Safety Science 72 (2015) 133–143

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Risk analysis and warning rate of hot environment for foundry industry using hybrid MCDM technique

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ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 11 June 2014
Accepted 24 August 2014
Available online 25 September 2014

Keywords:
Heat stress
ANP
Safety
Risk

ABSTRACT

A person working in extreme hot environment is at greater risk of heat-related disorders and safety problems. Protection of health and safety needs to evaluate the risk and warning rate of hot environment without compromising productivity of the organization. In this paper, a novel hybrid technique was proposed for assessing the work safety in hot environments using multi criteria decision making (MCDM) technique. The proposed model involves analytic network process (ANP) and linguistic fuzzy approach. The ANP approach is used to compute the weights of evaluation factors and triangular fuzzy numbers are used to handle imprecision and uncertainty during the decision making process. In the present study, a total of three main factors and ten sub-factors are considered for the evaluation process. A real case study example is conducted to ascertain the effectiveness of the proposed model. The results show that the criteria “worker” obtained over-all percentage of 64.8%; whereas, “environment” and “work criteria” was 27.8% and 7.4%, respectively. The safety performance of hot environment falls between medium and good. However, the safety grade and warning rate for work is II and I, respectively.

1. Introduction

Workers in hot environment are exposed to severe heat-related illnesses that can potentially cause fatal accidents. Protecting the workers from heat-related illness is important from the moral and economic perspective. Foundries, steel mills and glass factories are considered as the hot environment industries, which involve working near furnaces and extremely hot or molten metal. The body core temperature, heart rate and sweating are increased while working in hot environment (Brouha and Maxfield, 1962; Wang et al. 2011). The heat-related disorders such as heat cramps, heat exhaustion and heat stroke are due to heat imbalance in the human body. Hence, heat disorders are considered as a serious problem, which affect the worker’s health and safety (Warren et al., 1999).Thermal discomfort reduces the efficiency of the worker, which in turn leads to poor decision making accompanied with resultant process errors and increase in the risk of accidents. In studies related to the agricultural and nonagricultural industries published in the MMWR (2008), it was reported that 423 workers have died during the period between 1992 and 2006 due to environmental heat exposure. Inaba and Mirbod (2007) reported that an average of 13.8 workers per year have died in Japan from 1991 to 2000 due to heat illness.

World Health Organization (WHO, 1969) analyzed and reported that heat stress has reduced the human performance in hot working environment (Kampmann and Piekarski, 2000). To guarantee the workers health and safety, various efforts have been made on working in hot environments. Hancock and Vasmatzidis (1998) reported that performance decrement leads to severe safety problems and accidents due to poor attention toward warning signals while working in extreme conditions. Parsons (1999) suggested the ISO standards for the assessment of human responses for thermal environment. Lenzuni et al. (2009) further insisted on the thermal environment classification for assessing the specific work situation. Lu and Zhu (2007) evaluated the physiological index under different climatic conditions and also reported that heat exposure time and physiological values are required to ensure the safe hot working environment. Rodahl (2003) studied the impact of worker’s health in hot, cold and high pressure working environment. Miller and Bates (2007) proposed the thermal work limit for protecting the workers in thermal environment. Grahn et al. (2005) proposed that the heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. Zhao (2007) investigated the human responses to transient thermal environment carried out by the indoor environment group

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http://dx.doi.org/10.1016/j.ssci.2014.08.011
0925-7535/

at Tsinghua University. Nag et al. (1997) evaluated human tolerance limits based on physiological and psychophysical reactions. Petrus (2010) reported that heat acclimatization and heat stress management has an important function in engineering strategies to reduce the environmental heat load. In most of the situations, the workers in extreme hot environment are gradually induced to acclimatization. To improve the tolerance, dissipation of heat and heat acclimatization is a temporary physiological adaptation process.

Casa and David (2009) introduced the guidelines for secondary school athletics against heat acclimatization. Luo et al. (1999) have evaluated the exercising method for accelerating the body heat acclimatization effects. From the above literature, it was observed that the studies on thermal comfort and acclimatization of workers in hot environment have increased in recent years. However, a limited research has been carried out on the basis of risk evaluation of hot environment. To protect the workers from excessive heat, a number of heat exposure indices have been developed. There are two types of indices currently in use: empirical and direct indexes. The empirical indexes are constructed based on perceptual and physiological responses toward extremely hot environments. The direct indexes are formulated on the basis of environmental parameters such as dry bulb temperature, wet bulb temperature, temperature-humidity index (THI). Brake and Bates (2002) reported that to characterize the thermal stress imposed by the hot environment, more than 60 heat stress indices were developed over the last century; however, none of these has been accepted universally. Furthermore, all these indexes were only dealing with the measurement of basic environmental and physiological variables to evaluate the safety in hot environment. Many factors such as work system, safety training and work environment have to be considered for evaluating the safety in hot environment (Grote and Künzler, 2000; Champoux and Brun, 2003; Mearns et al., 2003).

In the present industrial revolution, the decision makers need to analyze a huge amount of data and consider many conflicting evaluation criteria and sub-criteria. Therefore, a safety evaluation in hot environment is considered as the MCDM problem. In the past few decades, the research on risk analysis using MCDM techniques is gradually increasing. Sachdeva et al. (2009) presented multi-factor failure mode critical analysis as an alternative to traditional Failure Mode and Effect Analysis (FMEA) and used Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS) for RPN. Liu et al. (2011) proposed the fuzzy evidential reasoning and gray theory approach for failure mode and effect analysis to increase the effectiveness of the traditional FMEA. Chin et al. (2009) proposed a newly developed methodology for multi attribute decision analysis using FMEA and evidential reasoning (ER). Geum et al. (2011) also proposed a systematic approach for identifying and evaluating potential failure using FMEA and gray relational analysis. Zhang and Chu (2011) used fuzzy set theory in FMEA to eradicate the vagueness and uncertainty of risk priority evaluation process. Liu et al. (2012) developed a tool to assess the risk priority numbers through integration of fuzzy FMEA with VIKOR. Ioannis et al. (2012) integrated FMEA with Analytic Hierarchy Process (AHP) for analyzing the operational failures in offshore systems. Chang et al. (2013) proposed a novel approach by integrating gray relational analysis and decision making trail and evaluation laboratory to rank the risk of failure. So, an evaluation model has been developed after eliminating aforementioned all the shortcomings for the evaluation of risk assessment in the view of improving efficiency of FMEA by combining both FMEA and Fuzzy Analytic Hierarchy Process (FAHP). Among the literature collected, only a limited number of papers have been published, which are related to safety evaluation using MCDM techniques. Zheng et al. (2012) proposed the application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments. Yan et al. (2012) conducted the study on early warning model of coal mining engineering with Fuzzy AHP. Although, the AHP has its own advantages and produced ideal results in various fields, researchers have found certain deficiencies that follows: the conventional AHP decision-maker determines weights by conducting pair-wise comparisons of criteria, which cannot fully reflect the human thinking style and also the ranking of AHP is not precise enough (Chan, 2003; Cheng et al., 1999; Deng, 1999; Mikhailov, 2003). In addition, the deterministic scale may produce some misleading consequences.

The AHP tool is the most widely used MCDM tool for finding the decision making problem, although it is hierarchal in nature. It is allows to compare only the two criteria available within it. Al-Najjar and Alsyouf (2003) suggested that AHP does not seem to be sufficient for an accurate decision making because it is non-monetary and difficult to quantify. Büyüközkan et al. (2004) reported that AHP was widely used as a decision making tool, but ANP is a method which is more powerful than AHP allows interrelationships among elements and replaces linear relationships with dependence and feedback. Hence, this paper aims to evaluate the safety and warning rate of hot environment of foundry industry. The proposed model encompass allows evaluate the criteria along with interdependence of sub-criteria and risks to be ranked using the hybrid MCDM techniques including ANP and fuzzy linguistics approach. In the present study, ANP is used to compute the weights of evaluation factors and triangular fuzzy numbers are used to handle imprecision and uncertainty during the decision-making process.

2. Methods

2.1. ANP method

The ANP method is a generalized form of AHP, which was proposed by Saaty (1996). The AHP method needs hierarchical structure and relationship among factors. It does not allow interdependent relationships within a cluster of factors. The ANP method goes beyond linear relationships among elements and allows interrelationships among elements (Tran et al., 2004). Instead of a hierarchy, the ANP based system is a network that replaces single direction relationships with dependence and feedback (Saaty, 1996, 2001, 2005). Therefore, ANP is more powerful than AHP in the decision environment with uncertainty and dynamics (Rao, 2004). The ANP method has been applied in many complicated decision-making problems in different sectors are given in Table 1.

Procedural steps involved in ANP are listed below:

Step 1: ANP model construction and problem structuring

The proposed framework of ANP model for risk evaluation of hot environment is shown in Fig. 1. The model consists of three stages namely, (i) Goal, (ii) Evaluation criteria and (iii) Warning rating of hot environment. The goal of the developed frame work is to evaluate the risk and provide warning rating of hot environment. Work, environment, and worker are considered as evaluation criteria and corresponding sub-criteria are taken into account for evaluation process. The interactions in between the sub-criteria are shown in Level 3 of the framework.

Step 2: Establishment of pair-wise comparison matrices

After the model construction, a pair-wise comparison matrix is constructed using the suitable Saaty scale given $C = \{C_j | j = 1, 2, \ldots, n\}$ in Table 2. Let be a set of criteria. The result of pair-wise comparison $a_{ij}(i, j = 1, 2, \ldots, n)$ on 'n' criteria can be summarized