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ASOC-3125; No. of Pages 10
ARTICLE IN PRESS
Applied Soft Computing xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Applied Soft Computing
journal homepage: www.elsevier.com/locate/asoc

Fuzzy fault tree analysis for patient safety risk modeling in healthcare under uncertainty

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ARTICLE INFO

Article history:
Received 15 February 2015
Received in revised form 31 July 2015
Accepted 2 August 2015
Available online xxx

Keywords:
Healthcare
Fuzzy sets
Trapezoidal fuzzy number
Fault tree analysis
The weakest-*t*-norm (T_ω)

ABSTRACT

Nowadays healthcare becoming more important aspect for everybody. Healthcare institutions now giving more attention to their patients' safety by reducing the frequency of medical errors and trying to provide all kinds of best facilities to them. Clinical processes can be understood as a series of interactions between patients, providers, and technologies. Therefore, there are some chances exist for medical errors due to the involvement of human beings and machines. A number of tools exist to prospectively analyze processes in healthcare which generally needs precise numerical data. In general, available or extracted data is not precise and sufficient to assess the clinical processes upto a desired degree of accuracy due to various practical and economic reasons. Thus, collected data may have some sort of uncertainties and quantification of these uncertainties should be done very carefully before analysing further. In this paper, a new fuzzy fault tree approach has been presented for patient safety risk modeling in healthcare. This approach applies fault-tree, trapezoidal fuzzy numbers, α-cut set, and the weakest-*t*-norm (T_ω) based approximate arithmetic operations to obtain fuzzy failure probability of the system. The effectiveness of the developed approach is illustrated with two different kinds of problems taken from literature related to healthcare. Also, Tanaka et al.'s approach has been used to rank the critical basic events of the considered problems. Computed results have been compared with results obtained from other existing techniques.

1. Introduction

As the living standard of human beings increases due to the increase in their economical and social levels, the need in healthcare is also increasing. Here, the term healthcare can be defined as a series of processes with a number of interrelated interventions leading to a particular outcome. For example, for a patient to receive the correct medication, there is a process in which a drug is first prescribed, then dispensed and then administered as shown in Fig. 1 [1]. In order to execute the safe medication treatment process, each of the steps shown in Fig. 1 must be completed correctly by giving full consideration to patient safety. However, a Joint Health Commission report indicates that medical errors result in the death of between 44,000 and 98,000 patients every year and concludes that healthcare is a high risk, error prone industry [2]. The healthcare institutions are exceedingly complicated systems where the likelihood of happening accidents, errors, close calls, sentinel events, failures, and adverse events are always exist. One possibility to have a safer healthcare system is to support the healthcare processes such as prescribing, medication administration by information technology (IT). Research showed that IT applications can have a potential to reduce clinical errors (e.g. medication errors, diagnostic errors), to support healthcare professionals (e.g. availability of timely, up-to-date patient information), to increase the efficiency of care (e.g. less waiting for patients) and to improve the quality of care [3]. In recent years, healthcare systems have been involved in a number of different changes, ranging from technological to normative ones, all asking for increased efficiency [4].

Since patient safety related problems are major concern for healthcare institutions around the world, so the healthcare institutions have to pointed out the main reasons of different kinds of medical errors and to find out the ways for reducing their frequency. In healthcare, more proactive risk analysis techniques should be applied for better and safe medication processes [5]. There are several examples where reliability analysis methods such as root cause analysis (RCA), failure mode and effect analysis (FMEA), fault tree analysis (FTA) and event tree analysis (ETA) have been applied for patient safety risk modeling in healthcare [3,6–9]. Fault tree analysis has been extensively used as a powerful technique in health related risk analysis from both qualitative and quantitative perspectives [8–10]. Hyman and Johnson [7] presents a FTA

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http://dx.doi.org/10.1016/j.asoc.2015.08.005
1568-4946/

Please cite this article in press as: Komal, Fuzzy fault tree analysis for patient safety risk modeling in healthcare under uncertainty, Appl. Soft Comput. J. (2015), http://dx.doi.org/10.1016/j.asoc.2015.08.005

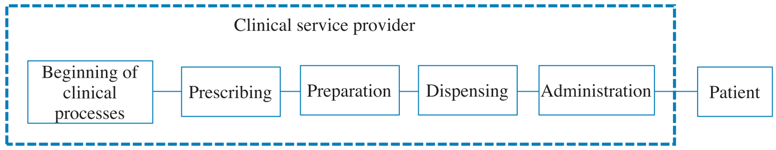

Fig. 1. Execution of clinical processes between providers and patients.

of the patient harm-related clinical alarms failures. They have also addressed human factor issues associated with setting, observing, and responding to alarms. Park and Lee [8] constructed a FTA of handwashing process to investigate the causes for faults in hygiene management. They suggested FTA as a good alternative approach to hazard analysis in hazard analysis and critical control point (HACCP) system implementation. Abecassis et al. [9] used FTA for preventing wrong-site surgery. They also suggested that FTA can be adapted by institutions or specialties to lead to more targeted interventions to increase redundancy and reliability within the preoperative process. Raheja and Escano [10] pointed out some medical error prone areas where FTA can be implemented. Some of the suggested healthcare areas where FTA can be used are equipment failures and malfunctions, material faults, human errors, environment-related risks, management deficiencies, communication and measurement errors, etc.

A conventional FTA is completely understood by the basic events represented by exact values of failure probabilities and logical gates used to combine all the basic events as per their relationships, and applies Boolean algebra to estimate system top event failure probability [11,12]. In practice, the exact values of system components' failure probabilities are difficult to obtain for any large and complex system due to lack of sufficient amount of data and thus the problem is associated with data uncertainty [13,14]. In most of the medical error related problems, uncertainty factor is not quantified significantly. As, there are mainly two causes of uncertainty, one is due to randomness (aleatory) while other is associated with lack of knowledge and information (epistemic) [15]. Uncertainty due to randomness is dealt with probability theory while later one is quantified using fuzzy set theory which was introduced by Zadeh way back in 1965 [16]. Fuzzy sets theory has been successfully employed to analyze the fault tree of various types of engineering and health related systems [3,17]. Generally, triangular fuzzy numbers (TFNs) and fuzzy arithmetic operations are utilized to assess fuzzy probability of top event for any complicated system under vague environment due to simplicity in calculations [18]. Tanaka et al. [19] in their pioneering work developed a fuzzy fault tree analysis (FFTA) method by replacing crisp probability in traditional FTA with trapezoidal fuzzy number (TPFN) to obtain system's fault interval. Singer [20], Cheng and Mon [21], Chen [22], Hong and Do [23] and Fuh et al. [24] analyzed fuzzy reliability of non-repairable two grinding machines working next to each other by utilizing different types of approaches. Singer [20] used *LR*-type fuzzy number to quantify uncertainties and utilized extended algebraic operations while Cheng and Mon [21] applied α-cut interval arithmetic operations. Chen [22] proposed a new and faster method to analyze fuzzy system reliability using fuzzy number arithmetic operations, where the reliability of each system component is represented by a triangular fuzzy number (TFN). Hong and Do [23] utilized T_ω (the weakest *t*-norm)-based addition and multiplication while Fuh et al. [24] used level $(\lambda,1)$ interval-valued fuzzy numbers to examine the fuzzy reliability of the system. Mon and Cheng [25] considered different types of fuzzy membership functions and nonlinear programming approach to analyze the fuzzy reliability of a non-repairable sump-pump system. Huang et al. [26] proposed posbist FTA method for the situation when historical data are scarce or the failure probability is extremely small. Ferdous et al. [27] presented a methodology for a fuzzy based computer-aided FTA and applied their approach to analyze the fuzzy reliability of an activated carbon filter safeguard system. Some researchers use vague sets while some of them applied intuitionistic fuzzy sets for assessing the failure probabilities of different types of systems under uncertain environment [28–33]. To handle uncertainty in healthcare related problems, vague and intuitionistic fuzzy sets may not be very good choices as they rely on hesitation theory. In the present study, an attempt has been made to compute the fuzzy failure probabilities of healthcare systems due to medical errors by developing an FFTA using available uncertain data. To quantify uncertainty, present study uses TPFN for representing basic events' uncertain failure probabilities. For computing system top event fuzzy failure probability, T_ω based approximate fuzzy arithmetic operations given by Lin et al. [34] for TFN have been extended for TPFN and then applied. Here, T_ω based approximate fuzzy arithmetic operations have been used because they give lesser fuzzy accumulation and consequently based on more accurate computed results, appropriate action plans could be chosen to reduce the frequency of medical errors in healthcare systems.

This paper is organized in six sections. Basic concepts related to the present study is given in Section 2. Section 3 briefly describes the process of existing FTA and FFTA while proposed FFTA is developed in Section 4 with detailed procedural steps. In Section 5, the proposed FFTA along with three other existing techniques have been applied to two different kinds of healthcare related problems taken from literature namely a medication pump failing to deliver medicine to a patient, and execution of redundant processes during inpatient transfers to radiology, respectively. The computed results have been compared graphically and given in tabular form. In Section 5, Tanaka et al.'s [19] approach has also been applied to find the most and least critical basic events for the considered problems. The concluding remarks are given in Section 6.

2. Some basic concepts of fuzzy sets theory

This section is devoted to giving brief idea about some basic concepts related to fuzzy sets theory including definitions of fuzzy sets, fuzzification, trapezoidal fuzzy number, fuzzy arithmetic operations, *t*-norm, the weakest *t*-norm (T_ω), T_ω based approximate arithmetic operations and defuzzification, respectively.

2.1. Fuzzy sets

Fuzzy sets were first introduced by Zadeh [16] in 1965 for quantifying uncertainty due to imprecision and vagueness. According to fuzzy sets theory, an element possess varying degrees of membership to the fuzzy set on the real continuous interval [0,1]. Mathematically, a fuzzy set $\tilde{A}$ in the universe of discourse U can be defined as a set of ordered pairs and is given by,

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) : x \in U\} \tag{1}$$

where, $\mu_{\tilde{A}}(x) \in [0, 1]$ is the degree of membership of an element x in the fuzzy set $\tilde{A}$.