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A quantitative Fuzzy Causal Model for hazard analysis of man–machine-environment system

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ABSTRACT

There are few quantitative analytical models for system safety which considering not only the probability interval of events occurrence but also the influencing degree of incidence relations between different events at present. In this paper, a Fuzzy Causal Model (FCA) for man–machine-environment system hazard analysis which embodying the both as above is brought forward and discussed and applied into hoisting operation superfluities risk computation. Primary achievements are obtained as followed:

A FCA based on fuzzy numbers is constructed, and computation analytic solution for the model on account of fuzzy number is put forward, in addition, the computation results are compared with those of α-cut set simplified computation method and Fuzzy Fault Tree (FFT), which shows computation scientificalness and accuracy of the FCA. Compared to FFT, FCA can better to describe fuzzy logic relations of events which lead to accidents; while compared to Bayesian Network, the inputs and outputs of FCA are defined as fuzzy numbers which can reflect data uncertainty and keep fuzzy information of data. Not only Accident occurrence possibility fuzzy values but also their membership degrees are computed based on the models which may give richer, more useable information for risk management of accidents. FCA could be applicable to safety assessment of system which implicates man–machine-environment interfering factors especially.

1. Introduction

The system hazard analysis (SHA) (Ericson, 2005) is an analysis methodology for evaluating risks and safety compliance at the system level, with a focus on interfaces and safety critical functions. This system-level hazard analysis (Allocco, 2010; Leveson, 2011) should include all possible causal factors from sources such as design errors, materials, tools, equipment, facilities, human errors, software errors, and the like.

Current approaches which could be applied in SHA can be divided into three major categories (Liu and Tsai, 2012), namely, qualitative analysis, semi-quantitative analysis, and quantitative analysis. Among these three categories, qualitative analysis (e.g., checklist, preliminary hazard analysis, and hazard and operability studies) is the most widely used approach due to its simple execution process. However, the information obtained from such analysis is extremely limited and excessively subjective. Semiquantitative analysis (e.g., matrix method, FMEA) is also widely utilized, and its principle is to analyze the level of hazards and risks according to former experiences and judgments; however, a more accurate risk assessment value cannot be obtained. Quantitative analysis (e.g., Fault Tree (FT), Bayesian Network (BN), Cause-Consequence Diagram (CCD) model, etc.) is used to accurately calculate risks. Some successful applications can be found in Aneziris et al. (2008, 2010a, 2010b).

However, it is difficult to apply either traditional FT or BN into quantitative safety analysis of man–machine-environment scenarios such as assembly operation sometimes as the both models are probabilistic reasoning methods based on crisp value. There are two primary reasons: firstly, it is hard to obtain the precise failure data in regard to human factors although several human error databases have been built up. Many human factors (Pengcheng et al., 2012) such as sense of responsibility, psychological state, memorized information and proficiency can lead to a range of operator errors fluctuation; secondly, it is impossible to acquire the failure data statistically relate to some products (especially for new ones), tools, equipments and situational factors for those cases such as construction industry (Liu and Tsai, 2012).

Some studies have improved traditional models to meet the requirements of the failure data fluctuations. Kim et al. (1996) presented the concept of events probability of Fuzzy Fault Tree (FFT) to describe the change of event occurrence probability. Suresh et al. (1996) discussed the difference between traditional probabil-

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ity and fuzzy probability of top event and put forward the computation method of basic event importance degree. An algorithm of the intuitionistic FFT analysis (Shu et al., 2006) was proposed to calculate fault probability interval of system components according to expert's knowledge and experience when applied for the failure analysis problem of printed circuit board assembly. Renjith et al. (2010) developed a two-dimensional analytical method for showing the hesitation degree of expert judgments.

In spite of these, it is difficult to use FFT to model some accidents scenarios, for instance, assembly operation, because the method is based on perfect logic relations of causal events which are often impossible for the process in which states of varieties of affecting factors such as worker, products and tools have fuzzy logic relations with regard to contributing to accidents. For the example of product assembly area, as can be seen in Fig. 1, the smooth floor in the working area causes the worker with a component to slip, thus leading to component damage following component falling to the ground; another example, worker's insufficient hazard perception incurs overloading handcart which results in the component in the handcart falling to the ground. In fact, "Smooth floor" increases the possibility of worker slip but does not have to lead to worker slip event definitely. Similarly, "overloading handcart" amplifies the probability of "component falls to the ground" yet is not bound to cause that and the probability of the both cases might be 70–90% or 40–60%. When the possibility of accidents is measured, the two cases aforementioned need to be analyzed and computed correctively. Except FFT, fuzzy Bayesian Network (Pengcheng et al., 2012) could be used to model the uncertainty of undesired events data such as human factors, however, the fuzzy data must be change to crisp value before computation by defuzzification which could cause loss of fuzzy information, finally, leading to computation results distortion.

A quantitative fuzzy causal analytical model embodying not only the probability interval of events occurrence but also the influencing degree of incidence relations between different events is put forward which integrating the fuzzy mathematics theories with diagram theories and its application into superfluities damage accident of hoisting is illustrated and computation results comparisons with FFT and BN are discussed.

This paper is organized as follows. After the introduction of Section 1, Section 2 briefly presents the model event symbols and operators and the computation methods of operators and shows the operator computation results comparison with other models. Section 3 presents the application of the Fuzzy Causal Model for quantify superfluities damage accident of hoisting risk in product assembly process. Section 4 gives the model computation results comparison with α-cut set simplified calculation and FFT, finally, Section 5 offers a summary and the conclusions.

2. Model

2.1. A fuzzy causal safety analytical model development

In contrast with traditional FT (Remenyte-Prescott and Andrews, 2008; Contini and Matuzas, 2011) and Bayesian Network (Maglogiannis et al., 2006; Mahadevan et al., 2001), the accident mechanism of a Fuzzy Causal Model also is explained by directed acyclic diagrams showing the logic relations between varieties of events. It is highlighted that not only the probability interval of events occurrence but also the influencing degree of incidence relations between different events are represented by triangular fuzzy number (l, m, u), consequently, the computed probability of the undesired event occurrence based on the model is a fuzzy number, but not limited to a triangular fuzzy number, according to probability theories (Ash, 2008) and fuzzy mathematics (Pillay and Wang, 2003). Here without loss of generality, triangular fuzzy number (l, m, u) is used to represent the probabilities, where l, m, n represent respectively the lower least likely value, the most likely value and the upper least likely value.

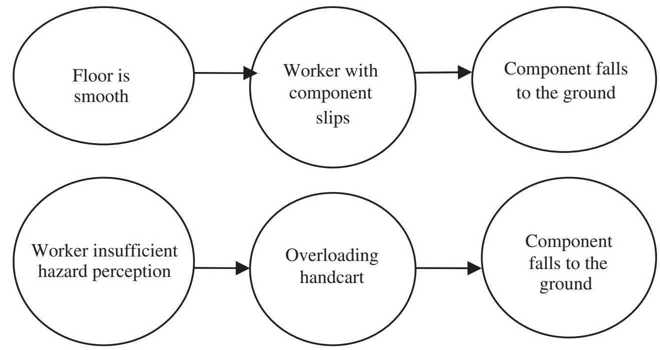

Fig. 1. Examples of causal relations of product assembly incident events.

Before development of the fuzzy causal analytical model, the definitions and presumptions are necessary as follows:

(1) The basic units of the model are three types of operators which are relaxed "and" operator, relaxed "or" operator and conditional operator and three types of event symbols which are initiating event, intermediate event and consequential event.
(2) Intermediate event and result event could be two states which are happening and not happening usually represented by 1 and 0 respectively while initiating event could be multi-state, for instance, event a has m states for maximum, namely, which represented by the a_i, $i = 1, 2, \ldots, m$.
(3) One state of an event is independent of other states of the event, that is, there is no any incidence relation among different states of the event.
(4) Input events are prior to an operator followed by output events and the state of the output event is decided by the states of input events exclusively.

2.1.1. Event symbols and operators

(1) Event symbols.
1. Initiating event.
Fig. 2 is symbol of initiating event x_1.

2. Intermediate event.
Fig. 3 is symbol of intermediate event x_1.

3. Consequential event.
Fig. 4 is symbol of consequential event x_1.
(2) Operator.
1. Relaxed "and" operator.

The perfect logic of Fault Tree "and" operator is that only if all the input events prior to the "and" operator happen, the output event following the operator is destined to happen (Ericson, 2005). However, sometimes even if all the inputs happen, the output is not bound to happen yet there is a great probability of the output to happen, specifically in some cases, that value of influencing degree will be 80–95%. In order to describe this real condition, relaxed "and" operator is defined in the model, represented by in Fig. 5a, which means on the premise of input event x_1 and x_2 all happening, the probability of output event x_3 will be 90% probably,