiencing growing interest within the field of life-cycle infrastructure engineering. This methodology can be used in assisting decision-making regarding the maintenance/retrofit activities to improve the performance of highway bridge network.

Sabatino *et al.* (2015a) presented a framework for life-cycle maintenance optimization of highway bridges that utilizes multi-attribute utility theory to quantify the sustainability performance metrics. The ultimate aim of implementing maintenance throughout the lifetime of a bridge is to mitigate the detrimental impacts of structural failure to the economy, society, and the environment. Optimum maintenance plans were obtained by carrying out a multi-criteria optimization procedure where the utility associated with total maintenance cost and utility corresponding to sustainability performance were considered as conflicting objectives. An existing highway bridge was utilized to illustrate the capabilities of the proposed decision support system for maintenance planning. The optimization was performed by simultaneously maximizing the utility associated with total maintenance cost and the annual minimum utility corresponding to the sustainability over the lifetime of the bridge.

The main results of the optimization procedure are the types maintenance actions performed on the bridge components and their respective times of application. The Pareto optimal solutions obtained considering three maintenance actions with a risk accepting and risk averse decision maker are shown in Figure 15. A solution is Pareto-optimal if there does not exist another solution that improves at least one objective without worsening another one. The weighting factors k_{econ}, k_{soc}, and k_{env} are all assumed to be the same (i.e., 1/3), representing equal contribution of detrimental economic, societal, and environmental impacts. The Pareto-optimal representative solutions A and B, denoting typical optimum maintenance plans resulting from a risk averse and risk accepting decision maker, respectively, are shown in Figure 15(a). The time-variant multi-attribute utilities associated with sustainability corresponding to representative solutions A and B are shown in Figure 15(b).

6. Conclusions

This paper presents a brief overview of the integration of risk, sustainability, and resilience measures into the LCM of deteriorating infrastructure systems with emphasis on bridges, bridge networks, and interdependent infrastructure systems considering climate change effects. The framework covers predicting the time-variant structural performance and the future interventions scheduling, including inspections, monitoring, maintenance, and/or repairs actions, such that an optimal management solution which satisfies the goals and constraints is achieved. Moreover, this generalized approach integrates risk and life-cycle loss assessment with multi-objective optimization techniques to determine optimum bridge and bridge network management plans to assist the decision maker. Various aspects of the LCM framework are briefly explained with special attention given to the performance assessment and the life-cycle optimization processes. The performance assessment of interdependent infrastructure systems under hazard effects is also incorporated within the LCM framework. By considering the probability of occurrence of hazard and structural deteriorations, the performance of interdependent systems in a life-cycle context could be investigated. Overall, the performance assessment of an interdependent healthcare - bridge network system under hazard effects provides system level probabilistic measures that can aid the emergency management process. Additionally, in order to investigate the detailed effects of climate change on performance of bridges, a large scale data analysis is needed to predict the hazard intensity and occurrence frequency.

Furthermore, this paper presents available methodologies for quantifying the economic, social, and environmental metrics to evaluate the sustainability of bridges and bridge networks. In general, a utility-based performance metric can provide an in-depth understanding of the current and future sustainability associated with infrastructure systems. The presented framework supports the sustainable development of infrastructure systems and provides the optimal intervention strategies to the decision maker that will ultimately allow for risk-informed decision making regarding life-cycle management of highway bridges and bridge networks. Overall, the key objectives of a probabilistic framework are to determine the likelihood of successful performance, find the total expected cost accrued over the entire life-cycle, and make optimal risk-, resilience-, and sustainability-informed decisions related to design, inspection, maintenance, monitoring, repair, and replacement of civil infrastructure systems under multiple objectives and constraints.

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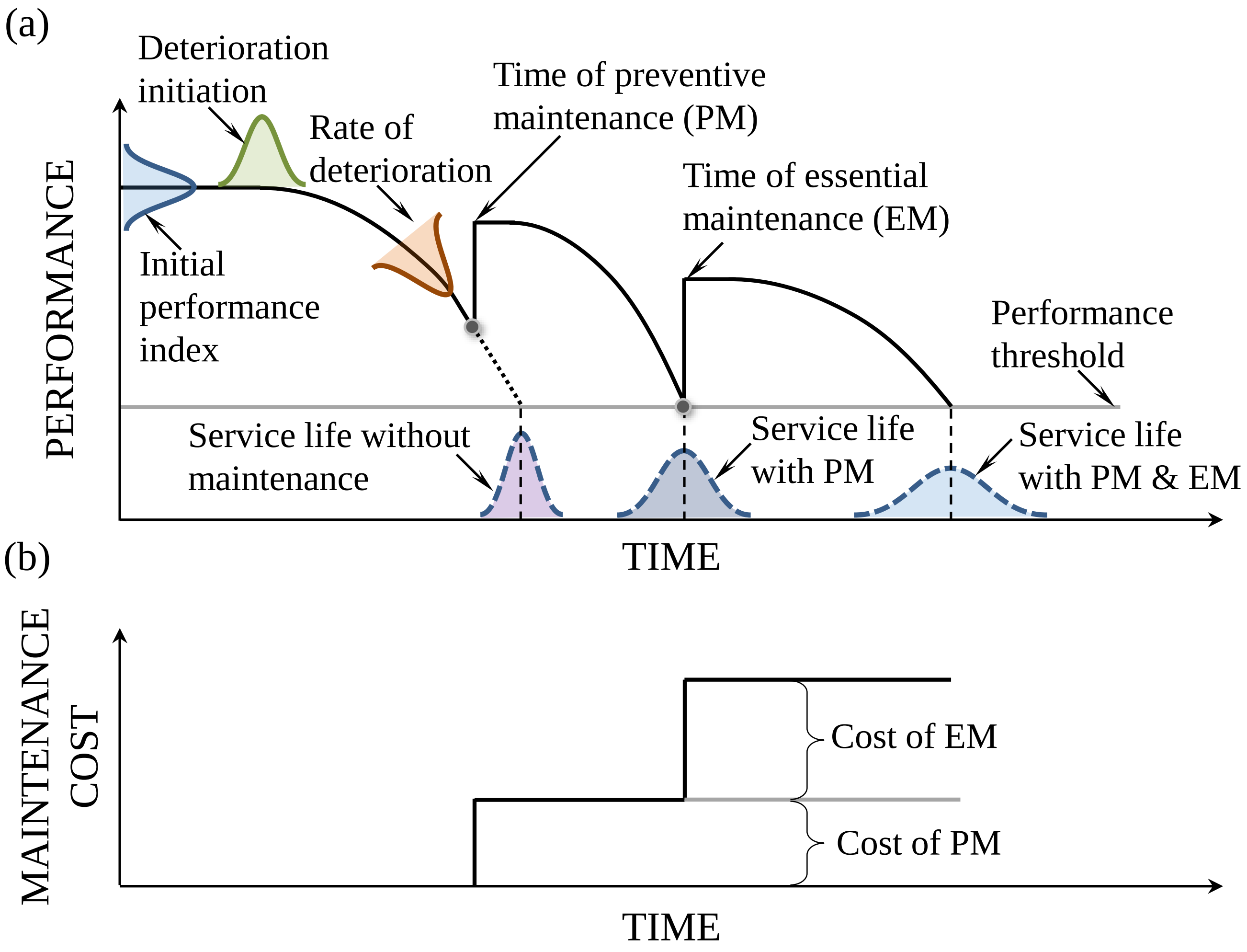

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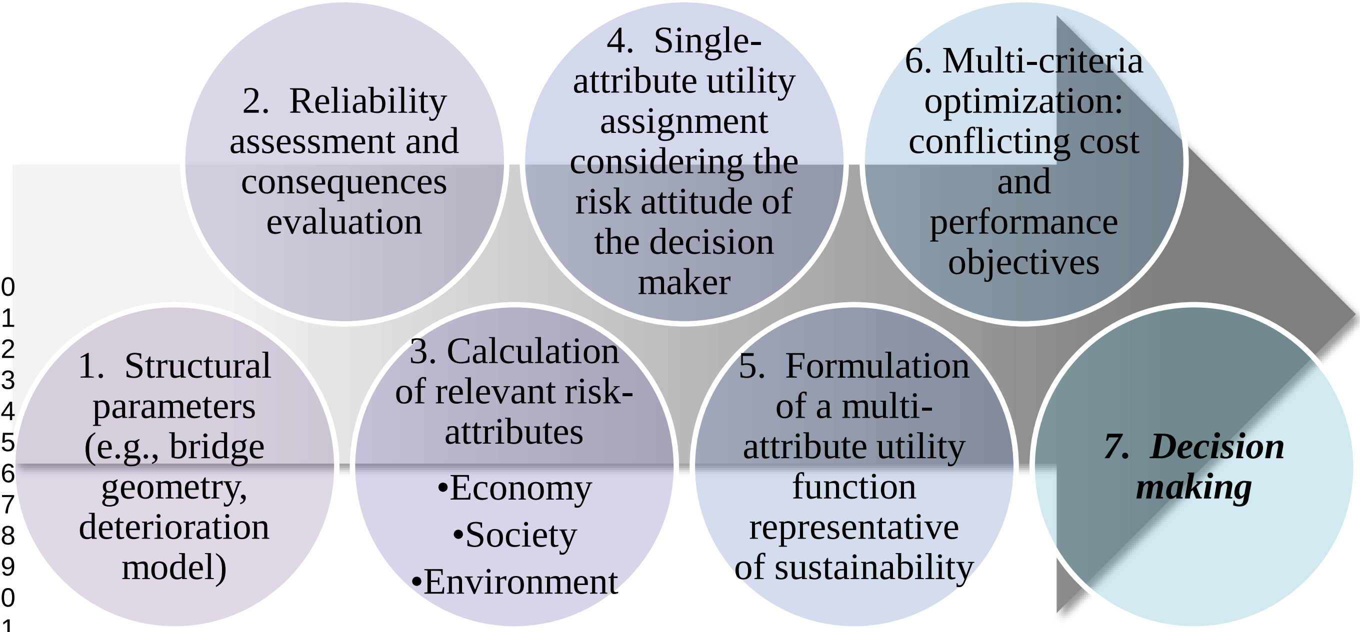

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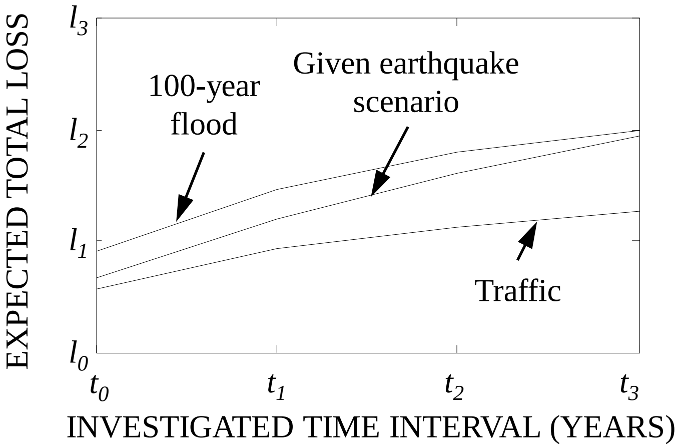

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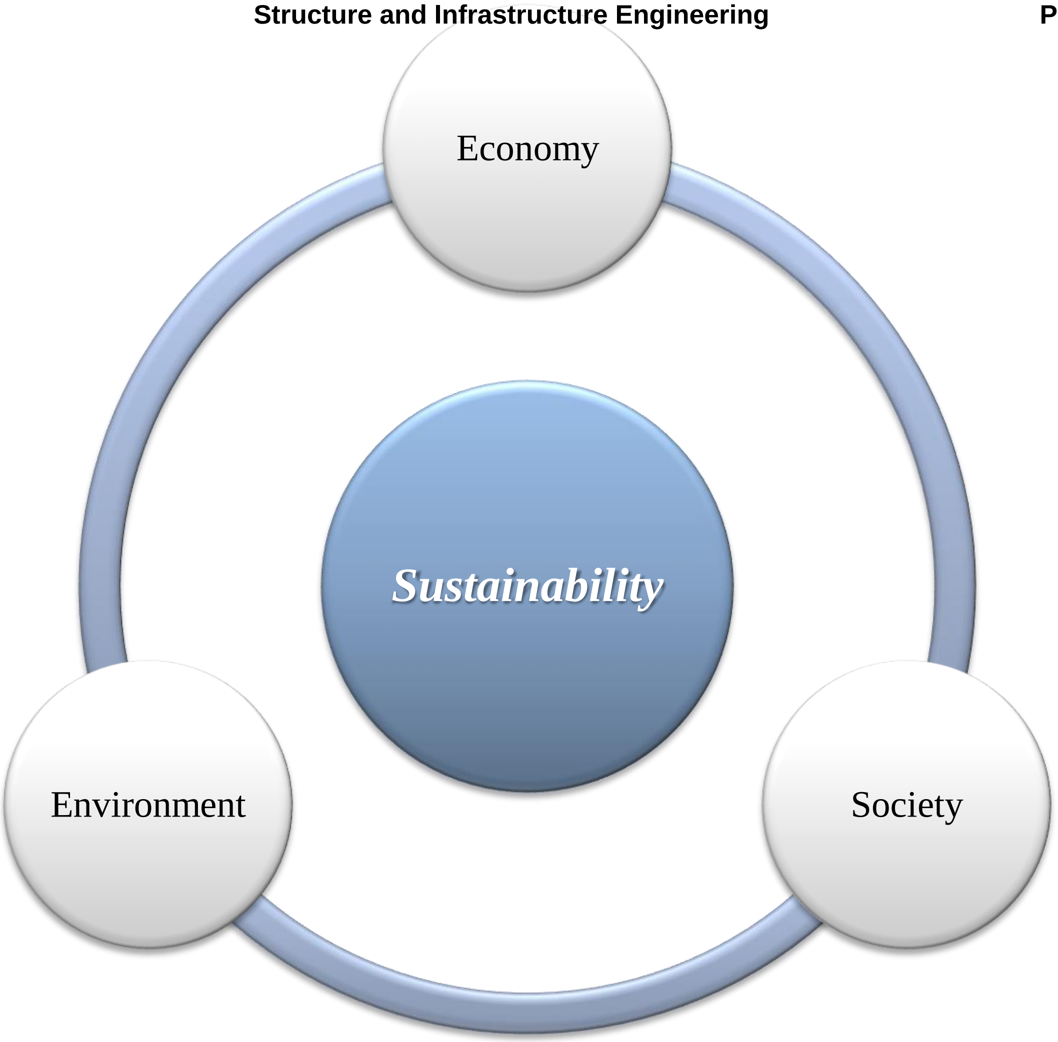

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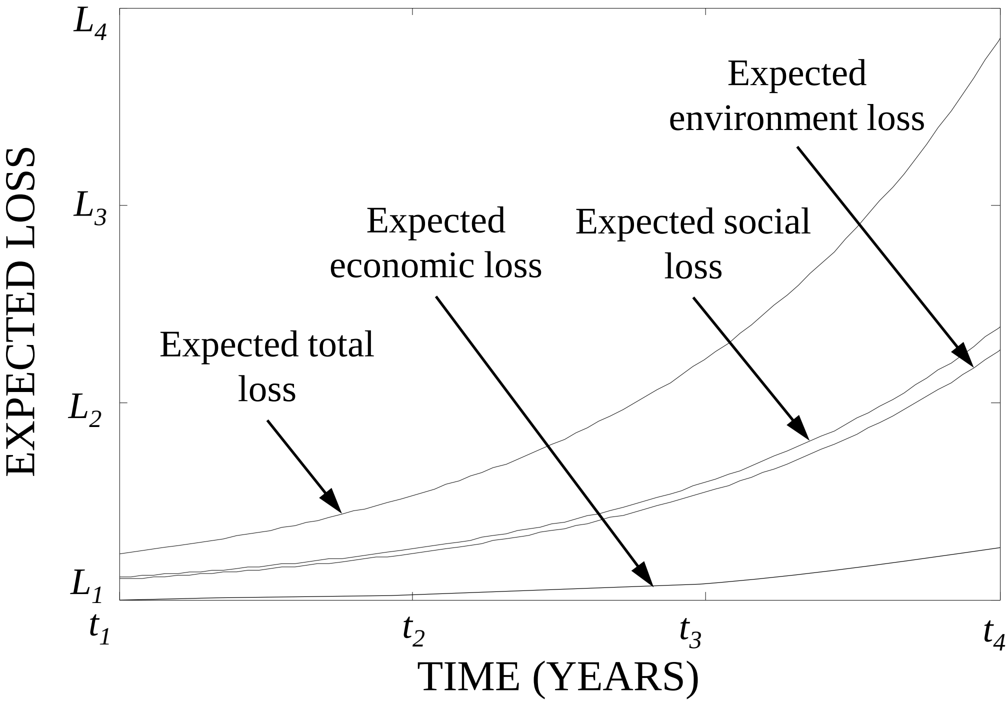

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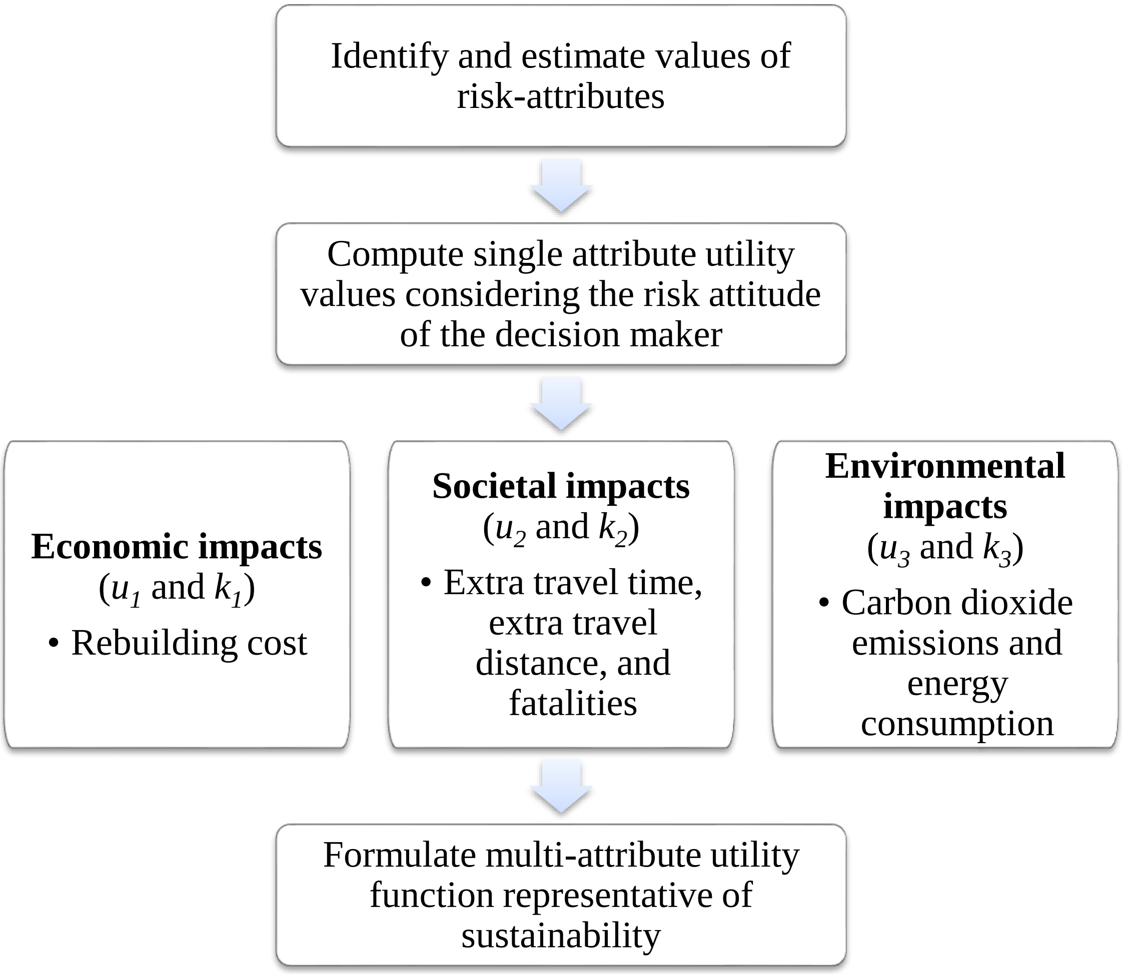

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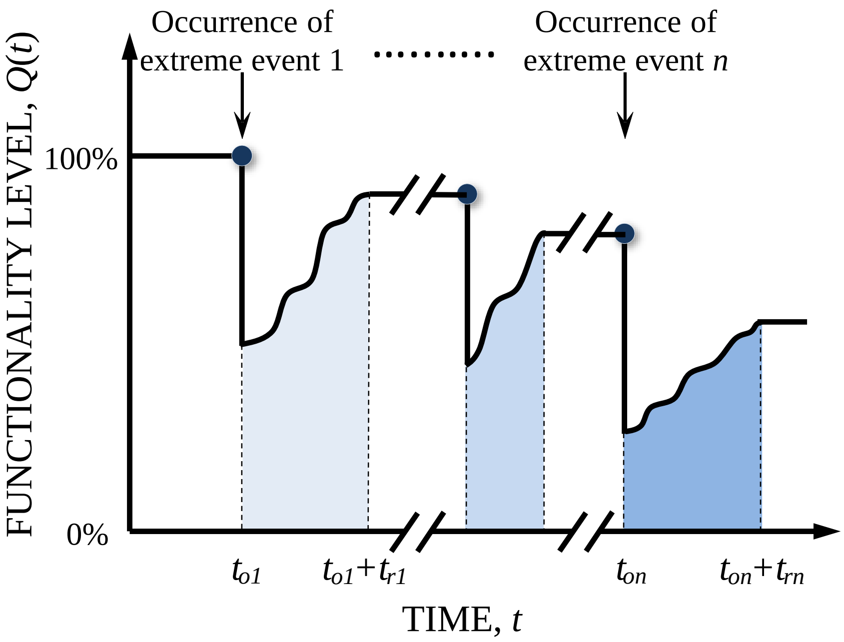

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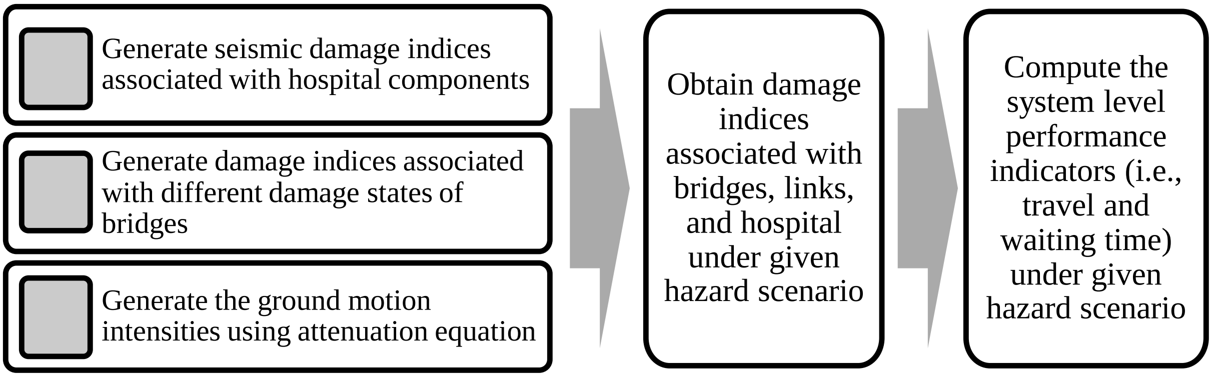

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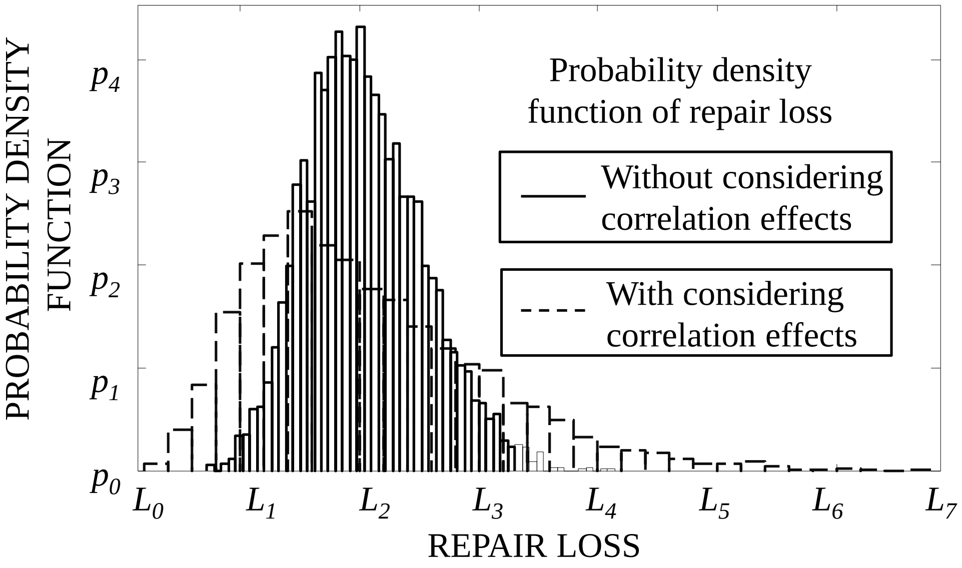

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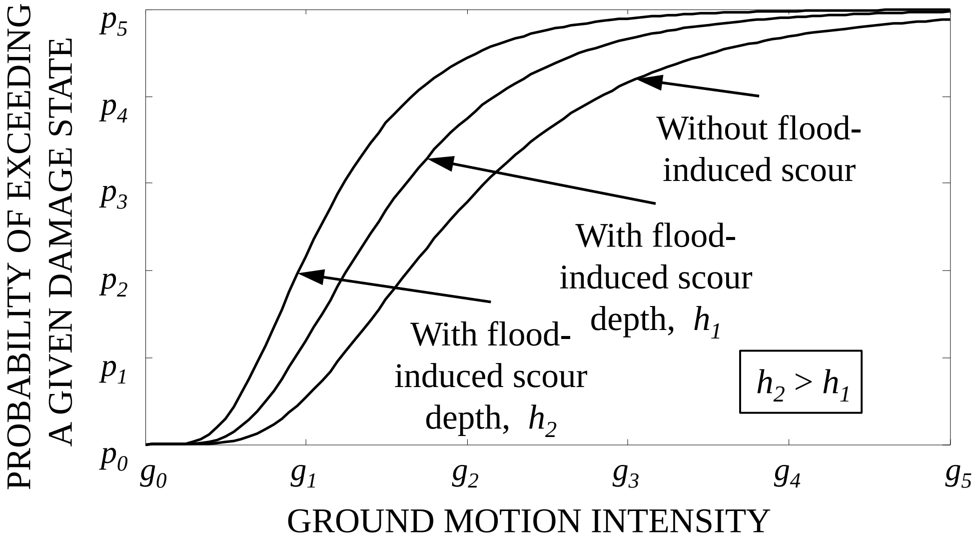

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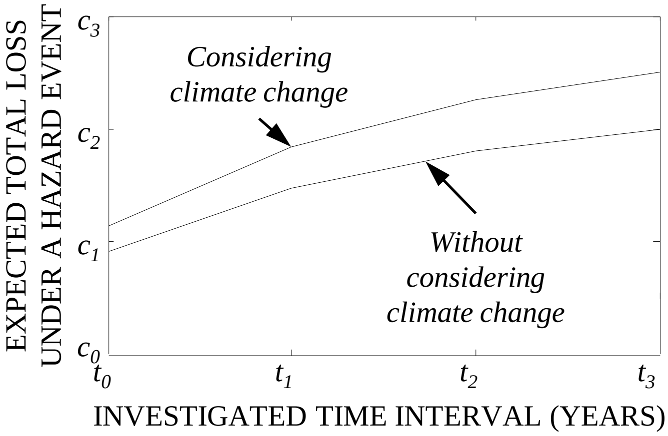

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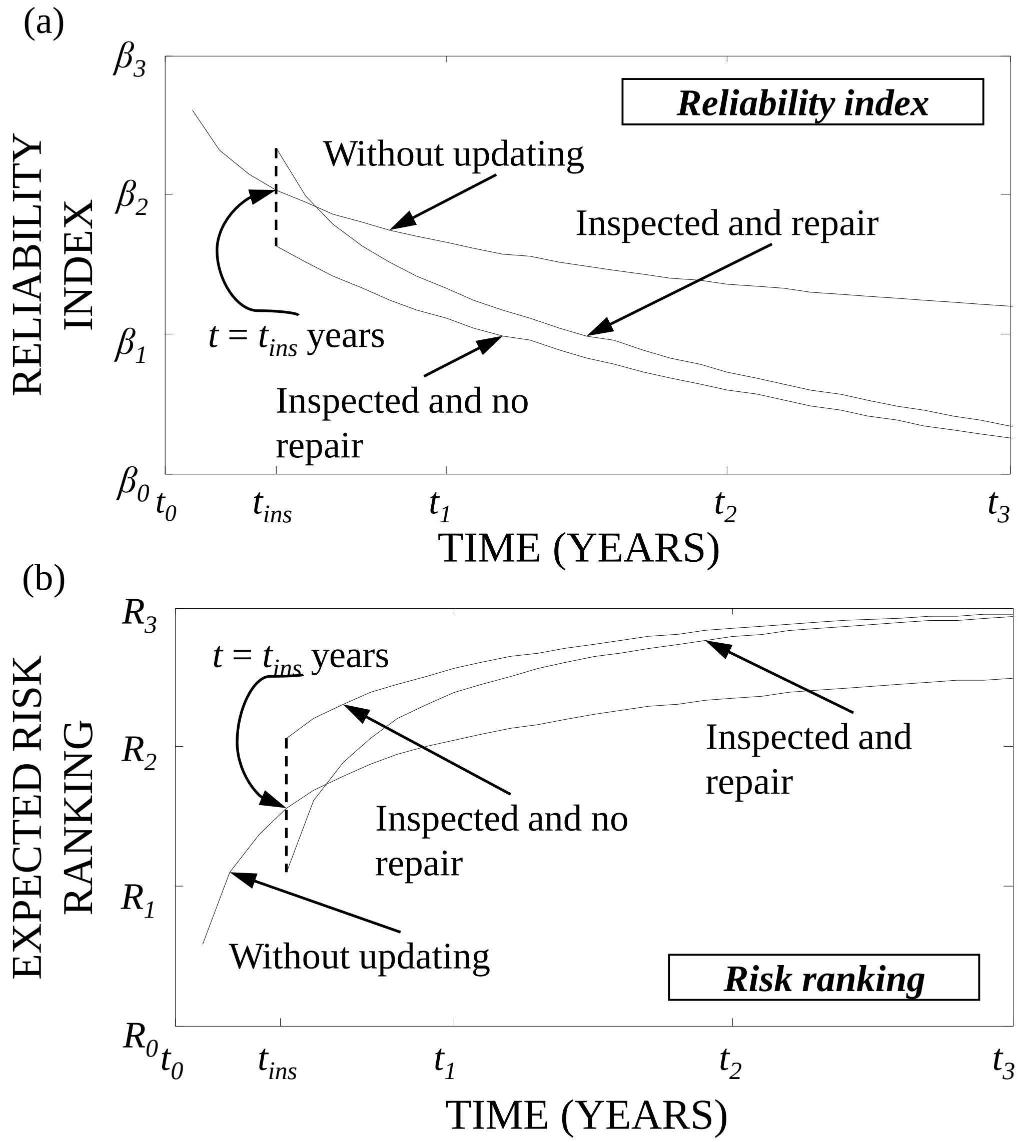

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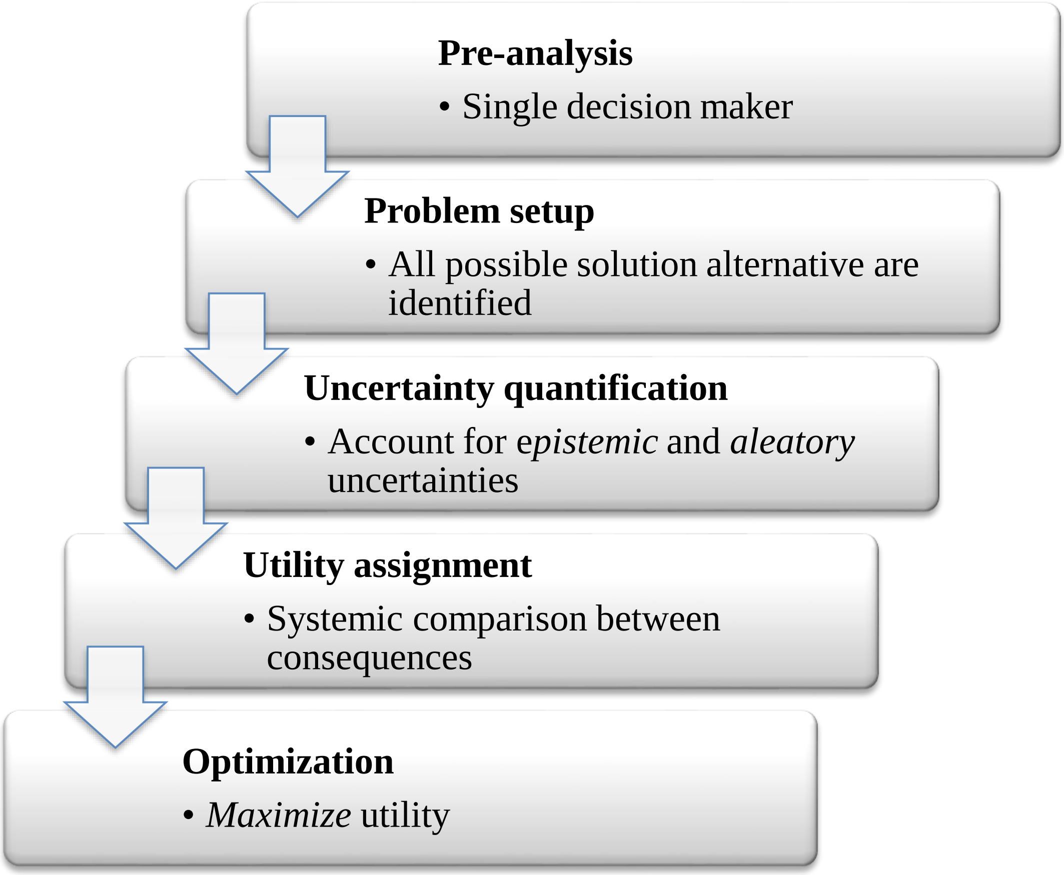

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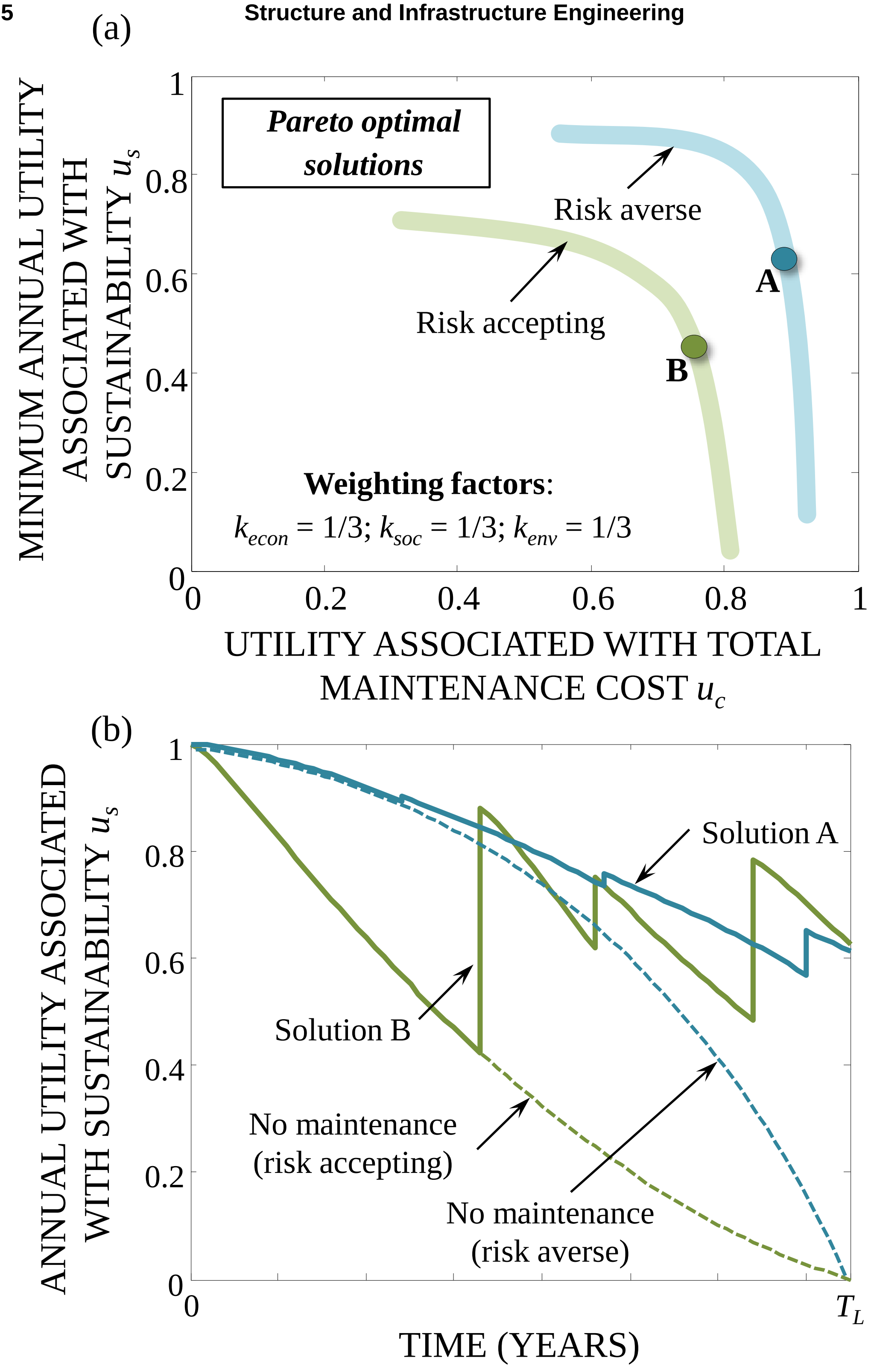

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