Safety Science 88 (2016) 76–87

Contents lists available at ScienceDirect

Safety Science

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

The simulation-fuzzy method of assessing the risk of air traffic accidents using the fuzzy risk matrix

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ARTICLE INFO

Article history:
Received 29 December 2015
Received in revised form 23 March 2016
Accepted 27 April 2016

Keywords:
Risk assessment
Fuzzy inference systems
Air traffic safety
Petri nets
Incidents and accidents analysis
Fuzzy risk matrix

ABSTRACT

Modernization efforts in air transport are preceded by analyses to make sure that they do not lead to excessive risk in air operations. The risk assessment methods that have been applied so far are insufficient since their classification of combinations of both the probability and consequences of an event is too rough. The aim of this study was to present a risk assessment method that allows to express risk by using a continuous numeric scale. Therefore, a fuzzy risk matrix is proposed in which both the probability and severity of the consequences are expressed by linguistic variables while the risk assessment is made by the fuzzy inference system. A model based on Petri nets was used to assess the probability of aircraft collision, while computer-implemented expert knowledge in the form of fuzzy inference rules was used to estimate the consequences. Experiments carried out using this tool allowed to assess the risk of a Runway Incursion-type traffic incident transforming into an accident at a *tolerable* level. Furthermore, it was found that the transition of this assessment to the level of *intolerable* is possible when unfavorable visibility conditions occur in connection with the delayed reaction of several participants of the incident. The proposed method is general and can be applied in different areas.

1. Introduction

Air transport has constituted the safest mode of traveling for years. This is the result of extensive usage of risk analysis methods which affects the vast majority of actions performed in the field of air traffic management. Every change of the operating procedure, implementation of new equipment or software, or modification of training programs is preceded by risk analysis in order to check whether implementation of the planned change will maintain at least the current safety level. Safety management systems have been implemented in many areas in which continuous monitoring of the safety system is being conducted and corrective procedures are initiated if there are any irregularities (ICAO, 2012).

An important part of the safety management process is the assessment of risk. In most cases a scale that is discrete and consists of three levels is used. The risk can either be acceptable, tolerable, or intolerable. This assessment is based on fusing the probability of an adverse event with the severity of its consequences. The probability, as well as the consequences, can be estimated by using analytic methods. In practice, expert opinions are used as well. Regardless of the way in which the estimates are obtained, they are usually classified into one of five exclusive categories. The result of the classification is the risk matrix in which each element (i.e. each combination of the probability and severity of the consequences) is tied to one of the three risk assessments (ICAO, 2012).

However, the above practice seems to be inadequate. Assessments of probabilities and consequences are often imprecise but are considered to belong to one particular category that determines further risk assessment. Also, the assessments often come from experts and have a descriptive (qualitative) nature. Such knowledge is subjective and, what is more, the linguistic terms that are used can be understood in different ways by different experts. Therefore, it is not possible to unequivocally and precisely tie those assessments to one of the several possible categories; there is a whole range of intermediate situations and the classic risk matrix does not allow to take those situations into account.

In this paper we proposed to apply fuzzy sets to determine both the probability and the severity of the consequences of an event. This results in the creation of a fuzzy risk matrix which is in fact a fuzzy inference system having two inputs and one output. Thanks to applying this mechanism we obtain a risk assessment that is continuous in a predetermined numerical scale. It allows us to compare the risk for different situations, even when they belong to one particular category, e.g. *tolerable*. Such comparisons allow to rationalize actions as a part of risk management systems.

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http://dx.doi.org/10.1016/j.ssci.2016.04.025

1.1. Literature review

Risk assessment methods in air traffic were proposed in many papers, for instance, by Stroeve et al. (2009), Di Gravio et al. (2015), Tamasi and Demichela (2011), Lee (2006), Ale and Piers (2000), and Janic (2000). Risk assessment consists of estimating the probability of events (Taleb, 2007; Yang et al., 2015; Shyur, 2008; Wong et al., 2009) and their consequences (Wilke et al., 2014; Ayres et al., 2013). In the latter aspect, a particularly important question is how to take uncertainty into account (Aven and Zio, 2011; Aven, 2013, 2015; Johansen and Rausand, 2015; Skorupski, 2014, 2015b). A review of methods for risk analysis under deep uncertainty can be found in (Cox, 2012). A more general review of risk assessment methods in civil aviation can be found in (Netjasov and Janic, 2008).

The case study analyzed in this paper belongs to the category of Runway Incursion. It was also analyzed by Chang and Wong (2012), Wilke et al. (2015), Stroeve et al. (2013, 2015), Yang and Ziqi (2014), and Schönefeld and Möller (2012).

The method proposed in this paper aims to change the approach to safety management, i.e. from a reactive to a proactive approach. This was suggested earlier by Herrera et al. (2009), Sawyer et al. (2015), Ternov and Akselsson (2004), and Kontogiannis and Malakis (2009). The method of obtaining a proactive approach is to put more emphasis on an analysis of incidents instead of accidents. Specific methods to analyze incidents were suggested by Ali et al. (2015), Lower et al. (2016), Brooker (2005), and Nazeri et al. (2008).

Fuzzy inference systems have gained increasing popularity in risk analysis in many areas of technology (Kahraman et al., 2008; Yang and Wang, 2015; Saracino et al., 2015). Fuzzy expert systems for aviation risk assessment have been investigated in (Ken, 2013; Skorupski and Uchroński, 2015a, 2015b; Hadjimichael, 2009; Żurek and Grzesik, 2015).

The concept of the fuzzy risk matrix that was used in this research was proposed by Markowski and Mannan (2008) for the analysis of a distillation column unit. It was also used by Khaleghi et al. (2013), Liu et al. (2014), and Ataallahi and Shadizadeh (2015). In this paper, a proposal for its adaptation and expansion to the problem of risk analysis in air traffic is presented.

1.2. The concept of the paper

The practice of risk analysis shows that using the intuitive opinions of experts which are, by their nature, inaccurate and inexact, is inevitable. This refers to many applications but is especially visible in air traffic management, where socio-technical systems with the vital role of the human factor are widely used. At the same time, risk models and applied calculating procedures are based on classical mathematics, assuming that input data are precise and accurate, but this is often not true. In this paper we proposed to use mathematical models that are adequate for the high level of uncertainty that occurs in practice. There are many possible solutions. In this paper, an approach based on a fuzzy risk matrix is used. The main element is the fuzzy inference system with a hybrid knowledge base, partially obtained from experts and partially from measurement, and with models built on classical mathematics.

The elements of a risk matrix are: the probability of adverse event occurrence and the severity of consequences caused by this particular event. Estimation of the probability is done by simulation and will be exemplified by a model of an air traffic accident created with the use of Petri nets (Skorupski, 2015a). In turn, estimation of the consequences cannot be effectively algorithmized, especially when taking into account not only the total loss of equipment or the loss of life of all the exposed people (which often happens in air traffic accidents), but also smaller damages or injuries. Expert methods are necessary in such situations. Fusing the use of expert opinions and the discrete risk matrix seems inappropriate. The boundaries between particular assessments of input and output values should be fuzzified. Therefore, a fuzzy risk matrix is proposed.

The structure of the remaining part of the paper is as follows: Section 2 describes the general concept of the simulation-fuzzy risk assessment method; Section 3 presents a serious air traffic incident that will be analyzed using the proposed method. The primary elements of the model for assessment of the probability that an air traffic incident will transform into an accident, as elaborated in (Skorupski, 2015a), are also presented; Section 4 includes a description of all the local fuzzy inference systems used in the risk assessment; Section 5 contains a description of the created computer tool as well as a presentation of the simulation experiments performed using this tool; Section 6 includes a summary and the final conclusions.

2. The simulation-fuzzy method for assessing the risk of accident by using fuzzy inference

The proposed simulation-fuzzy risk assessment method is based on two pillars. The first is a simulation analysis of the probability of an accident. The second is a fuzzy analysis of its effects. Both pillars depend on the number of input parameters, both static and dynamic. The final step of the method is risk assessment using the fuzzy risk matrix implemented as a fuzzy inference system.

2.1. General structure of the model

As was stated above, two estimates are necessary to perform an assessment of the risk of an accident. Both of the estimates (the probability of the accident and the severity of its consequences), being the input to the fuzzy inference system implementing the fuzzy risk matrix, are linguistic variables represented by fuzzy sets. A linguistic variable is a variable whose values are either words or sentences in a natural or artificial language. These words or sentences will be called the linguistic values of a linguistic variable. Details are provided in particular sections which describe subsequent linguistic variables. Also, a graphical interpretation of particular values of each of the linguistic variables is presented. A fuzzy set will denote a set of

$$A = \{(x, \mu_A(x)) : x \in X, \mu_A(x) \in [0, 1]\} \quad (1)$$

where μ_A is the membership function of this set.

Schematically, the fuzzy inference system is presented in Fig. 1.

For the input of the fuzzification block we give unfuzzy values $\boldsymbol{X}$ obtained through observation or measurements. In the fuzzification block, based on the specified membership functions, they are associated with the linguistic variables. The fuzzy values $\widetilde{\boldsymbol{X}}$ constitute the input for the inference block. This block uses the base of fuzzy rules which in our case are created by experts, practitioners in the field of airport safety. The inference block, on the basis fuzzy prerequisites and all the fulfilled rules, specifies the

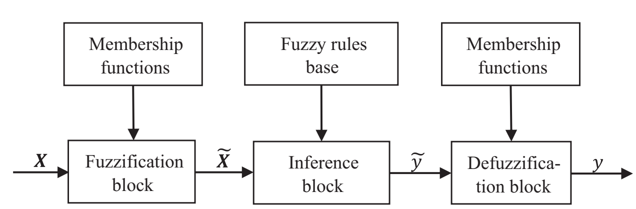

Fig. 1. General structure of the fuzzy inference system.