MAINTENANCE AND SAFETY OF DETERIORATING SYSTEMS: A LIFE-CYCLE PERSPECTIVE

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ABSTRACT

This paper reviews the key aspects associated with maintenance and safety of deteriorating infrastructure systems from a life-cycle perspective. The main conceptual aspects related to probabilistic optimization of maintenance and rehabilitation of structural systems are discussed. These aspects include life-cycle risk and sustainability assessment, risk-informed and utility-based decision making, and multi-objective optimization of interventions. In general, sustainability assessment is performed by quantifying economic, social, and environmental impacts associated with infrastructure management activities. This keynote paper also reviews various methods for determining optimum life-cycle maintenance, repair, and rehabilitation types and times, as well as the impact of such activities on the total life-cycle cost. The role of probabilistic performance indicators including reliability and risk, the sustainability assessment of deteriorating infrastructure systems, and risk- and utility-informed decision making are highlighted herein.

KEYWORDS

Deteriorating infrastructure systems, life-cycle engineering, risk, sustainability, decision making, optimal management of infrastructure.

INTRODUCTION

Improving the 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). These statistics highlight the dire need to implement rational management strategies that maintain structural performance within acceptable levels through the life-cycle of deteriorating civil infrastructure. Managers of infrastructure systems are usually in charge of allocating limited financial resources in a cost-effective manner to maintain adequate functionality of their systems (Liu and Frangopol 2005a). Life-cycle management is well recognized as an effective tool for maximizing the cost-effectiveness of implementing intervention actions that improve condition, safety, and extend the service life.

This paper presents the general concepts pertaining to maintenance and safety of deteriorating infrastructure systems, through a life-cycle perspective, with emphasis on bridges. In order to predict structural performance for life-cycle analysis under uncertainty, critical deterioration mechanisms for the investigated structural systems (e.g. corrosion and fatigue for bridges) must be accounted for. Furthermore, the effects of maintenance, repair, and rehabilitation on structural life-cycle performance must be well understood. The deterioration effects, as well as 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 2011). In such a framework, specific random variables associated with the load effects and structural resistances of a structural system's components are identified. 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. In addition to identifying the structural reliability against failure, it is also possible to consider various functionality aspects that affect infrastructure systems such as serviceability limit states.

In this paper, risk and sustainability are also investigated as rational performance indicators for the life-cycle behavior modeling of infrastructure systems. In general, approaches for the life-cycle management of infrastructure involving reliability performance indicators consider uncertainties associated with loads and resistance, but are not able to account for the consequences incurred from structural failure. Risk-based performance metrics provide the means to combine the probability of structural failure with the consequences corresponding to this event (Ang and De Leon 2005; Ellingwood 2007). Within this keynote paper, approaches which incorporate risk within the 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 indirect (e.g. environmental and social impacts), as well as, direct (e.g. economic impacts) losses. In general, within the field of life-cycle engineering, two definitions are usually referred to when developing appropriate sustainability metrics. The first representation of sustainability 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). Accordingly, a sustainability performance indicator, that incorporates economic, environmental, and social risks of structural failure, is presented in this paper. This novel sustainability performance metric is established considering multi-attribute utility theory, which facilitates the combination of several risks (i.e., risk attributes) while incorporating the risk attitude of the decision maker. This sustainability performance indicator incorporating multi-attribute utility theory has been applied to the life-cycle management of bridges (Sabatino et al. 2015) and bridge networks (Dong et al. 2015).

As infrastructure systems deteriorate with time, maintenance, repair, and rehabilitation interventions may be carried out to improve and/or sustain the structural performance above acceptable levels. In general, essential maintenance actions are typically applied when a performance indicator reaches a predefined threshold, leading to a substantial improvement in the structural performance. For instance, replacement of bridge superstructure components, such as the deck and girders, is considered as essential maintenance intervention. Figure 1 shows, conceptually, the effect of essential maintenance on the life-cycle structural performance and cost; also shown are the probability density functions of the initial performance index, deterioration initiation, rate of deterioration, and service life without and with maintenance. Another category of maintenance actions include preventive measures that normally repair smaller defects or decrease the rate of deterioration for a period of time. Examples of preventive maintenance include recoating a bridge deck and repainting the steel girders. Although maintenance and other types of interventions (e.g. rehabilitation) have the ability to maintain structural performance within prescribed levels, the cost of carrying out such actions must also be considered when developing life-cycle management plans. Thus, a comprehensive framework for the life-cycle management of aging structures considering risk, sustainability, and life-cycle cost is required in order to maintain structural performance and mitigate economic, environmental, and social consequences (Frangopol and Soliman 2015).

The application of utility-based decision making in the optimal lifetime intervention on civil structures is a topic of paramount importance and is experiencing growing interest within the field of life-cycle infrastructure engineering. In general, utility is defined as a measure of value (or desirability) to the decision maker. Utility theory provides a framework that can measure, combine, and consistently compare these relative values (Ang and Tang 1984). Utility theory is utilized herein in order to depict the relative desirability of optimal lifetime maintenance strategies to the decision maker. 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 (e.g. risk attributes) in order to facilitate decision making.

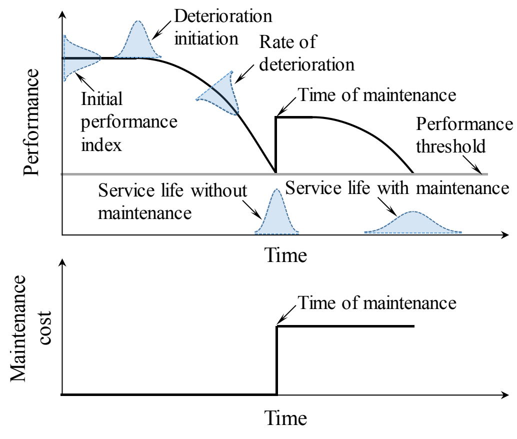

Figure 1 Effect of gradual deterioration and essential maintenance on structural performance and cost

Summarily, this keynote paper reviews the key aspects associated with maintenance and safety of deteriorating infrastructure systems from a life-cycle perspective. Life-cycle risk and sustainability assessment, risk-informed and utility-based decision making, and multi-objective optimization of interventions are discussed. Various methods for determining optimum life-cycle maintenance, repair, and rehabilitation types and times, as well as the impact of such activities on the total life-cycle cost are investigated. The role of probabilistic performance indicators including reliability and risk, the sustainability assessment of civil structures, and risk- and utility-informed decision making are emphasized via illustrative examples.

PERFORMANCE INDICATORS

Condition and Safety Indices

To date, most condition assessment activities associated with civil infrastructure rely on visual inspections results. For bridges, visual inspection results are typically used to establish a condition rating index to measure the bridge's remaining load-carrying capacity. Currently in-use bridge management systems characterize the performance of structural elements by discrete condition states which incorporate predefined degrees of damage (Thompson *et al*. 1998; Hawk and Small 1998). For example, reinforced concrete elements subject to an aggressive corrosive environment can be classified, based on visual inspection results, into one of four discrete condition levels. The bridge element under investigation may be categorized as condition state 0, 1, 2 or 3, which represent (a) no chloride contamination, (b) onset of corrosion, (c) onset of cracking, and (d) loose concrete/significant delamination, respectively (Liu and Frangopol 2005b). Based on the identified condition states, maintenance interventions may be prioritized among all inspected structural components.

Several 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. In a Markov chain model, the current condition states of the investigated system are considered to be dependent only on a finite number of previous states. 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. In the United States, bridge management systems, such as Pontis (Thompson *et al.* 1998) and BRIDGIT (Hawk and Small 1998), which are used by state departments of transportation, are established considering visual-inspection-based discrete condition states and Markovian deterioration modeling using stationary transition probabilities. A safety index can also be defined to model the life-cycle performance of deteriorating systems. In the United Kingdom, the safety index is defined as the ratio of available to required live load capacity (HA 2001). In this case, the performance is considered unacceptable if the value of safety index drops below 0.91. 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 2005b). 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.

Reliability

This section introduces the concept of reliability and its application in quantitatively incorporating uncertainty in structural performance prediction. Structural reliability can be defined as the probability that a component or a system will adequately perform its specified purpose for a specified period of time under specified conditions (Leemis 1995; Frangopol and Kim 2011). In reality, the reliability problem of engineering systems can be expressed as a problem of supply and demand which is modeled by means of random variables. For instance, if R and S represent the resistance and the load effect, respectively, 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 of the structural system. 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:

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

Furthermore, the reliability index can be expressed as:

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

where $\Phi^{-1}(\cdot)$ is the inverse of the standard normal cumulative distribution function (CDF).

A wide variety of research has been conducted that includes reliability analyses of infrastructure systems or networks of civil structures. Hendawi and Frangopol (1994) developed rational system redundancy- and reliability-based structural design and evaluation approaches. Within Hendawi and Frangopol (1994), the effects of material behavior, correlations between random variables, variability of resistances and loads, resistance sharing, structural damage, and number of members on the redundancy and reliability of a parallel system were investigated. Stewart (2001) demonstrated that the initial stage of performance based assessment techniques is to estimate the reliability of an existing infrastructure system. Cesare *et al.* (1993) calculated the reliability index for each structural element of a bridge using first-order reliability methods. The overall system reliability index of the bridge was calculated by combining the individual reliability of the components in a series system. Decò and Frangopol (2011) provided a rational methodology for reliability and risk analysis of existing highway bridges under a multi-hazard exposure and illustrated their approach on the I-39 Bridge crossing the Wisconsin River in Wausau, WI, USA.

In addition to bridges, reliability analyses have been performed on naval vessels and offshore structures. More specifically, Moan (2005) established an approach for reliability-based management of inspection, maintenance and repair of offshore structures and demonstrated how the interrelation between design, inspection, maintenance and repair requirements can be rationally dealt with. An approach for structural life-cycle management of ships under uncertainty was presented by Frangopol and Soliman (2015), and Kim *et al*. (2013) presented a generalized probabilistic framework for optimum inspection and maintenance planning of deteriorating structures. Decò *et al.* (2011) have used advanced statistical techniques such as Latin Hypercube Sampling (McKay *et al.* 1979) and second order reliability methods (Melchers 1999) to determine the probability of failure of ship hulls. Also Decò *et al.* (2012) proposed a framework for the assessment of structural reliability and redundancy of a Joint High Speed Sealift (JHSS) under different operational conditions. Polar representations of system reliability for different sea states and heading angles were presented. Additionally, an approach to account for the time-dependent corrosion and fatigue effects on the reliability of ship hull structures was provided in Kwon and Frangopol (2012).

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):

$$R = \int\int\cdots\int \kappa(x_1, x_2, \ldots, x_m) \cdot f_{\mathbf{X}}(x_1, x_2, \ldots, x_m) \cdot dx_1 \cdot dx_2 \cdots dx_m \quad (3)$$

where $\kappa(\mathbf{x})$ denotes the consequences associated with events resulting from certain hazards $\mathbf{x}$ and $f_{\mathbf{X}}(\mathbf{x})$ is the joint PDF describing the probabilistic behavior of the random variables $\mathbf{X} = \{ X_1, X_2, \ldots, X_m \}$. Typically, the consequences associated with events resulting from hazards are quantified in terms of monetary values. The m-fold integral within Eq. 3 is difficult to assess and often cannot be solved. Therefore, assumptions are established in order to obtain a simpler expression for total risk. If the hazards are considered mutually exclusive and collectively exhaustive, a more simplistic approach for calculating instantaneous total risk R is:

$$R = \sum_{i=1}^{n} C_m \cdot P[F \mid H_i] \cdot P[H_i] \quad (4)$$

where C_m represents the consequences of failure, $P[H_i]$ describes the probability of occurrence of a hazard, $P[F |H_i]$ is the conditional failure probability given the occurrence of a hazard, and n is the total number of hazards considered within the analysis. An even simpler formulation of time-variant risk was proposed by Ang and De Leon (2005) as:

$$R(t) = p(t) \cdot \chi(t) \quad (5)$$

where $p(t)$ denotes the probability of occurrence of an adverse event and $\chi(t)$ represents the consequences of the event at time t.

Several research efforts have been conducted involving the risk assessment of bridge structures. Decò and Frangopol (2011) developed a rational framework for the quantitative risk assessment of highway bridges under multiple hazards. Time-dependent profiles of risk, accounting for direct and indirect consequences, were calculated for an existing highway bridge considering abnormal traffic loads, environmental attacks, scour, and earthquakes. Similarly, Saydam *et al.* (2013b) proposed a methodology for quantifying lifetime risk of bridge superstructures based on the condition index. Within Saydam *et al.* (2013b), an illustrative example was presented to demonstrate the capabilities of this methodology; the time-variant expected losses associated with the flexural failure of girders and the risk-based robustness index were determined for an existing bridge located in Wisconsin, USA. Additionally, Cesare *et al.* (1993) calculated the total risk associated with a bridge using the reliability and consequence of closure of the bridge. Stein *et al.* (1999) developed an approach for assessing the risk associated with scour of bridge foundations. The risk of scour failure was determined by multiplying the cost associated with failure and the probability of scour occurrence. Similarly, Stein and Sedmera (2006) proposed a risk-based approach for managing bridges in the absence of foundation information.

Furthermore, risk analysis was utilized to assess the performance of networks of infrastructure systems. For example, the time-dependent expected losses of deteriorated highway bridge networks were investigated within Saydam *et al*. (2013a). Additionally, Decò and Frangopol (2013) 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.

Sustainability and Utility as Performance Indicators

Within a robust risk assessment, it is crucial to consider the economic, social, and environmental impacts of structural failure. Sustainability assessment involves the integration of these various risk values into a convenient index used to measure performance. In general, it is important to measure the performance of infrastructure systems and networks of structural systems whose functionality is vital for economic and social purposes (Saydam *et al*. 2013a). Recent research efforts have considered a wide variety of risks in order to effectively quantify sustainability. For instance, the time-dependent expected losses of deteriorated highway bridge networks were investigated within Saydam *et al*. (2013a). A five-state Markov model was proposed to predict the time-dependent performance of bridges within a network. The probabilistic variation of direct, indirect, and total expected losses in time was computed. The proposed approach was illustrated on an existing highway bridge network in the lower San Francisco Bay Area, California. Additionally, 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. The proposed approach was illustrated on a reinforced concrete 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.

In general, utility-based decision making may be divided into five separate stages: the pre-analysis, problem set-up, uncertainty quantification, utility assignment, and optimization, as shown in Figure 2 (Keeney and Raiffa 1993). 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 structural system. 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 civil infrastructure, decisions regarding life-cycle management must consider all relevant uncertainties associated with the probability of structural failure and its corresponding consequences (Ang 2011). For instance, life-cycle management problems involving deteriorating highway bridges have uncertainties that are present within modeling the structural resistance (e.g. material properties and element dimensions), the occurrence and magnitude of hazards that may impact the structure (e.g. corrosion, fatigue, earthquakes, floods, and hurricanes), operating conditions, and loading cases (Stewart 2001), in addition to those associated with the cost of interventions performed during the service life.

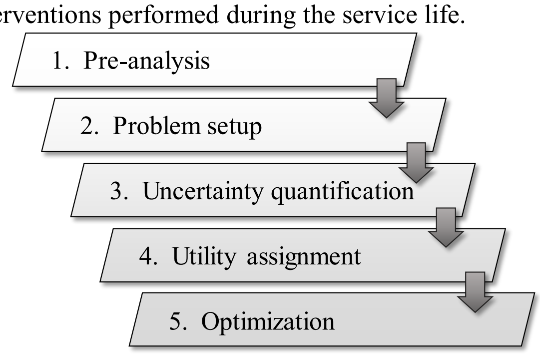

Figure 2 Utility-based decision making steps

After effectively incorporating the appropriate uncertainties, the decision maker may assign utility values to the investigated attributes (e.g. risk attributes) associated with each alternative considering his/her risk attitude.

Utility theory is applied in order to normalize each attribute value corresponding to solution alternatives to a number between 0 and 1; this ensures that all attributes are directly comparable to each other. The formulation of the utility function corresponding to each attribute depends on the knowledge, preferential characteristics, and risk attitude of the decision maker. Within the last step of the utility-based decision making framework an optimization procedure is carried out in order to find the alternative that maximizes the utility value.

Once the time-variant risks affecting a deteriorating system are calculated (e.g. using Eq. 5), the decision maker may assign utility values to the attributes associated with each alternative considering his/her risk attitude. As an example, the computational procedure for the multi-attribute utility assessment of a highway bridge subjected to a corrosive environment and time-increasing traffic loading is shown in Figure 3, where u_i and k_i, respectively, are the utility function and associated weighting factor corresponding to the ith risk attribute. A multi-attribute utility value is established that effectively represents sustainability performance by consolidating economic, social, and environmental risks.

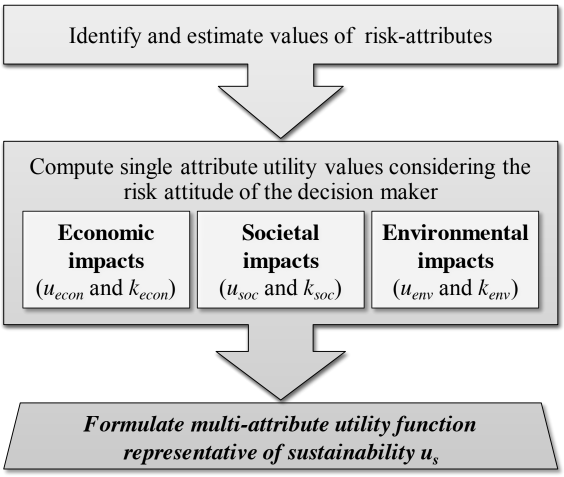

Figure 3 Flowchart describing the multi-attribute utility performance assessment.

For the risk attributes analyzed, each of the corresponding utility functions may be formulated as monotonically decreasing functions. Considering an exponential formulation, the utility associated with a single attribute (e.g. economic, social, and environmental risks) can be expressed as (Ang and Tang 1984):

$$u_{RA} = \frac{1}{1-\exp(-\gamma)}\left[1-\exp\left(-\gamma\frac{RA_{max}-RA}{RA_{max}-RA_{min}}\right)\right] \tag{6}$$

where RA is the mean of the risk attribute value under investigation, RA_{max} and RA_{min} denote the maximum and minimum value of the risk attribute, respectively, and γ is the risk attitude of the decision maker (i.e., $\gamma > 0$ indicates risk-aversion and $\gamma < 0$ denotes risk-acceptance). A monotonically decreasing function that has bounds of 0 and 1 must be utilized within the utility assignment procedure in order to accurately depict the relative utility of detrimental consequences.

Qualitative plots of the utility function corresponding to a single risk attribute with variable risk attitude, considering the exponential formulation, are provided in Figure 4. As indicated by Keeney and Raiffa (1993), for a single risk attribute, $u_{RA} = 1$ corresponds to the lowest possible loss while $u_{RA} = 0$ is associated with the largest possible loss. Alternatives associated with high utility values are usually preferred to those associated with small utility values (Howard and Matheson 1989). The concavity of these utility functions is highly dependent on the risk attitude of the decision maker. Risk averse and risk accepting attitudes yield concave and convex utility functions, respectively.

After the utility function associated with each risk attribute is appropriately established, multi-attribute utility theory may be employed to combine them into a single utility value that effectively represents a sustainability performance metric. Although there are various established types of multi-attribute utility functions, the additive formulation is utilized herein. Within the additive formulation for the multi-attribute utility function, marginal utility values associated with each attribute are multiplied by weighting factors and summed over all attributes investigated (Stewart 1996). Considering an additive formulation, the multi-attribute utility function is computed as (Jiménez et al. 2003)

$$u_s = k_{econ}u_{econ} + k_{soc}u_{soc} + k_{env}u_{env} \tag{7}$$

where u_s is the multi-attribute utility function associated with the sustainability performance metric; u_{econ}, u_{soc}, and u_{env} represent the marginal utility values associated with economic, social, and environmental risk attributes, respectively; and k_{econ}, k_{soc}, and k_{env} are the weighting factors corresponding to the three metrics considered in the sustainability assessment such that $k_{econ} + k_{soc} + k_{env} = 1$. Typically, these weighting factors are not known or are difficult to assess for certain decision makers. Therefore, it is advantageous to perform a sensitivity study concerning these weighting factors.

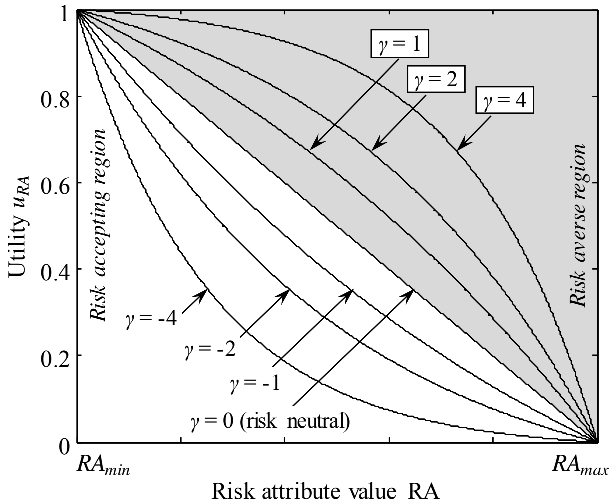

Figure 4 Qualitative representations of typical exponential utility functions that are monotonically decreasing as the expected value of the risk attribute value increases

UTILITY-BASED DECISION MAKING

Once the appropriate multi-attribute utility-based sustainability metric is established, it may be utilized within a life-cycle optimization to find the best intervention strategies for the investigated structure. In general, the presented generalized decision–support approach may be used to determine optimal repair, rehabilitation, and monitoring interventions. Accordingly, the effect of interventions on the sustainability performance must be examined. Within the generalized decision making methodology presented, two objectives, represented in terms of utility, can be simultaneously maximized: (a) the relative value of investment costs considering the risk attitude of the decision maker u_c, and (b) the sustainability of each alternative expressed in terms of the utility u_s. The cost associated with implementing optimal lifetime maintenance actions may be expressed in terms of utility by employing Eq. 6. Given the maximum cost investment that the decision maker can tolerate, a utility function representative of cost considering the attitude of the decision maker may be established. The formulation of the cost utility u_c effectively captures the decision maker's preference to investing money in the face of risk.

The cost u_c and sustainability u_s utilities are used within a multi-criteria optimization process as the objective functions to be maximized. More specifically, this optimization maximizes the minimum annual utility associated with sustainability while simultaneously maximizing the utility associated with the total maintenance cost. Generally, if the utility values of all the alternatives are available, the solution with the highest utility value is always preferred (Howard and Matheson 1989); thus, the two utility objectives are maximized within the presented optimization procedure. The main output of this bi-objective optimization, often carried out by using genetic algorithms (Davis 1991) in MATLAB (MathWorks 2013), comes in the form of a Pareto-optimal solution set that depicts optimal solutions outlining lifetime maintenance schedules. A solution is Pareto-optimal if there does not exist another solution that improves at least one objective without worsening another one. A plot depicting Pareto fronts for the lifetime maintenance planning of a bridge, considering a varying risk attitude, is shown in Figure 5. Within this example, the weighting factors associated with marginal economic, social, and environmental utilities are all assumed to be equal to 1/3; essentially, the decision maker weighs all three risks equally within the sustainability assessment.

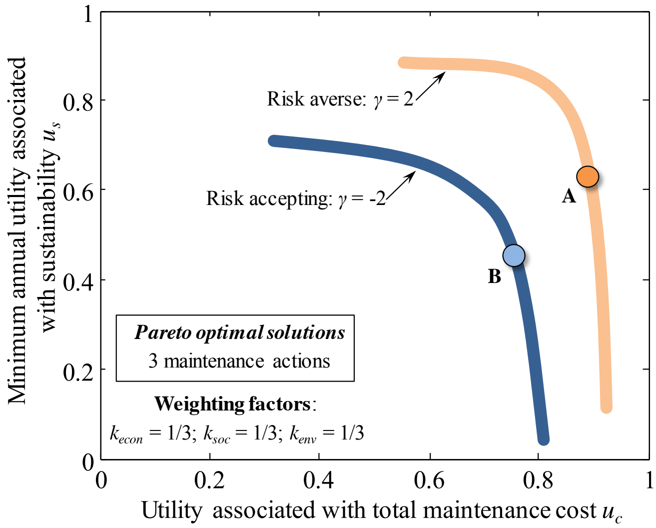

Figure 5 Effect of risk attitude on the optimal solutions for lifetime maintenance considering weighting factors equal to one third

Embedded within each Pareto solution contained in Figure 5 are the optimum maintenance plans that detail which structural components should be maintained and the optimum maintenance time. In this case, the investigated bridge has a predetermined lifetime of T_L years and three maintenance actions may be implemented throughout its life-cycle. 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 5. The time-variant multi-attribute utilities associated with sustainability corresponding to representative solutions A and B are shown in Figure 6a. Similarly, the economic risk profiles associated with solutions A and B are depicted in Figure 6b. In general, these plots show that the multi-attribute utility assessment of sustainability is highly dependent upon the risk attitude of the decision maker.

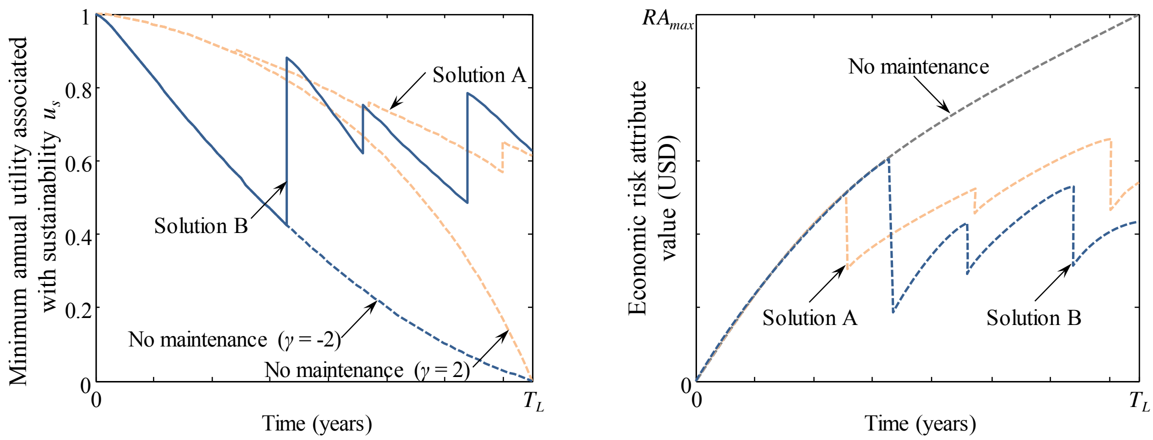

Figure 6 Time-variant profiles of (a) utility associated with sustainability and (b) economic risk for representative solutions A and B in Figure 5

The presented methodology can be used to assist decision making regarding intervention and operational actions. Depending on the maintenance cost, level of sustainability, and in turn, maximum annual risk attribute values desired, a decision maker can choose a Pareto optimal alternative that best satisfies his/her needs.

CONCLUSIONS

This keynote paper discussed various aspects pertaining to maintenance and safety of deteriorating infrastructure systems, from a life-cycle perspective. A utility and sustainability-based methodology to carry out probabilistic optimization of lifetime intervention actions of deteriorating structural systems was presented. The role of probabilistic performance indicators including reliability and risk, sustainability assessment of civil structures, and risk- and utility-informed decision making were highlighted. Furthermore, utility theory was introduced and a multi-attribute utility value representative of sustainability, established in order to effectively combine the effect of economic, social, and environmental of risks, was discussed. Multi-objective optimization procedures, with utility values as the objectives to be maximized, were used to determine the best maintenance plan for a highway bridge in the presented illustrative example. Accordingly, the decision maker will be able to make sustainability-informed decisions based on his/her particular preferences and the decision support system provided.

Overall, the methods presented herein can be utilized to facilitate informed decision making regarding the lifetime intervention scheduling of deteriorating infrastructure. Multi-attribute utility theory can be used to formulate a utility-based sustainability index which offers a measure of desirability of a given management alternative to the decision maker. An approach that incorporates multi-attribute utility theory provides a framework which can measure, combine, and consistently compare the relative values of different alternatives while taking into account the decision maker's attitude. However, sensitivity studies aimed to quantify the weighing factors which represent the effect of the decision maker's particular preference to which aspect of sustainability is most important are still needed.

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