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Optimized fire protection of cultural heritage structures based on the analytic hierarchy process

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ABSTRACT

Fire safety constitutes a significant part of engineering design practice that frequently lead designers to face critical decision-making type of questions. Especially in the case of fire protection of cultural heritage structures, the challenges that engineers confront are sometimes very difficult to deal with. Conventional prescriptive-based fire protection codes cannot be implemented for the protection of such structural systems; on the other hand, performance-based design (PBD) procedures can provide reliable solutions for this type of structures. Fire safety upgrading of historic structures can be expressed as multi-criteria decision making (MCDM) problems. In this context, we propose a model based on the analytic hierarchy process (AHP) that is able to assess the overall fire safety level of a structure in terms of the fire protection measures implemented. Moreover, a generic selection and resource allocation (S&RA) model is applied that in conjunction with the proposed AHP model leads to optimized solutions. In this study, the implementation of the proposed optimized fire protection upgrade framework along with its advantages is presented for the case of the Mount Athos monastery of Simonos Petra and results are discussed.

1. Introduction

Fire has always been considered among the biggest threats for historic structures. There are many examples in the past, where fire caused significant damages to priceless monuments of the world cultural heritage (for example Chiado area in Lisboa, Portugal 1988; Fenice Theatre in Venice, Italy 1996; Windsor Castle, England 1992; Simonopetra Monastery in Mount Athos, Greece 1990, etc). In the case of historic buildings, human life is not the only concern for which fire protection measures have to be implemented; in many cases the building itself, and sometimes its contents, have to be protected as well. Such structures, however, exhibit special features such as inadequate exits, combustible materials, confusing evacuation paths, and many others that are not consistent with the requirements of modern fire protection codes. Moreover, some fire protection measures might be inappropriate for specific type of structures (e.g. fire suppressions water systems are not suitable for the case of libraries or galleries). The problem becomes even more complicated given the fact that historic buildings are often not used for the purposes that were designed for (i.e. houses that are currently used as offices, museums, galleries etc.), which implies additional risks.

In these cases, the necessity to preserve the authenticity of historic structures usually leads to expensive fire safety solutions, due to the application of special materials and advanced fire protection techniques. The available budget, however, is limited and therefore has to be optimally allocated in order to maximize the level of fire safety upgrade. As a result, conventional prescriptive fire protection codes and regulations fail to deal with the issue of historic buildings fire protection adequately, i.e. to achieve acceptable satisfactory solutions both in terms of fire safety and authenticity preservation, subjected to budget restrictions.

Dealing with the issue of historic structures' fire protection might lead to decision-making challenges (e.g. selection between two different fire protection measures etc.). The analytic hierarchy process (AHP) is a structured technique used in multiple-criteria decision analysis, which was initially developed by Saaty in 1970s [1,2], while later it has been extensively studied and further developed [3–5]. Furthermore, it has been applied into a wide range of applications [6–8]. AHP provides an elegant framework for formulating a decision-making problem that is able to represent and quantify its multiple parameters, which are related to the overall goals, and evaluate alternative solutions.

Specifically, according to AHP, a decision-making problem is decomposed into a hierarchy of sub-problems, each of which can

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be treated independently. Once the levels of the hierarchy have been identified, the various elements in each level are specified and weighted with respect to their impact on the elements of the upper level (prioritization of criteria). The final step of AHP includes the evaluation of the elements of the bottom level (alternatives) in order to determine their relative ability to achieve the decision goal. Among the advantages of AHP is that it represents an easy-to-use method, which has been tested in a wide range of applications. It provides an effective, yet simple way to organize the criteria into a hierarchy, leading the user to the best possible decisions.

During the last decades fire protection of historic buildings became an important discipline for fire engineers and researchers. In particular, NFPA 914 [9] is the first code that describes the principles and practices of fire safety for historic structures and for those who operate, use, or visit them. Watts and Solomon [10] described the background, revision process, and current proposed content of NFPA 914, while Watts [11] made a comprehensive review of fire safety codes in the U.S. Watts and Kaplan [12] proposed the Historic Fire Risk Index, which uses a linear additive model of multiple attribute evaluation to produce a measure of relative fire risk. In this context, FiRE-TECH project [13] took place during 2002–2005, aiming to evaluate the risk that fire poses to our cultural heritage and to suggest methods by which that risk can be quantified and managed.

In fire protection of historic buildings many methods for multi objective decision-making has been extensively used. Specifically, AHP has been adopted in previous works in order to facilitate the reduction of fire risk in cultural heritage premises. Shi et al. [14] proposed an improved version of AHP, based on the coherence of conventional AHP and the fault tree analysis, which was applied to the Olympic venues in China. Qiu and Liu [15] discussed the DS-AHP method and used the convex function to set up its optimization model. Shen et al. [16] discussed the factors of apartment building fire hazards, and used AHP to determine the weights of all fire hazard factors in order to provide a reference for public fire safety assessment. Fera and MacChiaroli [17] used different techniques taken from the decision support tools, such as AHP, and through the use of a fire dynamics simulator, suggested a new priority in the classification of the fire-fighting systems in tunnels. Shao et al. [18] used AHP for the improvement of the fire control and fire safety for old buildings management focusing on prevention before a disaster. Yu [19] applied fuzzy comprehensive evaluation to extract risk factors of evaluation of fire safety of historic buildings. Vadrevu et al. [20] designed a participatory multi-criteria decision-making approach involving AHP to arrive at a decision matrix that identified the important causative factors of fires.

It is apparent that fire protection should be a concern for all structures, including buildings of cultural heritage. However, the later ones exhibit special characteristics and requirements compared to modern buildings. Fire protection of cultural heritage represents an area where advanced and sophisticated techniques, like those that originate from the performance-based design, have to be implemented rather than the conventional prescriptive codes. Decisions about the extent of the application of the various fire protection measures have to be based on the impact that these have on the overall safety level, considering the possible need for preservation of the authenticity of the building and of course under the constraint of the available budget. Although the principles of fire protection interventions were substantiated through text-declarations, the plethora of which clearly demonstrates that they come as a product of applied fire protection techniques and technologies, on the other hand an optimized decision making approach of interventions decision making has not been presented yet.

In this context, the subject of the current study is to provide an integrated systemic scheme, which embodies innovative tools and new technologies for the solution of the optimum performance-based fire protection of cultural heritage buildings. In particular, we propose an AHP hierarchy combined with a generic selection and resource allocation (S&RA) model for fire safety upgrading of historic buildings, along with an effective technique for efficiently solving the model for real-world test cases. The two questions that this paper is trying to answer are: (a) Given a specific budget, which is the best mixture of fire protection measures to achieve the optimum fire safety level and (b) Which is the minimum required budget to achieve a pre-defined fire safety level? Furthermore, the efficiency of the model is presented for the case of the Mount Athos monastery of Simonos Petra. The remainder of the present paper is structured as follows: the next section offers an overview of the AHP with special reference to the fire protection problem. Then, the S&RA model for the problem at hand along with the proposed solution method is presented. An application of the model for the case of Monastery of Simonos Petra is provided and results are discussed.

2. Analytic hierarchy process

The analytic hierarchy process (AHP) is a widely used model for dealing with multi-criteria decision making (MCDM) problems. MCDM represents a sub-discipline of operations research which deals with solving decision making problems that involve multiple, usually conflicting, criteria. Within this context, AHP provides a comprehensive and rational framework able to formulate efficiently the decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. A typical hierarchical tree of the AHP model is given in Fig. 1. The basic concept of the hierarchical approach is the decomposition of the problem into multiple levels of hierarchy, usually four or five.

The development of a hierarchical approach to fire ranking was initially undertaken at the University of Edinburgh [21–23], in an attempt to create a systematic model for the evaluation of fire safety in hospitals. Usually, there is a need for more than two levels of hierarchy for the case of the fire safety. In the current study four different "decision making levels" have been used (as denoted in Fig. 2): (i) Policy (PO) level which represents the general plan for overall fire safety, (ii) Objectives (OB) level which denotes specific fire safety goals to be achieved, (iii) Strategies (ST) level which designates independent fire safety alternatives, each of which contributes entirely or partially to the fulfillment of the fire safety objectives and (iv) Measures (M), which are components of the fire risk that are determined by a direct or indirect measure or estimate.

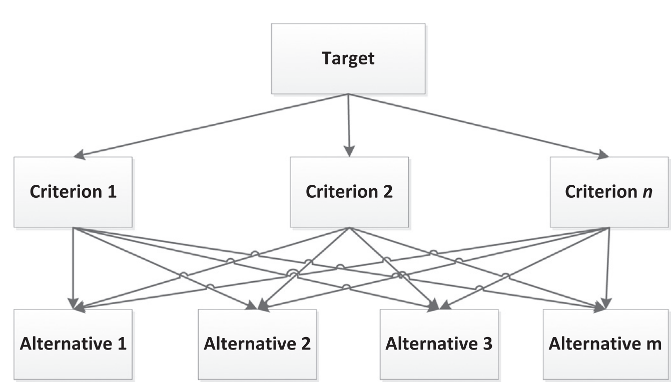

Fig. 1. Typical form of AHP tree.