Risk-Informed Decision Making for Disaster Recovery Incorporating Sustainability and Resilience
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**ABSTRACT**

The significance of resilience and sustainability-based management of urban systems has increased in the last few decades mainly due to concerns related to the sustainable use of the Earth’s resources and unpredicted structural failures associated with disaster effects. This paper presents a generalized framework for urban disaster risk-mitigation and structural system recovery that incorporates sustainability and resilience. The ultimate goal of this approach is to aid the risk-informed decision making process. Risk-based performance measures combine the probability of system failure with the consequences associated with this event. Since failures associated with urban structural systems result in significant economic, social, and environmental impacts, risk-based methodologies are most appropriate for disaster recovery. The importance of resilience as a performance indicator is also emphasized in this paper; resilience is incorporated within the disaster recovery process in order to minimize social disruption and mitigate the effects of future extreme events. The presented approach aims to effectively employ multi-criteria decision making techniques to determine recovery strategies that reduce the extent of disaster effects on society, the economy, and the environment.

**Introduction**

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 \cite{8}. These staggering statistics highlight the need for effective hazard recovery strategies associated with urban structural systems. Moreover, the significance of resilience and sustainability-based management of urban systems has increased in the last few decades mainly due to concerns related to the sustainable use of the Earth’s resources and unpredicted structural failures associated with disaster effects \cite{10}. This paper presents a generalized framework for urban disaster risk-mitigation and structural system recovery that incorporates sustainability and resilience. The ultimate goal of this approach is to aid the risk-informed decision making in life-cycle management of civil infrastructure systems \cite{11}.

Risk-based performance measures combine the probability of system failure with the consequences associated with this event. Since failures associated with urban structural systems result in significant economic, social, and environmental consequences, risk-based methodologies are most appropriate for disaster recovery. Additionally, increases in the occurrence of disruptive hazards across the world have determined a shift in the focus of scientific communities and decision makers to develop approaches which can improve the resilience of infrastructure to disasters \cite{5; 6}. The three aspects (i.e., economic, social, and environmental) constitute the three pillars of sustainability. For the proper life-cycle performance assessment of structural systems, it is necessary to take into account not only functionality and

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performance deterioration, but also economic, social, and environmental metrics of sustainability during this process. Moreover, the importance of resilience as a performance indicator is emphasized in this paper; resilience is incorporated within the disaster recovery process in order to minimize social disruption and mitigate the effects of future extreme events.

A global strategy that considers a particular balance between economic impacts, social consequences, detrimental environmental effects, and resilience is required. The ideal combination of the different attributes comprising sustainability and resilience associated with urban disaster recovery can be determined by employing Multi-Attribute Utility Theory (MAUT) [13]. The presented approach aims to effectively employ multi-criteria decision making techniques to determine recovery strategies that reduce the extent of disaster effects on society, the economy, and the environment. The goal of the MAUT is to transfer the three metrics of sustainability into one combined value that has a single unit, which is representative of sustainability of an infrastructure system.

**Risk, Resilience, and Multi-Attribute Utility Assessment**

The probability of failure of a structural system is defined as the probability of violating any of the limit states that define its failure modes. Under the assumption that resistance ($R$) and load effect ($S$) are statistically independent random variables, the instantaneous structural probability of failure is [14]

\[
P_f(t) = P(g(t) < 0) = \int_0^\infty F_R(x,t) f_S(x,t) dx
\]

where $R$ is the resistance in a certain failure mode; $S$ is the load effect associated with same failure mode; $g(t)$ is the performance function; $F_R(x,t)$ is the instantaneous cumulative probability distribution function (CDF) of the resistance at time $t$; and $f_S(x,t)$ is the instantaneous probability density function (PDF) of the load effects at time $t$.

Risk, as a performance indicator, provides more insight to the structural performance by integrating the consequences of failure into the performance index formulation. In general, risk is defined as the combination of chances and consequences of events generated by hazards in a given context. The equation for the evaluation of the instantaneous total risk is [7]

\[
RISK(t) = \sum_{i=1}^n C(t) \cdot P_{f|H_i}(t) \cdot P(H_i)
\]

where $P(H_i)$ is the probability of occurrence of a hazard $H_i$; $P_{f|H_i}(t)$ is the associated conditional failure probability; $C(t)$ represents the monetary value associated with the consequences of failure; and $n$ is the number of the considered hazards. For the proper sustainability and risk analyses, the consequences associated with structural failures should include the economic, social and environmental metrics, by taking into consideration rebuilding, running, time loss, and environmental costs, among others. The probability of failure can be mitigated through the development of timely and effective maintenance and management plans.

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 [3] “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 

\[ RE = \frac{1}{t_r} \int_{t_o}^{t_o + t_r} Q(t) dt \]  

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. (3) can be illustrated graphically as shown in Figure 1(a) and (b) for one and multiple extreme events during the life-cycle of a system, respectively.

![Figure 1. Quantitative definition of resilience for (a) one and (b) multiple extreme events](image)

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. 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 [15]. The additive form of the multi-attribute utility function is adopted herein. The multi-attribute utility associated with a structural system can be computed as 

\[ u_S = w_{Eco} u_{Eco} (Eco) + w_{Soc} u_{Soc} (Soc) + w_{Env} u_{Env} (Env) \]

where \( w_{Eco}, w_{Soc}, \) and \( w_{Env} \) are the weighting factors corresponding to each sustainability metric; \( u_{Eco}, u_{Soc}, \) and \( u_{Env} \) are the utility functions for the economic, social, and environmental attributes, respectively; and \( Eco, Soc, \) and \( Env \) are the values of the three metrics associated with sustainability. Overall, the proposed global strategies may be adopted for a variety of applications, including but not limited to bridges, buildings, and infrastructure networks.

**Conclusions**

This paper presented a brief overview on the integration of the risk, sustainability, and resilience measures into hazard assessment of deteriorating infrastructure systems. This approach integrates the sustainability assessment with multi-attribute utility techniques to assess infrastructure system performance under hazard effects. The paper presented the available methodologies for
quantifying the economic, social, and environmental metrics to evaluate the sustainability of infrastructure systems (e.g., bridges and buildings). In general, sustainability can provide an in-depth understanding of the current and future risk 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 informed decision-making regarding life-cycle management of infrastructure systems [8].

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