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# Life-time reliability based optimization of bridge maintenance strategy considering LCA and LCC

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ABSTRACT

Maintenances are necessary to ensure the safety and serviceability of existing bridges. With the increasing number of existing bridges, maintenances cost a large proportion of financial fund and have significant impact on environment. Implementation of preventive maintenance (PM) could reduce the frequency of essential maintenance (EM) and corresponding cost, leading to considerably lower environmental impact of maintenances. Different from planning of EM, which depends on the structural condition of an existing bridge, PM is periodical. Selection of initial time and time interval of PM will influence the life cycle cost and environmental impact of existing bridges. In this study, a framework for the maintenance scheme optimization of existing bridges based on the genetic algorithm was proposed. Maximum safety, minimum life cycle cost and life cycle environmental impact were taken as optimization objects to find a more rational initial time and time interval of PM of the bridges. To verify the effectiveness of the proposed optimization procedure, a case bridge was selected and the cumulative failure probability, life cycle cost, and life cycle environmental impact of the case bridge with different maintenance schemes were calculated. An optimal maintenance schemes set of the case bridge was obtained. Comparison among the optimal schemes and the scheme without PM was conducted. It can be concluded that PM is of great importance on bridge management. Selection of the initial time and time interval of PM rationally would decrease the bridge's life cycle environmental impact effectively. The reduction of the life cycle cost of the bridge caused by maintenance scheme optimization is not significant. This is because that time value of cost was considered by introducing discount rate into the framework.

## 1. Introduction

Bridges subjected to environmental attack and load effects experience changes in resistance during their lifetimes (Enright and Frangopol, 1988; Neves and Frangopol, 2005). A large number of bridges were built over the past decades in the world. Most of them need to be rehabilitated after a period of operation to guarantee their safety and serviceability. An annual budget of approximately $10 billion were spent on the maintenance of existing bridges in the U.S.A. (Shepard, 2005). Besides, bridge maintenance would consume large amount of energy and resource and causes big impact on environment. Meanwhile, life-cycle engineering, starting from initial design and construction to dismantling the system at the end of its service life, provides rational means to optimize all the aspects in the lifetime of bridge (Frangopol and Soliman, 2016). Thus, it is essential to manage the bridge maintenance from life cycle perspective, considering three pillars of bridge performance: structural safety, cost, and environmental impact.

As traditional pillars, structural safety and cost have attracted many researchers' attention in life time management of existing bridges. Thoft-Christensen (1995, 2000) proposed that reliability should be used to evaluate the safety of bridges in bridge management system. Frangopol et al. (1997) introduced a lifetime optimization methodology for planning inspection and repair of deteriorating structures. The introduced optimization methodology was conducted through minimizing the expected life-cycle cost while maintaining allowable lifetime reliability of the structure. Thoft-Christensen (2004) presented a simplified strategy for Preventive Maintenance (PM) of concrete bridges to estimate the optimal time between PM activities. In the simplified strategy, the effect of a PM activity was modelled based on three average parameters, namely the effect of a PM action on the deterioration rate,

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on the reliability, and on the delay time of deterioration. From a social aspect, Thoft-Christensen (2009) discussed how the total maintenance costs (including user costs) of a large bridge stock may be estimated. Recently, Orcesi and Cremona (2011), Paulsson et al. (2013) and Safi et al. (2014) presented alternative views on how life cycle cost (LCC) analysis can be used for maintenance decisions. Barone et al. (2013) constructed a novel optimization procedure for life-cycle inspection and maintenance planning of aging structures. Both expected system failure rate and expected cumulative inspection and maintenance cost over the life-cycle of the structure were regarded as the objectives of the optimization. Biondini and Frangopol (2016) reviewed the studies concerned on maintenance strategies optimization of bridge considering life cycle cost and safety, and pointed out that significant efforts were also needed to advance the implementation in design practice of life-cycle reliability-based multi-objective optimization methods. These methods can be useful to support the decision-making process involved in the design of new structures and maintenance of existing structures.

With the increasing number of existing bridges, it is gradually recognized that not only construction but also operation would consume large amounts of energy and resource and causes impact on our environment. PM and essential maintenance (EM) of bridges are the main sources of environmental impact of the bridges during their operation. Similar to decrease of environmental impact through developing production technology during PM and EM, reducing the numbers of PMs and EMs through bridge management optimization from a perspective of life-time management would also decrease the environmental impact of operation phase and realize cleaner production. Life Cycle Assessment (LCA), a comprehensive method for assessing environmental impacts of products or services from cradle to grave, is also applied to quantify the environmental impact of bridges. Jönsson et al. (1997) firstly used LCA in civil engineering to evaluate the environmental impact of three flooring materials during their life cycles. In 1998, LCA method was firstly employed in bridge engineering to quantitatively assess environmental burdens between two types of concrete bridges (Horvath and Hendrickson, 1998). Hettinger et al. (2011) adopted LCA to analyze environmental impact of composite bridges, illustrating the benefit of steel recycling properties in the assessment on the basis of a case study. Pang et al. (2015) analyzed the Life Cycle Environmental Impact (LCEI) of different strengthening schemes for existing reinforced concrete bridges by LCA method. Zhang et al. (2016) provided a comprehensive environmental impact assessment of bridge with data uncertainty, by assigning probability distributions on the considered parameters, assessing the variability in the acquisition of inventory and identifying the key parameters with significant environmental impacts. Some studies (Liu and Wang, 2017; Bizjak et al., 2017) conducted LCA analysis on environmental impact estimation of road projects, transition zones construction et al., and some studies (Nabavi-Pelesaraei et al., 2017a, 2017b) used LCA analysis in decision-making of municipal solid waste management. These studies promoted the improvement of LCA method and stimulated the application of LCA in bridge engineering. However, in the studies mentioned above, only environmental impact of design schemes was assessed, which is one-sided in scheme comparison.

In recent years, some researches focused on the structural evaluation from the perspective of LCA and LCC. Some of them aimed at selection of design proposal through comparing cost and environmental impact. Gervásio and Silva (2008) presented an integrated LCA and LCC methodology and conducted the proposed method to comparing prestressed concrete bridge and steel-concrete composite bridge. Kendall et al. (2008) developed an integrated LCA and LCC analysis model to compare the sustainability of different bridge deck designs. Rodrigues et al. (2016) investigated the sustainability of bridge under a threefold environmental, economic, and sociocultural perspectives to compare alternative timber-concrete composite bridge decks. Some researchers paid their attention on operation phase of existing bridges. Tapia and Padgett (2016) posed a framework based on a multi-objective genetic algorithm to help identifying optimal retrofit and repair combinations which ensure public safety and minimize lifetime environmental, economic and social performance of bridge exposed to natural hazards. García-Segura et al. (2017) considered the time of maintenance as a perspective of optimization, presenting a lifetime reliability-based approach for the optimization of post-tensioned concrete box-girder road bridges. However, only removal of old concrete cover was considered as maintenance action, and initial time and number of maintenance during the lifetime were optimized. Essential maintenance was not considered in the bridge management.

Taking both PM and EM into account, this study aims to propose a framework to optimize the maintenance strategy of bridge from the life cycle perspective, considering safety, cost, and environmental impact simultaneously. Optimal PM schedules would be determined to maximize structural safety and minimize LCC and LCEI, which would be helpful for bridge managers to make decision. To accomplish this end, an effective multi-objective optimal method, Genetic Algorithm (GA) (Whitley, 1994; Youssef et al., 2016), was adopted to find out the most rational management schemes. Safety and cost of the existing bridges were evaluated by time-dependent reliability model and LCC analysis method. Environmental impacts of PM and EM of existing bridges were analyzed through Eco-indicator 99 method, which is most commonly used in LCEI assessment (Bare et al., 2000; Ribakov et al., 2016; Hischier et al., 2010; Morosuk et al., 2016; Liu et al., 2016). Initial time and time interval of the PM were selected to be the variability in the optimization. By comparing the reliability, LCC and LCEI of each maintenance scheme, the optimal scheme could be found out.

## 2. Evaluation method for safety, LCEI, and LCC

In order to take the safety, cost, and environmental impact of bridges into account in bridge management, time-dependent reliability, LCC, and LCA methods were adopted to quantify the three elements.

### 2.1. Time-dependent reliability model of bridge

Reliability describes the ability of a system or component to function under stated conditions for a specified period of time (IEEE, 1990). In practice, reliability is usually used to predict and evaluate the performance, such as safety and serviceability, of bridges. Taking the time dimension into account, time-dependent reliability can be adopted to estimate the age that the bridge needs to be rehabilitated in bridge management. In reliability analysis, state of bridge structure, $Z(t)$, can be presented by a performance function, expressed as Eq. (1).

$$Z(t) = R(t) - S(t) \tag{1}$$

where, $t$ is the age of bridge structure; $R(t)$ is the resistance changing with time; $S(t)$ is the load effect changing with time.

Many uncertainties, divided into aleatory and epistemic uncertainties, exist in the design, construction, and operation phases of the bridge (Ang and De Leon, 1997). Aleatory uncertainty is due to natural variability and usually is modeled by random variables, such as the uncertainty related to the dimension of bridges and mechanical characteristics of materials. In contrast to aleatory uncertainty,