On Converting Crisp Failure Possibility into Probability for Reliability of Complex Systems

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Abstract. The reliability of complex systems is analyzed based on several systematic steps using many safety engineering methods. The most common technique for safety system analysis and reliability, vulnerability and criticality estimation is the fault tree analysis method. There exist numerous conventional and fuzzy extended approaches to construct such a tree. One of the steps of the fuzzy fault tree analysis method (FFTA) is the conversion of crisp failure possibility (CFP) into failure probability (FP). This paper points out the drawbacks of one of the formulas for conversion of CFP into FP, and discusses ways to improve the formula for the FFTA. The proposed approach opens a corridor for the researchers to re-think the previous studies, and is susceptible to improve the future applications for safety and reliability engineering.

Keywords: Safety engineering · Fuzzy FTA · Reliability · Crisp failure possibility · Failure probability

1 Introduction

Fault tree analysis (FTA) is used to analyze complex systems in isolation and in a holistic manner to deduce a global reliability and criticality measures [4]. FTA method and its fuzzy extended version (FFTA) have been the subject of extensive research [7, 15]. It is difficult to point of field of research in which they were not applied [17, 20]. Examples of applications areas of FTA and FFTA include reliability evaluation of fire alarm systems [2], human factor analysis of engine room fires on ships [18], system failure probability [2, 24]. Some of the other applications can be summarized as technical factor analysis [25], Arctic marine accidents [3, 16], chemical cargo contamination [19], crankcase explosion [22] and strategic management [1].

Most of the studies in the literature rely on a conversion formula given in detail in the Section 2. The authors mostly refer to the studies of Takehisa Onisawa [9–14] for insights into using this formula. The formula is also used in several

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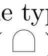
studies such as [5, 23] . We want to quote the intuition behind this formula [24] as "...this equation is obtained by certain characteristics including appropriateness of anthropomorphic feeling to the logarithmic amount of a physical value". Similar explanation can be found in [8]. However, the most comprehensive explanation is due to Lin and Wang (1997) [6] as they refer to the study of Swain and Guttmann (1983) [21]. According to [6], Swain and Guttmann (1983) suggest that an upper and lower bound of the error rate of a routine human operation is $10^{-2} \sim 10^{-3}$ and 5×10^{-5}, respectively [21].

The objective of this paper is to point out the drawbacks of one of the formulas for conversion of CFP into FP, and to discuss ways to improve the formula for the FFTA. The originality of the proposed approach is that it opens a corridor for the researchers to re-consider the previous studies, and is susceptible to improve the future applications for safety and reliability engineering. We claim that this formula should be improved or changed and that the study of Swain and Guttmann (1983) requires an adjustment. The statistics and the data that are the source for inspiration for this formula are vague and based on nuclear power plant applications. The comparison between the results and real time observations prove that the rationale behind the formula seems problematic.

The ideas behind this formula are given in Section 2 and the main problems are explained in Section 3. Section 4 presents the proposed approach and provides an application along with limitations and future directions. Finally, Section 5 concludes the paper.

2 General approach for the formula of converting crisp failure possibility (CFP) into failure probability (FP)

FTA involves a bottom-to-top computation process.The inputs are obtained as a FP from the BE at the bottom, then the calculations are performed accordingly based on the types of the gates. If two events are connected each other with the AND gate (), calculation is made as in in Equation 1 :

$$P_0(t) = \prod_{i=1}^{n} p_i(t) \tag{1}$$

If two events are connected with each other with the OR gate (), calculation is done as given in Equation 2:

$$P_0(t) = 1 - \prod_{i=1}^{n} (1 - p_i(t)) \tag{2}$$

The inputs for the FTA are the values of FP. In the literature, general formula for the conversion of CFP to FP is given in Equation 3:

$$FP = \begin{cases} \frac{1}{10^K}, & \text{if } CFP \neq 0 \\ 0, & \text{if } CFP = 0 \end{cases}, K = \left[\left(\frac{1 - CFP}{CFP}\right)\right]^{\frac{1}{3}} \times 2.301 \tag{3}$$

CFP is the defuzzification of aggregated fuzzy evaluations. Please refer to the following works [17, 20] for the aggregation and defuzzification of a trapezoidal fuzzy number for more details.

3 Main problems of general approach

CFP values are always between 0 and 1. According to several tests we conducted (0.0001 to 1.0000) to cover all the range of possible values, we find the FP values as given in Figure 1. As we can see, the trend is almost constant between 0 and 0.6, then the sharp increase starts after 0.9.

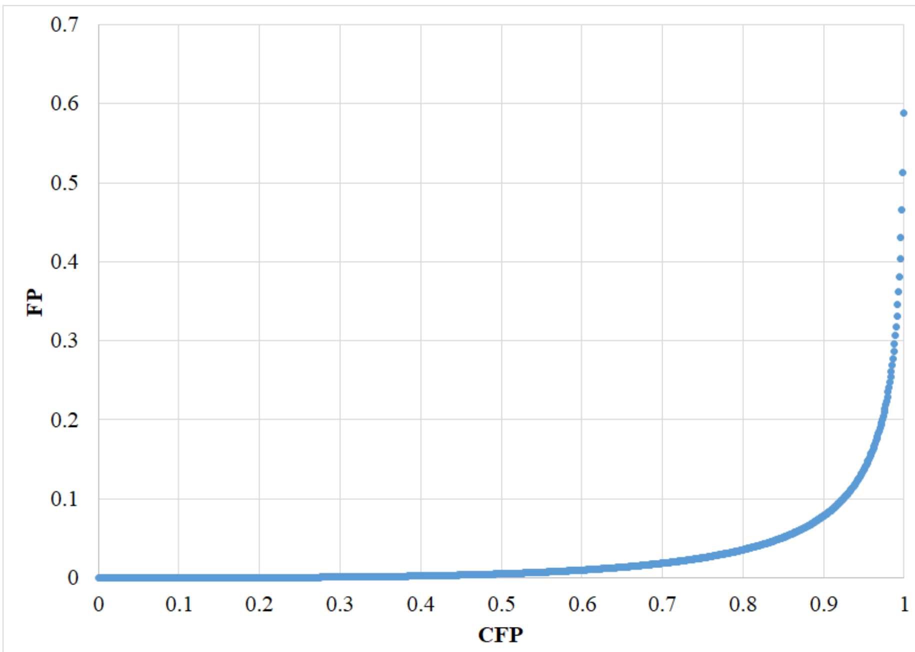


Fig. 1: General trend of FP using CFP

There are three main problems with this approach and the formula given in Equation 3:

- There is no logical explanation for this graph given in Figure 1.
- In the Figure 1, we did not compute FP value when CFP is equal to 1, because we want to observe the trend and values in a detailed manner. If CFP is equal to 0.999, FP is found as 0.588604054. However, if CFP = 1, FP is found as 1 which means a huge difference. Similarly, if CFP = 0.9999, FP is obtained as 0.781976102. Comparing to CFP = 0.999 and CFP = 0.9999, the

difference is 0.0009 but the change in probability is 0.193372048. Similarly, if CFP = 0.99999, FP is 0.892126197. So, this proves that the formula has a big problem. Even if this sharp increase at the graph is mathematically correct and acceptable, this might not be logical in practice since those tiny changes cause big differences.
- Secondly, a single formula (Equation 3) and only one trend (Figure 1) for all different problems might limit the flexibility of the problems. This might also prevent finding exact solutions for the problems.

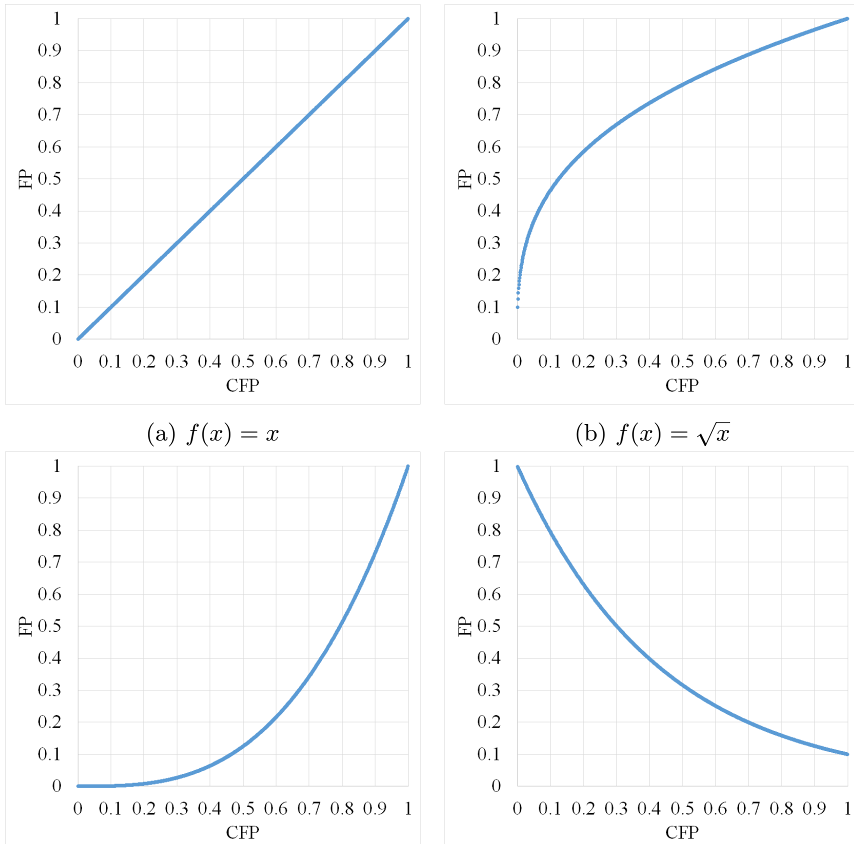
4 Proposed approach

In this paper, we propose use of conversion functions for each BE. The conversion functions might be different based on the characteristics of the BE. The decision makers or the moderators determine the type of the conversion functions since they know the problems in a detailed manner. Let the conversion function be $y = f(x)$ where $y \in [0, 1]$. In this case, FP=f(CFP) where FP $\in [0, 1]$. This is better because FP only depends on CFP. Different types of conversion functions can be used, and this entirely depends on the problem's characteristics (Figure 2). Some of the examples are given below:

- Constant Function: $f(x) = a$
- Linear, Identity Function: $f(x) = x$
- Quadratic Function: $f(x) = x^a$, $f(x) = x^2$
- Cubic Function: $f(x) = x^3$
- Exponential Function: $f(x) = a^x$
- Logarithmic Function: $y = log_2(x)$, $y = log_e(x)$, $y = log_{10}(x)$
- Square Root, Cube Root Function: $f(x) = \sqrt[a]{x}$
- Any Function: $f(x) = x^3 - 5x^2 + 4x$

4.1 An application

In this example, a simple fault tree analysis is provided based on the pre-defined conversion functions. For the BE_1, a square root function, for the BE_2, exponential function and for the BE_3 a linear function are preferred as an example (Figure 3). Table 1 gives the aggregated fuzzy assignments and defuzzified values of the BEs for two different examples. As shown in the table, we converted CFP into FP based on the proposed and the conventional approaches. Then, we calculated the probability of TEs for both two examples. For the first example, we calculate the probability of TE as 0.000484 for the conventional approach and 0.5245 for our proposed approach. For the second example, we calculate the probability of TE as 0.000273 for the conventional approach and 0.447412 for our proposed approach. The values obtained based on our approach are quite higher than the conventional approach, however field experiences prove that it is more realistic than the conventional results.



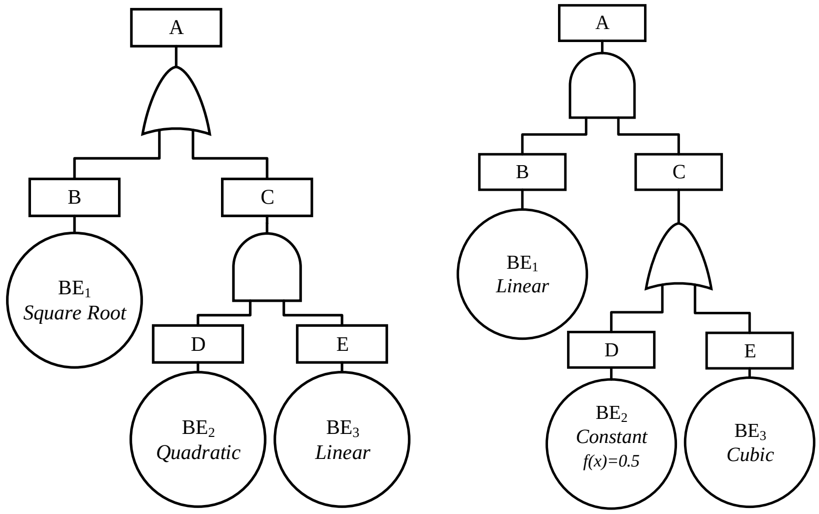
(a) $f(x) = x$ (b) $f(x) = \sqrt{x}$

(c) $f(x) = x^a$ (d) $f(x) = a^x$

Fig. 2: Some examples of conversion functions

Table 1: Fuzzy inputs and probability values for two examples

				Conversion CFP to FP		
1		Aggregation of BE	Defuzzification values	Conventional approach	Proposed Approach	
	BE_1	(0.1,0.2,0.3,0.4)	0.25	0.00048	Square root	0.50000
	BE_2	(0.2,0.3,0.4,0.5)	0.35	0.00148	Quadratic	0.12250
	BE_3	(0.3,0.4,0.4,0.5)	0.4	0.00232	Linear	0.40000
2				Conversion CFP to FP		
		Aggregation of BE	Defuzzification values	Conventional approach	Proposed Approach	
	BE_1	(0.7,0.8,0.9,1.0)	0.85	0.05121	Linear	0.85000
	BE_2	(0.3,0.4,0.5,0.6)	0.45	0.00347	Constant	0.50000
	BE_3	(0.1,0.2,0.3,0.8)	0.375	0.00187	Cubic	0.05273



(a) Fault tree example 1 (b) Fault tree example 2

Fig. 3: Random fault trees for the application

4.2 Limitations

The proposed approach has some limitations as given below:

- The probability is the function for a crisp value of possibility which is based on aggregated expert opinions. Therefore, the experts or moderator might not be able to determine the exact functions for their fuzzy inputs. The function assignments must have proven groundings.
- The values for the probability must be between 0 and 1. Therefore, the moderator or the experts should define the constraints of their functions. For example, if there is a reciprocal function $f(x) = \frac{1}{x}$ or reciprocal inverse squared function: $f(x) = \frac{1}{x^a}$, boundaries should be set earlier since the maximum value exceeds 1.
- More experiments should be conducted to observe the changes, and it is needed to get double-checked whether there exists a parallelism in terms of the validation of final results, experts' opinions and intentions.

4.3 Future Directions

Proven groundings should be discussed in the future in order to explain how possibility and probability can be associated with a function and what are the fundamentals of the conversion formulas between possibility and probability. In the future, it should be studied that if there is a standard system that can be used to convert possibility into probability. To do that, previous studies in the literature might be re-applied to observe and compare the results to validate the standard system. We have to note that the results will mostly be different than the conventional results since we make a substantial improvement in the FFTA method. The comparisons and validations might be conducted based on the real cases of which their impact values and final probabilities are already known.

5 Conclusions

This study discusses a formula which converts CFP into FP. The conversion formula mentioned in the paper is important because of massive studies in the literature and their high impact on the results and reliability of complex systems. We find that conventional technique has some drawbacks, and we open a discussion to improve this formula. We offer using any pre-defined conversion function for BEs of FFTA applications under several constraints. Thus, further complex system applications might reach to the more realistic results.

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