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An integrated framework for effective safety management evaluation: Application of an improved grey clustering measurement

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ABSTRACT

Safety evaluation is an important and challenging issue in many industries and is also a key component of risk management. Various evaluation methods have been proposed to make safety evaluation more consistent and objective. However, a major concern is that many existing safety evaluation measurements are still subjective and are not easy to obtain in a uniform way. This paper aims to develop a framework suitable for evaluating the safety performance at organizational or project levels in a comprehensive way that may be expected to reflect all risk assessment aspects and make best use of professional talent and experiences from different evaluators. In this paper, a structural evaluation logic is proposed, based on an improved grey clustering method. First, a grey clustering-based indicator system is developed to avoid the arbitrary selection of indicators. Then, a novel interval-grey-number reciprocal-judgment-matrix based AHP (GRAHP) is proposed that extends the classical analytic hierarchy process to deal with the possible contradictory opinions from experts in different fields as well as the standardization problem of collected independent and uncertain data in evaluation. Additionally, the transformation and optimization method of the new proposed grey hierarchy analysis model are given. Finally, an improved grey variable weight clustering evaluation model is built based on the above described methods. We illustrate the practical implementation of the proposed methods using actual aviation data from China. The results show that the proposed framework and methods have good ability in safety evaluation for large and complex engineering projects.

1. Introduction

Safety evaluation is widely used in various industries and engineering management. It is important for understanding the current state of target object and designing countermeasures for risk mitigation. An overall safety evaluation is not only a key component of risk management, but also becomes one of the most important parts in project development. It receives more and more interest among scholars and project managers.

Safety evaluation methods have been developed for many decades. Literature survey reveals that it is a popular topic in many fields: medical science (Xie, Wang, Cao, & Harpur, 2013), environmental science (Herva & Roca, 2012; Zhao & Pei, 2012), food science and technology (Goodman, Panda, & Ariyarathna, 2013), public health studies (Bartroff, Lai, & Shih, 2013; Zoni & Lucchini, 2012), civil engineering (Elvik & Greibe, 2005), chemical engineering (Rizal, Tani, Nishiyama, & Suzuki, 2005), manufacturing (Shimizu & Sahara, 2000) and so on. Thereby various methods are developed and used in different areas. For example, the microbial growth models used in food safety evaluation, the statistics methods in environment evaluation and the expert judgment methods (e.g., the Delphi survey) that usually used in civil engineering. In this paper, the evaluation framework and methods are proposed mainly for engineering project management. But because the selection of index system is required in almost all evaluation programs, methods in this paper can also be used in safety evaluation problems in other disciplines.

Some existing evaluation methods have become standard methods in certain fields. Failure mode and effects analysis (FMEA) has proven to be a useful tool in assessing potential failures (Sankar & Prabhu, 2001). FMEA has been used in a wide range of industries (Chin, Wang, Poon, & Yang, 2009a; Chin, Wang, Poon, & Yang, 2009b; Sharma, Kumar, & Kumar, 2005). However, this method requires a precise determination of the so-called risk priority numbers (RPNs). Wang, Chin, Poon, and Yang (2009) introduced the fuzzy linguistic terms and fuzzy rating method into the risk factors assignment to overcome this drawbacks. Then they used the fuzzy weighted geometric mean (FWGM) for risk

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evaluation instead of the fuzzy if–then rules. Similar improved methods can be found in (Liu & Tsai, 2012; Zhang & Chu, 2011). Most recent studies applied the fuzzy theory to improve the performance of FMEA, but there are other available methods. For example, Chin et al. (2009a,b) used the evidential reasoning (ER) approach to capture the diversity opinions of FMEA team members. Xiao, Huang, Li, He, and Jin (2011) extended Pickard, Muller, and Bertsche (2005) by proposing a multiple failure mode analysis method based on the minimum cut set and weight parameter setting. Fault tree analysis (FTA) is another widely used method in safety-related research. Cheng, Lin, Hsu, and Shu (2009) applied the intuitionistic fuzzy sets (IFS) theory to the FTA and obtained both the intuitionistic fuzzy fault-tree interval and the intuitionistic fuzzy reliability interval, which provided useful information for finding critical components and weak paths in an emergency shutdown system. To reduce effects of state space explosion and the exponential distribution constrain for basic events in FTA, Manno, Chiacchio, Compagno, D'Urso, and Trapani (2012) integrated the Monte Carlo Simulink tool in FTA. Their method showed better modeling capabilities for dynamic fault trees and saved the computational time. The hazard and operability analysis (HAZOP) is a third widely used method. Its relation to the FTA has been reported in earlier studies (Hoepffner, 1989). It also shows limitations under some conditions. Thus Eizenberg, Shacham, and Brauner (2006) divided the analysis process into several sections and models to reduce the quantitative variation appeared in HAZOP result. Later, the human–machine interface (HMI) technology was integrated into HAZOP, and this helps analysts to obtain data from simulation and use them to design optimal safety operation (Jeerawongsuntorn, Sainyamsatit, & Srinophakun, 2011). HAZOP was also employed with other safety techniques, such as the accidental risk assessment methodology for industries (ARAMIS) in identifying the effect of human errors in offshore evacuations (Deacon, Amyotte, Khan, & MacKinnon, 2013).

Analytic hierarchy process (AHP), developed by American mathematician Saaty (1977), Saaty (1988), Saaty (1990), is one of the most widely used methods in safety assessment for its simplicity. It does not involve cumbersome mathematics and can effectively handle both qualitative and quantitative analysis in risk management. For example, Badri, Nadeau, and Gbodossou (2012) used this method to design the weights for their proposed concept called risk factor concentration. It was also used by Aminbakhsh, Gunduz, and Sonmez (2013) to obtain reliable prioritization of identified risks while considering project funding limits. Their work provides a framework for decision makers to set suitable project targets without compromising safety. The role of AHP in weighting risk factors and synthesizing hierarchy evaluation can also be found in Mabrouki, Bentaleb, and Mousrij (2014) and Podgórski (2015). For other recent works on AHP-based methods for safety risk assessment, readers can refer to papers (Gao, Xu, Liu, & Cao, 2014; Grošelj, Stirn, Ayrilmis, & Kuzman, 2015; Reyes, San-José, Cuadrado, & Sancibrian, 2014).

Some new methods have been developed in recent years. Hong and Jing (2011) built a matter-element model for coal mine safety evaluation based on the extension theory. Chuansheng, Dapeng, Shengping, Xin, and Yingjie (2012) combined the AHP and entropy analysis to establish safety indicators for smart grid. The same entropy weight design method was also used by Li et al. (2011) in their coal mine safety study, but this time it was combined with technique for order preference by similarity to an ideal solution (TOPSIS) method. Based on Mamdani fuzzy inference and jFuzzyLogic library, Camastra et al. (2015) developed a fuzzy decision system for the environmental risk assessment of genetically modified plants.

The above methods and some other classical evaluation methods provide useful ways for safety management. However, they have some shortcomings: the unsuitability of FMEA to complex failure logic (Khan & Abbasi, 1998), the special analysis training requirement of FTA (Shu, Cheng, & Chang, 2006), lacking quantitative data in HAZOP (Vernez, Buchs, & Pierrehumbert, 2003) and so on. Even the most widely used AHP method is criticized for its prerequisite for the consistency of judgment matrix (Triantaphyllou & Mann, 1990). Su, Yu, and Zhang (2010) also pointed out that this method cannot handle the inherent uncertainty and imprecision of evaluators' opinions. They extended the 9-value scales in AHP to 9-value scopes and added indicator weights in a fuzzy integrated judgment (FIJ) step to get the final evaluation. In addition, when using AHP method, the decision problem is usually divided into a hierarchy of decision elements, which are required to be independent of each other. This is usually difficult to achieve when choosing evaluation criterion during the initial phases of safety assessment.

In many studies, the hierarchy of evaluation system and the selection of indicators are not clearly explained. A safety evaluation system usually contains various indicators, so it is possible that some indicators are positive related. If this relationship is strong, small changes of one indicator score may cause similar changes of others and consequently have large fluctuations on the final system evaluation. Uncertainties of evaluator's scores also affect the application of above methods. Though theories of uncertainty, especially the fuzzy theory (Abdullah & Najib, 2013; Jiang, Zheng, & Shi, 2012), have been applied to deal with this problem. They have some weaknesses that demarcations between safety levels are clear. In recent years this problem has been given considerable attention among researchers. Aven and Renn (2009) claimed that risk expresses an ontology dependent of the background knowledge and it is essential to distinguish between the concept of risk and how it is measured. They also pointed out that risk refers to uncertainty about and severity of the consequences, but argued against narrow risk perspectives based on probabilities and expected values (Aven, 2013a; Aven, 2014; Aven & Renn, 2014). Their work established some new frameworks for the various risk perspectives and provided new concepts, such as the "assumption deviation risk", to reflect the strength of knowledge in risk assessments (Aven, 2013b). These provided some guidelines for the development of risk assessment and risk management.

In this paper, we present a framework for overall safety evaluation of complex systems. The framework is mainly based on grey theory and analytic hierarchy process, but it does not simply combine these two methods in different evaluation steps as many published studies did. To overcome the disadvantage of AHP, many recent works applied the Analytic Network Process (ANP) method to allow for more complex relationship among the decision levels and attributes, but ANP requires more calculations and formation of additional pair-wise comparison matrices. Therefore, the complexity of ANP is higher than AHP and its accuracy may be affected by the expertise of evaluation experts (Chen, Huang, & Cheng, 2009). The proposed method in this paper is based on the AHP but with several modifications to improve its applicability: the grey clustering method is employed in the first step to choose the appropriate indicators for safety evaluation. The most important feature of this step is integrating the highly correlated risk factors and improving the independence of elements in safety evaluation hierarchy. Then a grey interval number based judgment matrix is designed and applied in the proposed grey analytic hierarchy process method, which describes the perception uncertainty of evaluators and improves the consistency of evaluation. Mathematical properties of the grey judgment matrix are analyzed and a constraint programming model is provided to find the optimal weights of indicators. Moreover, the classical grey variable weight clustering evaluation model is modified by incorporating