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Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty

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ABSTRACT

Today, bridge design seeks not only to minimize cost, but also to minimize adverse environmental and social impacts. This multi-criteria decision-making problem is subject to variability of the opinions of stakeholders regarding the importance of criteria for sustainability. As a result, this paper proposes a method for designing and selecting optimally sustainable bridges under the uncertainty of criteria comparison. A Pareto set of solutions is obtained using a metamodel-assisted multi-objective optimization. A new decision-making technique introduces the uncertainty of the decision-maker's preference through triangular distributions and thereby ranks the sustainable bridge designs. The method is illustrated by a case study of a three-span post-tensioned concrete box-girder bridge designed according to the embodied energy, overall safety and corrosion initiation time. In this particular case, 211 efficient solutions are reduced to two preferred solutions which have a probability of being selected of 81.6% and 18.4%. In addition, a sensitivity analysis validates the influence of the uncertainty regarding the decision-making. The approach proposed allows actors involved in the bridge design and decision-making to determine the best sustainable design by finding the probability of a given design being chosen.

1. Introduction

In the past, construction rules were based on the principle of cost minimization. Since the World Commission on Environment and Development (WCED) proposed a long-term vision to maintain the resources necessary to provide future needs (Butlin, 1989), these rules have been changing, and civil structure projects are attempting to consider sustainable aspects in the selection of structural materials (Castañón et al., 2015), to promote low-carbon construction processes (Chen et al., 2010; Wong et al., 2013) and to select the best design (García-Segura et al., 2014; Yeo and Potra, 2015). This is particularly important in the construction sector, since it is one of the main sectors generating greenhouse gases (Liu et al., 2013) and using natural resources (Lippiatt, 1999). So much so that the United Nations Environment Programme has highlighted that, if existing construction industry patterns do not change, the expansion of construction will destroy or at least disturb natural habitats and wildlife of more than 70% of the Earth's surface by 2032 (United Nations Environment Programme, 2002). Given that sustainable development is mainly based on meeting the three pillar of economic, social and environmental development, each of which has different goals and approaches (Penadés-Plà et al., 2016), the difficulty of optimizing a set of objective functions from non-predefined bridge solutions requires further study.

Bridge design selection for sustainable development represents a multi-criteria decision-making problem (MCDM) (Ardeshir et al., 2014; García-Segura et al., 2017a; Malekly et al., 2010). The MCDM problems can be treated as multi-attribute decision-making (MADM) or multi-objective optimization, depending on whether the alternatives are predefined or defined implicitly through a programming formulation (Singh et al., 2016). The design of a bridge involves a combinatorial problem of variables which focuses on optimizing the objective functions while guaranteeing the structural constraints. The multi-objective optimization has the advantage of providing the best solutions regarding the objectives studied (Pareto front) while avoiding the previous articulation of preferences (García-Segura and Yepes, 2016). However, two main problems are detected: the multi-objective optimization is time consuming due to the structural analysis and the large number of variables and objectives involved (García-Segura et al., 2017a), and

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the large number of solutions forces the selection of one solution by an *a posteriori* MADM process (Karimi et al., 2017; Yepes et al., 2015a) whose results might be influenced by the uncertainty of the judgements (Bañuelas and Antony, 2007; Chatterjee et al., 2018; Gervásio and Simões da Silva, 2012). Therefore, there is a need for addressing a research that studies the techniques to design optimum bridges in terms of sustainable criteria and considers the uncertainty associated with the importance of the criteria. This paper aims to answer the following research question: can sustainable bridges be optimally designed under the uncertainty related to the comparison of criteria in the decision-making?.

2. Literature review

Metaheuristics are considered as particularly useful algorithms for the multi-objective optimization of structures, since these techniques allow for problems with non-linear, non-differentiable or noisy objectives to be handled, which types of problems are common in structural engineering (Zavala et al., 2013). Paya et al. (2008) employed a simulated annealing algorithm to optimize reinforced concrete building frames based on constructability, economic cost, environmental impact and overall safety. Chiu and Lin (2014) applied particle swarm optimization to determine the optimum maintenance plan considering life-cycle cost, maintenance times, safety, serviceability and rationality. García-Segura and Yepes (2016) presented a multi-objective harmony search to study the best designs for a bridge based on cost, CO_2 emissions and the overall safety factor. As the algorithm was successfully used to optimize the bridge design selection, the algorithm was also used to study the cheapest solutions with respect to different safety and durability levels (García-Segura et al., 2017a).

Nevertheless, multi-objective optimization of a bridge problem implies a high computational cost, required to analyze multiple bridges and check their safety and serviceability (García-Segura et al., 2017a). In this sense, metamodels, or surrogate models, provide a relationship between the variables representing the response of the original simulation model. These models are used to effectively simulate processes in the construction sector (García-Segura et al., 2017a; Ozcan-Deniz and Zhu, 2016), especially when a large computational time is needed to solve the problem. Despite the fact that other surrogate models exist, such as polynomial response surfaces, radial basis functions and Kriging models, Artificial Neural Networks (ANN) are considered to be a powerful computation tool for complex structure problems (Caglar et al., 2008; Deb and Nain, 2007; García-Segura et al., 2017a). ANN is a model instrument based on artificial neurons that solves complex and non-linear problems. This instrument learns from training examples and approximates non-linear functions to provide a response or output.

Regarding design criteria, economic structures tend to reduce material consumption, and this also contributes to the minimization of emissions (García-Segura et al., 2015) and energy use (Martí et al., 2016). In this sense, cost optimization is a good approach to achieving an environmentally friendly design (García-Segura and Yepes, 2016). However, as the environmental and economic unit costs of construction materials do not have a proportional relationship to one another (Yepes et al., 2015b), environmental criteria should be considered to achieve sustainable infrastructures (Barandica et al., 2013; Zastrow et al., 2017; Zhong and Wu, 2015). Both the CO_2 emissions and the embodied energy have also been selected as interesting objectives for environmental optimization (Martí et al., 2016; Yeo and Gabbai, 2011; Yeo and Potra, 2015).

Social aspects relating to the sustainability of infrastructures are studied in depth in several publications since this is an emerging topic (Penadés-Plà et al., 2016; Sierra et al., 2018a; Yu et al., 2017). In bridge planning and design, researchers carry out strategies to improve the aesthetic feel (Ohkubo et al., 1998), cultural heritage and public perception of the bridge (Ugwu et al., 2006), in addition to vehicle operation costs and safety costs (Gervásio and Simões da Silva, 2012), among other factors. Despite authors highlighting the lack of unanimity in the social pillar (Penadés-Plà et al., 2016; Sierra et al., 2018b), it is important to select the criteria based on the characteristics of the case study to achieve the objective sought. Social investments within long-term care include those in improving quality of care and quality of life, increasing capacities to participate in society and the economy and promoting sustainable and efficient resource allocation (Lopes, 2017). In this sense, the design of a bridge must meet the needs for which it has been planned and reduce the long-term use of resources. In order to extend the service life of structures and to optimize maintenance actions, the durability condition and safety criteria should be considered (García-Segura et al., 2017b; Neves and Frangopol, 2005). Additionally, the durability condition also has an influence on the life-cycle cost, since the maintenance of corroded components represents the greater part of the life-cycle costs of long-span coastal bridges (Cheung et al., 2009).

The multi-objective optimization of sustainable criteria provides a Pareto front of efficient solutions which have conflicting objectives. MADM are used to select these trade-off solutions based on certain information, experience and judgment. In the literature, there are many MADM methods which have been reviewed in a number of publications (De Brito and Evers, 2016; Jato-Espino et al., 2014; Vicent Penadés-Plà et al., 2016). The multi-criteria optimization and compromise solution (VIKOR, derived from the Serbian name Vlse VlseKriterijuska Optimizacija I Komoromisno Resenje) (Opricovic, 1998) rank the alternatives according to the distance to the ideal point, which is in line with the multi-objective optimization. VIKOR method focuses on ranking and selecting a solution from a finite set of feasible alternatives which are in the presence of conflicting criteria with different units (Chatterjee and Chakraborty, 2016). VIKOR is a helpful tool particularly in a situation where the decision-maker is not able, or does not know to express his/her preference at the beginning of system design (Opricovic and Tzeng, 2004). Therefore, this method can be combined effectively with the multi-objective optimization to select a solution of the Pareto front. As the compromise solution will depend on the value that the decision-maker wants to place to each criterion, the combined use of the Analytical Hierarchy Process (AHP) and VIKOR provides a powerful tool to obtain the closest compromise solution to the ideal point from the verbal judgements of the decision-makers (Chatterjee and Kar, 2017; Pourebrahim et al., 2014; Singh et al., 2016). AHP is a technique used in the decision-making process to help decision-makers set priorities among alternatives and make better decisions by taking into account qualitative and quantitative aspects of the decision (Bañuelas and Antony, 2007). This method has been successfully used in facilitating the judgment of complex problems, as decision-makers are not required to make numerical guesses as subjective judgments are easily included in the process and the judgments can be made entirely in a verbal mode (Korpela et al., 2001). AHP method is suitable for problems which can be decomposed into a hierarchy (Güngör et al., 2009). In addition, this method can check inconsistencies in the decision-maker's assessments (Saaty, 1987). AHP has been used to select the best bridge construction site (Aghdaie et al., 2012; Ardeshir et al., 2014), the type of bridge (Farkas, 2011) and the bridge construction method (Pan, 2008), among others. A correspondence analysis showed that AHP is centered and located in an intermediate position between the