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Application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments

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ABSTRACT

Hot and humid environments are prevalent in many industries. People working in hot and humid environments are at great risk of specific heat-related disorders, the productivity decrease and safety problems. In order to guarantee workers' health and safety, safety evaluation and early warning rating of the hot and humid environments are studied in this paper. The fuzzy analytic hierarchy process (AHP) method is proposed to evaluate the work safety in hot and humid environments. Trapezoidal fuzzy numbers are adopted to handle inherent uncertainty and imprecision of the data involved in decision process. Within the proposed methodology, a decision group is firstly established. A safety evaluation framework containing three factors (work, environment, and workers) and ten sub-factors are established. The fuzzy weights of the factors and sub-factors are calculated based on the pair-wise comparisons. Then the fuzzy evaluating vectors of the sub-factors and factors can be calculated according to the initial evaluation data. Therefore, the comprehensive safety index, safety grade and early warning grade can be determined. An example is given to demonstrate the proposed method. The results demonstrate the engineering practicability and effectiveness of this method in extreme environment evaluation.

1. Introduction

Extreme hot and humid environments are prevalent in some industries, such as iron, steel, glass and calcium carbide manufacturing, mining, operating in boiler room, and in some military and special facilities such as aircrafts and submarines (Zhao et al., 2009). Working in hot and humid environments results in the increasing of the body core temperature, heart rate and sweating. The heart rate is increased to move blood and heat from heart, lungs, and other vital organs to the skin (Brouha and Maxfield, 1962; Wang et al., 2011). Sweating is increased to help cool blood and body. If the excessive heat is not fully dissipated, body heat storage will occur, and core temperature will increase (Nielsen, 1938, 1966; Robinson, 1949). When heat gain from any sources is more than the body can compensate for by sweating, people are at great risk of a variety of heat-related disorders, such as heat rash, heat cramps, heat syncope, heat exhaustion and heat stroke (Warren et al., 1999; Ramsey, 1999; Inaba and Mirbod, 2007). Worker's exposure to heat can also lead to performance decrement. A number of recent studies have analyzed different aspects of the effects of heat exposure on productivity. Lieberman et al. (2005) studied the effect of a number of concurrent stressors on cognitive performance and mood during an intense military training exercise over 3 days. Hancock and Vasmatzidis (2003) proposed that a dynamically changing deep body temperature leads to a division of attention, resulting in decreased performance. The effects of heat on the worker's task performance can negatively affect the operations of controls, attention to warning signals and reaction-response times, therefore, heat and humidity tends to promote safety problems and accident risk. From 1991 through 2001, in Japan, an average of 13.8 Japanese workers per year died from heat related disorders (Inaba and Mirbod, 2007). In the United States, 423 workers in agricultural and nonagricultural industries were reported to have died from exposure to environmental heat during 1992–2006 (MMWR, 2008). Nevertheless, heat-related deaths at work have occasionally been reported, starting with classical studies in South Africa (Wyndham, 1965).

In order to guarantee workers' health and safety, attempts and efforts have been conducted on working in hot and humid working environments. Fuller (1981) evaluated safety physiological values in a hot workshop. Nag et al. (1997) evaluated the human tolerance limits according to physiological and psychophysical reactions. Minson et al. (1998) summarized the relationship between the skin temperature increase and thermal adjustment of cardiovascular in extreme hot environment. Baker et al. (2000) described how thermal sensation could reflect physiological heat strain. Moran et al.

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(2003) developed an environmental stress index for physiological variables. Kenney et al. (2004) studied anecdotes, clinical cases, and results of laboratory experiments related to extremes of heat stress to examine environmental "extremes", and to highlight the exquisite precision and adaptability of human thermoregulation. Ooka et al. (2010) proposed a new sweating model for the evaluation of thermal safety in hot environments that reflects heat stress and dehydration potential. Hao et al. (2004) studied the trends of psychological and physiological changes of drivers when driving in the hot environment in armored vehicles. Liu (2007) surveyed the degree of physiological and psychological harm to miners in the environment of high temperature and high humidity.

From above literatures, studies on workers' physiological and psychological reactions in the hot and humid environment have proliferated in recent years. As stated above, efforts to provide work safety in workplace are not only important for the health of workers but also inevitable managerial activities for productivity and safety of the facility and the quality and continuity of production (Beatriz et al., 2007). However, safety evaluation and early warning rating of the hot and humid environment is not so much. Wang et al. (2011) examined the prediction accuracy of the predicted heat strain (PHS) model on human physiological responses while wearing protective clothing ensembles was examined. Brake and Bates (2002) indicated there have been more than 60 heat stress indices developed over the last century to characterize the thermal stress imposed by the environment and no single index that adequately reflects the resulting thermal strain has been universally accepted. In ISO 7933 (2004), the PHS model was adopted as a method of evaluating safe thermal environments for workers. Ren et al. (2009) established an evaluation framework for assessing the hazard of heat stress in hot environment and then indicated that the wet bulb globe temperature (WBGT) index and the highest degree of the physical workload can be used to rank the hazard of the heat stress in hot environments. From above literatures, single index is usually adopted to evaluate the work safety in the hot and humid environments.

The safety in a work system always depends not only on the perception of workers but also on many other complicating factors such as the safety training and work environment. Work safety evaluation is a function of many factors (Grote and Künzler, 2000; Champoux and Brun, 2003; Mearns et al., 2003). Therefore, work safety evaluation in hot and humid environments should be analyzed from a holistic point of view and should be considered as a multiple criteria decision making (MCDM) problem.

This paper aims to find an effective method to establish a work safety evaluation and early warning rating system for hot and humid environments. Based on the safety evaluation and early warning rating results, proper precautions against the risks and hazards in the hot and humid environments can be made to prevent and reduce the harm effects of heat exposure.

Several methods have been developed for MCDM problems, such as analytic hierarchy process (AHP), fuzzy AHP, analytic network process (ANP) (Metin et al., 2008), grey method, and extenics theory. There are no better or worse techniques, but some techniques better suit to particular decision problems than others do (Mergias et al., 2007). Fuzzy AHP is a useful tool to deal with imprecise, uncertain or ambiguous data and the high non-linearity and complexity of ecosystems and ecological and environmental issues (Fulvio et al., 2004). Decision makers usually feel more confident to give linguistic variables rather than expressing their judgments in the form of exact numeric values. Therefore fuzzy AHP is more appropriate for work safety evaluation in the hot and humid environment.

For traditional fuzzy AHP, the rating level is usually obtained by the maximum membership grade. And when calculating the final evaluation results, the linguistic variables are often expressed by exact values. In addition, when determining the weights of the indexes, 9-point scale is usually used to represent subjective pair-wise comparisons in most problems. The advantages of fuzzy theory are weakened in traditional fuzzy AHP.

This paper utilizes trapezoidal fuzzy numbers to determine the weights of the indexes and evaluate the performance of the indexes. The primary purpose of the paper is to develop a methodology for the work safety evaluation and early warning rating system. This paper also aims to establish a safety grade and early warning grade system to reduce threat to workers' health, safety and performance in hot and humid environments. This is done with the aim of attracting some attention to the risk analysis and early warning system in hot and humid environments.

This paper is organized as follows. The first section includes the introductory part; Section 2 introduces the methodology; Section 3 describes the work safety evaluation and early warning rating system; Section 4 illustrates a case to perform the work safety evaluation in a hot and humid environment; Section 5 contains discussion, and the last section concludes.

2. Methodology

2.1. Analytic hierarchy process (AHP)

The AHP established by Saaty (1977) is a method to solve multiple criteria decision problems by setting their priorities (Karahalios et al., 2011). AHP aims to settle the conflict between practical demand and scientific decision making, and it also aims to find a way to blend process qualitative analysis and quantitative analysis (Mu, 1997). Decisions made using the AHP occur in two sequential phases: hierarchy design, which involves decomposing the decision problem into a hierarchy of interrelated decision elements (i.e., goal, and evaluation criteria); and hierarchy evaluation, which involves eliciting weights of the criteria and synthesizing these weights and preferences to determine alternative priorities (Sanjay and Ramachandran, 2006).

The AHP is one of the extensively used MCDM methods (Bagranoff, 1989; Arbel and Orgler, 1990; Moutinho, 1993). It has been successfully used in maintenance policy selection (Arunraj and Maiti, 2010), environmental decision-making (Patrick and Laurence, 1999; Chiang and Lai, 2002), resources planning (Willett and Sharda, 1991), and conflict management (Saaty, 1990a; Kang et al., 2007). AHP has also been employed for the risk assessment (Mustafa and Al-Bahar, 1991; Gaudenzi and Borghesi, 2006; Zayed et al., 2008).

From the above literatures, one of the main advantages of the AHP method is the simple structure. The AHP is designed in a way that represents human mind and nature. Therefore, AHP can create the chance of searching and evaluating the cause and effect relationship between goal, factor, sub-factor and alternatives using breaking down the structure of the problem (Milosevic, 2003). Moreover, the use of AHP does not involve cumbersome mathematics, thus it is easy to understand and it can effectively handle both qualitative and quantitative data (Cengiz et al., 2003).

2.2. Fuzzy theory

In the traditional AHP method, the scale of pair comparisons among criteria is restricted to crisp numbers (Chen, 1996; Hauser and Tadikamalla, 1996). And the AHP method does not take into account the uncertainty associated with the mapping of one's judgment to a number (Ayağ and Özdemir, 2006). Therefore, AHP is criticized for its unbalanced scale of judgment and failure to precisely handle the inherent uncertainty and vagueness in carrying out pair-wise comparisons (Gupta et al., 2005). In addition, for safety evaluation, factors affecting work safety in hot and humid