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A fuzzy integrated methodology for evaluating conceptual bridge design

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ABSTRACT

Choosing the most suitable superstructure is vital for the success of a small to medium-span highway bridge design. Numerous attributes must be considered and evaluated in terms of many different conflicting criteria in the conceptual design of a bridge, leading to a large set of subjective or ambiguous data. Furthermore, integrating experts' knowledge and experiences to make appropriate decisions is a commonly used method. In order to solve this problem, project managers and design engineers need to evaluate their initiative designs carefully and make accurate decisions. For this reason, a systematic decision process for selecting the best design idea by means of a novel integrated optimization-based methodology is proposed. In the first phase, Quality Function Deployment (QFD) is employed for translating the project requirements into design requirements. In the second phase, Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) is utilized to select the best superstructure as an alternative, based on the weighted criteria achieved from the first phase. In this study the rating values regarding to each alternative and criteria throughout the phases are described in a fuzzy environment by means of linguistic variables. Finally, a case study is provided to illustrate the implementation process of the integrated methodology for bridge superstructure design. For this purpose, an expert team has been formed to collect and verify the expectations of the project, which located in Tehran, Iran. The results demonstrated that the proposed methodology could be successfully applied in the highway bridge projects as a useful tool to facilitate decision making.

1. Introduction

Planning and designing bridges are partly art and partly compromise, the most significant aspect of structural engineering. It is a manifestation of the creative capability of designer and demonstrates his/her imagination, innovation, and exploration (Wai-Fah & Lian, 2000).

Bridge engineering covers planning, design, construction, operation, and maintenance of structures that carry facilities for movement of humans, animals, or materials over natural or created obstacles. Some recently-published papers are categorized as follows:

- Planning and design (e.g. Hong, Chang, & Lee, 2002; Srinivas & Ramanjaneyulu, 2007).
- Construction (e.g. Lee & Jeong, 2006; Pan, 2008).
- Operation and maintenance (e.g. Chen & Chang, 2003; Pan, Chiu, & Chen, 2008; Wang & Elhag, 2006, 2007, 2008a, 2008b; Wang, Liu, & Elhag, 2008).

The design of bridge structure consists of two stages: the first stage is conceptual design in which the overall form of the structure is decided upon. While the second stage focuses on more detailed structural analysis, during which calculations are carried out to verify the conceptual design choice and determine component dimensions (Miles & Moore, 1991; Moore & Miles, 1991; Moore, Miles, & Rees, 1997). The first stage is considered as the crucial stage within a bridge design process. Wood and Agogino (1996) cited various sources that demonstrate the conceptual design stage, which takes up the initial 10–20% of the total design time, influences the entire design process including costs. Moreover, Xu, Li, Li, and Tang (2005) and Machwe and Parmee (2007) stated poorly conceived design concept can never be compensated by a good detailed design and also the importance of taking correct decisions early on in the design process is now well understood.

The most important sub-stage in conceptual design of a short and medium span highway bridge is to select the superstructure type that is based on variety of factors ranging from maintenance considerations to designer preference. Specifically, some of the crucial criteria which have been neglected simultaneously in selecting the type of superstructure to be used are: *availability*, *construction cost*, *construction time*, *construction complexity*, *design complexity*, *durability*, *environmental impacts*, and *aesthetics*. An improper superstructure selection may adversely affect the bridge

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project by reducing the quality of the structure, thereby reducing productivity as well as profitability. Furthermore, the superstructure usually represents about 70% of the total structural cost (Menn, 1990), therefore it is adopted as the main sub-stage.

The major objective of this paper is to present an optimization-based methodology to solve the superstructure selection in the conceptual design of highway bridge. Two aspects of this study include great practical significance: first, the methodology considers for a novel integration of QFD method with TOPSIS method in a fuzzified decision making process, and second, finding an optimum justifiable solution using a systematic approach for the problem of the best superstructure selection that is undoubtedly important, especially as a bridge design engineer needs a measurement and analysis tool which can guide him/her to identify project's needs.

The rest of the paper is organized as follows: The next section presents an overview of the techniques used in the bridge design stages. The details of the fuzzy integrated methodology are given in Section 3. An application of the proposed methodology is described through a real case study in Section 4. Finally, the last section contains some concluding remarks and possible perspectives.

2. Literature review

Bridge design stages have received enormous attention in the last decades. Different approaches have been defined to cope with these stages. These can be categorized into two general approaches:

- Artificial Intelligence (AI)-based techniques.
- Mathematical Programming (Optimization Techniques).

The first approach is based on AI techniques. This includes Expert Systems (ES), Decision Support Systems (DSS), meta-heuristics, and Neural Networks (NN). Several scholars have developed the ES with application of AI for the bridge superstructures design (Biswas & Welch, 1987; Burgoyne & Sham, 1987; Spencer, Atkins, & Podlaha, 1989; Welch & Biswas, 1986). Maher (1987) presented four ESs; HI-RISE, FLODER, LOCATOR, and STRUPLE for the structural design process of the bridge, especially during conceptual design. Choi and Choi (1993) developed the rule-based system based on experience and knowledge of the domain bridge expert. The system was implemented to select the superstructure type of bridges. Stuurstraat and Veen (1994) presented the ES used to elicit the knowledge from expert bridge engineers and provided a source of information about their experience.

Several researchers proposed the DSS that was viable for the selection bridge foundation and conceptual design (Hurd, 1994; Moore et al., 1997; Philbey, Miles, & Miles, 1993; Stuckrath & Grivas, 1990). Sham (1991) presented the experimentation conducted in knowledge elicitation with application of AI techniques for the conceptual design of bridge. Miles and Moore (1991) developed the user oriented Knowledge-Based System (KBS) based in the conceptual design. This system was extracted from several experts and was verified with the original experts, independent experts and potential users. Moore, Miles, and Evans (1996) demonstrated the KBS for assessing the bridge aesthetics and checking the correctness of the experts' rules for small to medium size. Boulanger and Hirt (1998) proposed a multi-sourced knowledge acquisition approach with application to human-based explanations in order to develop a design tool called FIBRES. Wang and Gero (1997) and Fu and Reich (1999) presented the application of a machine learning technique based on a sequence-based prediction method for the conceptual design of bridges.

Reich (1993) developed a model by using a learning algorithm for the incorporation of aesthetic criteria between various design bridge elements particularly in the preliminary design of cable-stayed bridges. Hong et al. (2002) proposed the conceptual design system for cable-stayed bridges based on Artificial Neural Network (ANN).

The other approach is Mathematical Programming or Optimization Techniques which often leads to optimum solution and also optimization algorithms are mainly based on linear programming, integer programming, mixed integer programming and non-linear programming. Many researches have tried to develop multi-level and multi-objective optimization models for bridge design stages particularly for superstructure design of a short and medium-span highway bridge, including materials, structural type and configuration as well as component sizes. Aguilar, Movassaghi, Brewer, and Porter (1973) presented a unified bridge design optimization theory that simultaneously considered the structure and the geometry of the bridge by using a dynamic programming. Lounis and Cohn (1993) defined the optimal bridge superstructure as *one of minimum total cost*, *with standardized girder sections and traffic loading* by using a linear programming method. Aparicio, Casas, and Ramos (1996) developed a computer-aided design system for prestressed concrete highway bridges. Optimization routines are applied to adjust the final design of structure. Long, Troitsky, and Zielinski (1999) proposed the procedure that is applied to minimize the cost of materials of the cable-stayed bridge design based on general mathematical and the optimization process.

Hassanain and Loov (2003) studied the potential economic benefits of using of high-performance concrete for continuous, precast, and pretensioned highway bridges. A non-linear programming was applied for solving the design optimization problem. Sirca and Adeli (2005) presented an optimization method for the total cost optimization of precast, and prestressed concrete bridge systems. The problem is formulated as a mixed integer-discrete non-linear programming problem. Janjic, Pircher, and Pircher (2003) proposed a method that takes into account all relevant effects for the design of cable-stayed bridges based on non-linear programming. This method is called the *unit load* method that allows the definition of a *desired-moment distribution* in the final structure of bridge.

Ohkubo, Dissanayake, and Taniwaki (1998) developed fuzzy optimum design method for selecting a large scale prestressed concrete bridge. The proposed method utilized the multi-objectives concept and fuzzy decision making techniques by considering cost and aesthetic criteria. Lee, Cho, and Cha (2006) presented life-cycle cost methodology for the optimum design of steel bridges considering the time effect of bridge reliability under environmental impact. Ugwu, Kumaraswamy, Wong, and Ng (2006) discussed project-level sustainability assessment using the mathematical models and computational in the infrastructure project for the design stage of real case. Kripakaran, Gupta, and Baugh (2007) described new optimization approach for minimum cost design of trusses. The cost function consists of costs on the weight of the truss and the number of products in the design. Srinivas and Ramanjaneyulu (2007) developed an integrated approach by using ANN and Genetic Algorithms (GA) for cost optimization of bridge deck configurations. ANN is used to predict the structural design responses which are used further in evaluation of fitness and constraint violation in GA process. Machwe and Parmee (2007) described multi-objective analysis in a user-centered evolutionary design system. The research evaluated both engineering and aesthetic aspects of design solutions during conceptual design phase. Hasançebi (2007) proposed evolution strategies to optimize the design of truss bridges. The optimization problem associated with mixed design variables, since it involved identification of the bridge's shape and topology configurations in addition to the size of the structural members for minimum weight. Narasimhan and Chew (2009) presented an explicit durability design procedure for the reinforced concrete structural elements. The study attempted to directly integrate considerations of durability into the