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A systematic approach to identify the hierarchical structure of accident factors with grey relations

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ABSTRACT

Work safety represents a complex systems-phenomenon and should be analyzed with systematic approaches. Hierarchies are fundamental in the study of complex systems. By integrating Grey Relational Analysis and Interpretive Structural Modeling, this paper proposes a quantitative approach which permits an automatic development of the graphic hierarchy of accident factors on the basis of their behavior sequences. The accident factors are identified from the law-enforcement checklists. With Grey Relational Analysis, the relations among the accident factors are calculated based on their time series, which are generated from law-enforcement checklist records. By matrix operation, the grey reachability matrix of these factors is derived from the grey adjacency matrix which is composed of the grey relations. Following the steps of Interpretive Structural Modeling, the reachability matrix is partitioned into different levels by algebraic manipulations, and the factors are arranged in a hierarchical structure. The resulting hierarchy provides a holistic scenario of accident factors, which helps to effectively trace backward and forward the related accident factors in spot check, and serves as a theoretical foundation to conduct comprehensive treatments to eliminate accident factors. An example with the data from Xicheng District Administration of Work Safety is illustrated to show how the proposed approach works.

1. Introduction

Work safety is the state of human, equipment and facilities, and environment being "safe", being protected against hazards, damages or other consequences of failure, error, accidents, or any other event which could be considered non-desirable, in production and business activities (State Administration of Work Safety of the People's Republic of China, 2008).

Safety is a system property, not a component property, and must be controlled at the system level not the component level (Leveson, 2011). Work safety is a function of many factors (Grote and Künzler, 2000; Champoux and Brun, 2003; Mearns et al., 2003). The relationships between these factors and the safety status of the system are multivariate in nature (Khanzode et al., 2012). Accidents are not usually caused by a single failure or mistake, but by the confluence of a whole series, or chain, of errors (Ren et al., 2008). At the same time, a factor of the work system could affect another factor, and there may be interrelations among these factors. For this reason, work safety should be analyzed from a holistic point of view (Metin et al., 2008), and need to be analyzed using a systematic approach (Yu et al., 2008). For any system, with certain elements and environment, its structure determines its function (e.g. Miao, 2006). Efforts to reveal the relationships and structure among accident factors could give valuable guidance for effective accident prevention and investigation.

The systems approach is arguably the dominant paradigm in accident analysis (Underwood and Waterson, 2013). Various systematic accident analysis methods and models have emerged over the past decades (see Salmon et al., 2012; Underwood and Waterson, 2013 for a review). Some of the more well-known models include Accimap (Rasmussen, 1997), Human Factors Analysis and Classification System (HFACS; Wiegmann and Shappell, 2003), Systems Theoretic Accident Modelling and Processes model (STAMP; Leveson, 2004a), and Functional Resonance Analysis Method (FRAM; Hollnagel, 2004). These methods and models have gained a variety of applications in modeling accident factors structure (e.g. Reinach and Viale, 2006; Johnson and de Almeida, 2008; Baysari et al., 2009; Jenkins et al., 2010; Patterson and Shappell, 2010; Salmon et al., 2010; Kontogiannis and Malakis, 2012; Chauvin et al., 2013). Most of these methods provide generic skeletal structures for accident factors modeling in advance. For example, Accimap analyses always focus on contributory factors across the following six organizational levels: government policy and budget-

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Nomenclature

Φ	the empty set	I	identity matrix
e_i	the ith accident factor	M	grey reachability matrix
x_i	time series of e_i	m_{ij}	entry of M in row i and column j
$x'_i(k)$	initial image of $x_i(k)$	R	reachability matrix
LY_{gr}	difference information space	r_{ij}	entry of R in row i and column j
$\delta_{ij}(k)$	absolute difference between x_i and x_j	$R(e_i)$	reachability set of e_i
$\gamma(x_i, y_i)$	grey relational measure between x_i and y_i	$A(e_i)$	antecedent set of e_i
ζ	distinguishing coefficient		
e_iRe_j	grey relational grade between e_i and e_j		
G	grey adjacency matrix		

ing; regulatory bodies and associations; local area government planning and budgeting; technical and operational management; physical processes and actor activities; and equipment and surroundings. In other words, these structures are preset by experiential knowledge. Everything has its two sides. On the one hand, these skeletal structures may act as a filter and bias toward considering only certain events and conditions or they may expand consideration of factors often omitted (Leveson, 2004b). On the other hand, these preset structures might not be of enough flexibility while modeling the structure of accident factors. Accident factors in different systems may have their specific structures, which should be identified on the basis of their own behavior sequences, rather than be casted to artificially preset ones. In fact, some studies (e.g. Underwood and Waterson, 2012) have already examined the lack of method reliability caused by their qualitative nature.

Many other studies turned to system structure modeling approaches in Systems Engineering to reveal the intrinsic structures of accident factors, instead of shoehorning them into preset frameworks or skeletal structures (e.g. Paul and Maiti, 2007; Jha and Devaya, 2008; Chen et al., 2010; Ye and Lu, 2011; Wang et al., 2012; Gao and Yang, 2013), and the major tool is Interpretative Structural Modeling (ISM; Warfield, 1973a, 1973b, 1974), the most popular algorithm of structure modeling in Systems Engineering (Xiao and Fei, 1997). ISM promises to synthesize an objective hierarchy of the elements by mathematical deduction, given the pairwise relations among the elements. Following its development, ISM was reported to be applied to form a multi-level stratum structure among safety factors (Ye and Lu, 2011), to establish risk factors charts (Jha and Devaya, 2008; Iyer and Sagheer, 2010; Gao and Yang, 2013), to reveal risk generating mechanisms (Yang et al., 2010), to build layer structure of problem attributes in occupational accidents (Chen et al., 2010), to assess the pattern and strength of relationships of factors with work injuries (Paul and Maiti, 2007), and to analyze complex system accident causation network (Wang et al., 2012). The successful application of ISM depends on the accurate adjacency matrix of system elements (Zhang et al., 2005). The logical properties of contextual relations can be sources of confusion and error for the use of ISM (Waller, 1980). However, the adjacency matrix in traditional ISM is established by artificial experience and qualitative judgments. Facing complex systems such as work safety, it is practically impossible to enumerate completely the accident factors and understand thoroughly their internal mechanisms, thus it is difficult for experts to reach an agreement and form correct judgments about the relations between and among accident factors correctly and effectively. More quantitative tools are needed.

In short words, while modeling the structure of accident factors, some system-based approaches such as Accimap and HFACS provide generic skeletal structures, which are preset by experiential knowledge and may not reveal the intrinsic structures in different situations. Some other systematic approaches such as ISM do establish the structures by mathematical deduction instead of artificially presetting. However, its elementary structural information, namely, the adjacency matrix, still rests with experience judgments. Just as Deming (in Hastie et al., 2008) claimed that "In God we trust, all others bring data", the pairwise relations among the accident factors, which are to compose the adjacency matrix, should also be data-based and calculated objectively.

The aim of this paper, therefore, is to propose a thoroughly quantitative approach to identify the hierarchical structure of accident factors, with seldom artificial intervention. By introducing Grey Relational Analysis (GRA; Deng, 1982, 2005; Liu et al., 2010), the relations of each factor to each other factor, which compose the adjacency matrix, are calculated based on the law-enforcement checklist records, instead of by subjective judgments. Given the objective adjacency matrix, the hierarchical structure of accident factors is derived through mathematical deduction by Interpretive Structural Modeling. With computer assistance, the approach proposed in this paper permits an automatic development of the graphic structure of the accident factors on the basis of their behavior sequences. Namely, it permits an automatic conversion from the behavior sequences of the accident factors to systematic hierarchical structural diagram.

The remainder of this paper is organized as follows: Firstly, the law-enforcement checklists, based on which the accident factors are identified and measured, are introduced in Section 2. The data for this research, namely the law-enforcement checklist records from Xicheng District Administration of Work Safety, is also described. Secondly, the principle of the proposed approach will be illustrated, and the main procedures will be depicted step by step in Section 3. Thirdly, in Section 4, the data presented in Section 2 will be calculated with the model depicted in Section 3. Some interpretations of the resulting hierarchy will be provided. Fourthly, Section 5 will discuss the academic and managerial implications of the proposed approach. Its applicability and limitations will also be presented. Finally, some concluding remarks are made in Section 6.

2. Materials

2.1. Law-enforcement checklists and accident factors

Just as Leveson (2004a) pointed out, in our increasingly complex and interrelated societal structure, responsibility for safety is shifting from the individual to government. Individuals no longer have the ability to control the risks around them and are demanding that government assume greater responsibility for controlling behavior through laws and various forms of oversight and regulation. In China, the special government agencies responsible for work safety are the vertical administrations of work safety at all levels, e.g., the State Administration of Work Safety, Beijing Muni-