Fuzzy fault tree analysis of resilient safety culture in Australian construction industry

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Abstract

Resilient safety culture (RSC) model earlier developed by authors is defined and categorized into three groups: behavioral, psychological, and managerial capabilities. These groups are further sub-divided based on various subconstructs and indicators as found in the literature. Resilient safety culture comprises of the static and the dynamic component which makes it challenging to understand and control. This model thus shows how resilience in organizations can help in defending against uncertainty and safety hazards.
This study predicts weak areas in resilient safety culture in Australian construction industry using 4 organizations. The prediction of future failures can be done to some extent by studying the fissures in the resilient safety culture system. This system can be modelled based on fault tree analysis and since fuzziness is involved in the survey inputs, fuzzy fault tree analysis (FFTA) is used to predict the failure modes in the system.

Keywords

Safety, Resilience safety culture, Fuzzy set theory, Fault tree analysis

1. Introduction

Resilient safety culture (RSC) model was generated as seen in earlier studies (A Garg & Mohamed, 2018; Arun Garg, Tonmoy, & Mohamed, 2019). In this study, the methodology of using RSC uses the indicators or items using a survey which give an overall approach or holistic view of how the system is behaving. This system then gets the resilience level at the indicator, sub construct and the construct level. That resilience level shows the weak links and nodes which need resource allocation. It does not identify risks in a very local sense such as "how will this machine fail in interaction with the human behavior or how this hazard will be dealt with?" but it looks at how the organization as a system is behaving as well as its human resource management. How is the socio technical system behaving? There is off course a connectivity between risk and resilience engineering and that is the resilience engineering helps give pointers where the weak nodes and linkages need to be focused. The survey questions are not specific in nature but holistic in approach which gives it unique sense.

These studies then showed how this model can be quantified. This took into consideration the risk approach where probability analysis was used using fuzzy fault tree analysis (FFTA) and kept the indicators same throughout and not reducing them. This approach thus gave the probability numbers of those indicators, sub construct and constructs. This is more of the unified approach as described by (Aven, 2018).

1.1. Resilient Safety Culture Model

RSC is a new concept which has been proposed to cover the weaknesses of safety culture. It is a safety culture with resilience, learning, continuous improvements and cost effectiveness (Shirali, Shekari, & Angali, 2016). RSC is based on three factors: 1) Psychological/cognitive capability 2) Behavioral capabilities and 3) Managerial/contextual capabilities to anticipate, monitor, respond and learn in order to manage risks in a resilient organization. Resilience engineering (RE) is added in the safety culture to look at safety in safety-II way.

Figure 1 shows the overall system interaction and behavior of an independent system. Resilience is a characteristic which is added and defined for the system. It takes care of any uncertainty which arise along with safety issues.

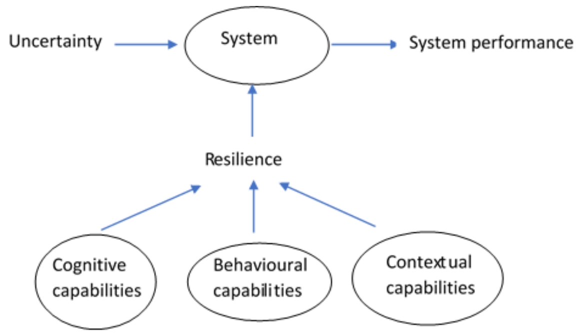

Figure. 1. A resilience incorporated system as perceived by authors

1.2. Fault Tree Analysis

Fault tree analysis (FTA) was developed in 1962 and is frequently used in the fields of safety engineering (Shoar and Banaitis 2019). It is a top down deductive failure analysis for estimating system reliability using Boolean logic. FTA is used to provide framework using the defects and weaknesses of the system can be analyzed qualitatively and quantitatively. FTA begins with the aim of identifying the causes of the undesired event. The relationships between the top event, intermediate and basic events are presented by logical gates such as OR and AND. OR gate indicates the occurrence of any lower event would result in the occurrence of the upper event and AND gate indicates that if lower events occur then upper event will occur as well. In conventional FTA, the failure probabilities of the basic events (BE) are exact values but getting the precise estimation of failure probabilities of BE is not easy and impractical due to insufficient data (Cheliyan and Bhattacharyya 2018). It is often necessary to work with possibility as compared to probability. Thus, the use of fuzzy failure fault tree analysis (FFTA) was incorporated in this study.

1.3. Fuzzy Fault Tree Analysis

The fuzzy approach deals with fuzzy logic and membership function. This idea was first introduced by Dieter Klaua in 1965 and L.A Zadeh (Akter et al. 2019). A fuzzy FTA approach is applied when sufficient and reliable database is not available. In this approach, subjective expert opinions can be employed to deal with lack of data in basic events. Fuzzy approach helps in determine the basic events (BE) probability values when less quantitative information is available, where the BE probabilities are treated as fuzzy numbers. It uses triangular, trapezoidal and gaussian fuzzy numbers. There are three steps to implement the fuzzy logic technique. Fuzzification, fuzzy inference and defuzzification. The relationships between a parameter and the membership function are described by a fuzzy number (Rai, Sharma, and Lohani 2014). The value of the membership function ranges from 0 to 1. The fuzzy number can assume any justified shape according to the information available. Most common functions used to represent linguistic variable are triangular and trapezoidal (Huey-Ming Lee 1996). Fuzzification coverts the crisp data into fuzzy data or membership function, fuzzy inference combines the membership function with control rules to get the output and defuzzification lead to crisp output of the fuzzy number. Centroid and centre of area method are the two most commonly used defuzzification methods (Yager 1980). In this research, the trapezoidal fuzzy numbers are used to provide more precise descriptions and to obtain more accurate results.

2.0 Research Methodology

FTA helps determining all possible situations that can result in the occurrence of undesirable event. Analogy of this concept with RSC is made and in the case of RSC, the fault tree model can help to identify the probabilistic estimation of resilience (top event). The higher the probability of occurrence of individual construct and its sub constructs (downstream nodes of the fault free), the higher the probability of the safety culture to be more resilient. Probabilities of sub-constructs can be estimated by conducting a survey.

This research study was done using four construction organizations (D, E, F, G) in Australia. The surveys were completed by different employees including engineers, supervisors, and managers. There was no limitation on who could fill the survey since the goal is to gauge the perception of all employees working in these organizations along with other attributes about the safety culture. There were 42 items in the survey. Nine items were for "psychological capability", fifteen items were for "behavioral capability" and eighteen items were for "managerial capability". Total forty two items were inferred using the various indicators of RSC model (A Garg & Mohamed, 2018). Likert scale from 1-5 was used to rate these items, where 1 on the low side or lower expectancy and 5 on the higher side or higher expectancy.

It is difficult to determine the exact probability of occurrence between events (Pan & Yun, 1997). The fuzzy numbers are thus used to deal with imprecise and vague information such as extremely likely, likely, extremely unlikely etc. In our Likert scale, the survey gives five options starting from 1 which denotes very low expectancy (VLE), 2 denotes low expectancy (LE), 3 denotes medium expectancy (ME), 4 denote high expectancy (HE) and 5 denotes very high expectancy (VHE). These linguistic expressions describe the probability of the indicator's occurrence. These linguistic values can be represented by various forms of fuzzy numbers. It also uses fuzzy theory for fault tree analysis.

2.1. Steps to modelling the problem

1) Choose multiple companies for the survey, in this case there are 4 companies
2) Choose employees of various backgrounds who can understand the questions well to give ratings on importance of indicators using a survey
3) Use Likert scale to rank for importance from 1-5 (Shoar et al. 2019), the ranking is between groups of psychological, behavioural, and managerial of the RSC model.
4) Choose the experts which can be as low as 4 (Shoar et al. 2019) for giving likelihood of occurrence.
5) Use the survey to find the likelihood of occurrence using zones from "very low (VL)", "Low (L)", "medium (M)", "high (H)", "very high (VH)". This is the linguistic expression to fuzzy number step. We use the trapezoidal fuzzy number as represented by four values (a, b, c, d) for the five membership functions (VH, H, M, L, VL). (Cheliyan et al. 2017)
6) Do the aggregation for driving the estimates of the basic events (Cheliyan et al. 2017)
7) Défuzzification process (Cheliyan et al. 2017)
8) Converting fuzzy possibility score to fuzzy failure probability (get the selected basic event probability) (Cheliyan et al. 2017)
9) The weight distribution for the indicators is according to as earlier done (Ebrahemzadih ,2016), the weights are equally distributed under each sub construct or construct.
10) The weights which is equally distributed and the probability scores for selected basic events, now in this step, relative probabilities are calculated for the whole network and construct an FTA model.

2.2. Model Application

Figure 2 shows the proposed fault tree for RSC which includes 3 constructs and 10 sub constructs of the RSC model. It is understood through literature that all the constructs of RSC follow an "AND" gate which is progressive relationship as defined by Cooper et al (Cooper 2000). This is assumed that resilience level can only be achieved if employees can perceive about safety (psychological) and have behavioral capability and have managerial system in place. In the absence of any of these three, there is no resilience in the culture. However, in the case of measuring sub-constructs and indicators, "OR" gates is used. This is mainly because OR gates are parallel relationship which allows achieving a construct (or sub-construct) partially even one sub-construct (or indicator) are absent. As an example, some degree of 'Behavioral capability' (which is a construct) within an organization is possible to achieve even if some of its measuring sub-constructs or indicators are absent. It should be noted that the OR and AND gates are used in this study because it is assumed that the indicators, sub-constructs and constructs all follow the true relationships as defined. There is no cross relationship.

Behavioral capability construct is used as an example to show the breakdown of FTA in more detail towards the events level. Figure 3 shows illustration of the construct "Behavioral capability" denoted by B0 (Chen et al. 2016). After OR gate, B1, B2, B3, B4 are its sub constructs namely "Learned resourcefulness", "Counterintuitive agility", "Practical habits", Behavioral preparedness". X10 to X24 are the basic events or indicators (Garg, Alroomi, Anwar, et al. 2019; Garg and Mohamed 2018). There are 42 indicators in the whole RSC. Probabilities of achieving each constructs and sub-constructs can be estimated by conducting a survey among employees within the organization.

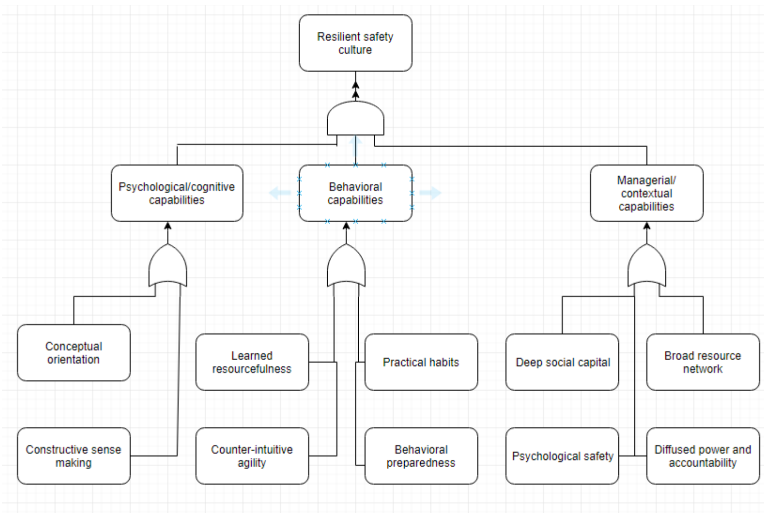

Figure 2: Proposed fault tree for resilient safety culture (RSC)

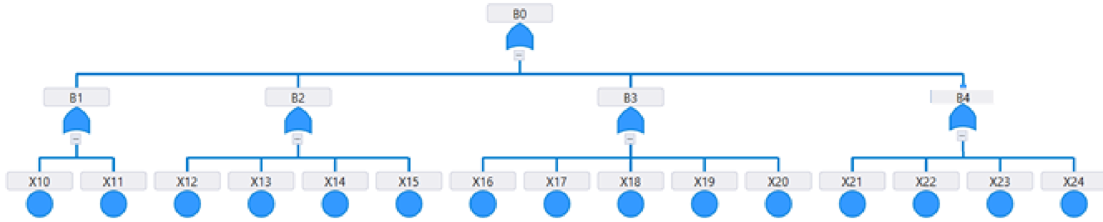

Figure 3: Proposed fault tree for "Behavioural capability" B0 construct.

Equation 1 shows the construct's probability which is calculated using summation of weighted sub constructs.

$$P = \sum_{i=1}^{n} a_i p_i \qquad (1)$$

P is the relative probability of construct B0, *a* is the factor weight and *p* is the probability of various sub constructs. The reliability probability of this sub-system is calculated using equation 1. P_{BO} is the total probability of this sub-system where as p_1 is the probability of the node B1 (sub construct) which is calculated using the equations 1 and 2 relationships using p_{10} and p_{11} likewise other probabilities like p_2, p_3, p_4 can be calculated. The weight of node B1 is a_1

whereas a_{10} is the weight for node X10 (indicator). Equation 2 calculates the probability for parallel relationships which means happening together since this system has OR gates.

It is assumed that the weightages are same for each indicator in same sub construct level and same weightage for each sub construct under similar construct level. The parallel relationships (OR gates) are independent of each other so they are assigned weights but progressive (AND gates) are not independent so no weights are assigned (Ebrahemzadih and Haedari 2016). This is the construct level where no weights are assigned.

$$P_{BO} = a_1p_1 + a_2p_2 + a_3p_3 + a_4p_4 \quad (2)$$
$$p_1 = a_{10}p_{10} + a_{11}p_{11}$$
$$p_2 = a_{12}p_{12} + a_{13}p_{13} + a_{14}p_{14} + a_{15}p_{15}$$
$$p_3 = a_{16}p_{16} + a_{17}p_{17} + a_{18}p_{18} + a_{19}p_{19} + a_{20}p_{20}$$
$$p_4 = a_{21}p_{21} + a_{22}p_{22} + a_{23}p_{23} + a_{24}p_{24}$$

Finally, using equation 3, relative probability of the progression relationships (AND gate) is calculated which means factors happen in-sequence. Superior factor's (top event) probability is the product of inferior factors (all three constructs). In this case, equation 3 is used to calculate RSC.

$$P = \prod_{i=1}^{3} p_i \quad (3)$$

3.0. Results

3.1. T tests

Table 1 shows unpaired t-test results for company D, E, F, G. One sample t-test was performed for companies D, E, F and G for likelihood of occurrence data which provided comparable sample size data for the companies. For t-test for all companies, the two tailed P value is less than 0.0001. By conventional criteria, this difference is extremely statistically significant. Table 1 shows t-test results for companies D, E, F and G.

Table 1: One sample T-test of Companies D, E, F, G

Group	Company D	Company E	Company F	Company G
Mean	4.007	2.803	3.273	3.761
Std Dev.	0.474	0.473	0.514	0.340
Sig. (2-tailed)	0.0001	0.0001	0.0001	0.0001

3.2. Linguistic expressions to fuzzy numbers

Expert opinion is used to compute the failure probability of the basic events (BE) those are indicators in this case used for a structured questionnaire survey. Experts apply natural linguistic expressions such as "very low or VL", "low or L", "medium or M", "high or H" and "very high or VH" to describe the probability of the BE (basic event or indicators). These are related to the membership function as shown in figure 4 which consists of both triangular and trapezoidal fuzzy numbers. The triangular fuzzy numbers are converted to trapezoidal fuzzy numbers for ease of computation. Each trapezoidal fuzzy number is represented by four values (a, b, c, d) for the five membership functions (VH, H, M, L, VL).

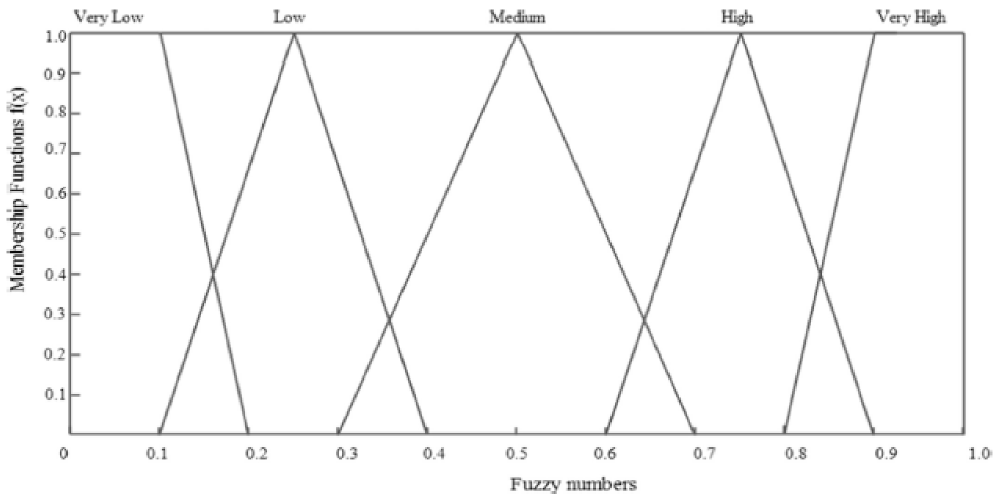

Figure 4 : Fuzzy membership function for fuzzy numbers (Adapted from Cheliyan and Bhattacharyya 2018)

3.3. Finding the estimates of the basic events

Every BE is given a rating by experts. All the ratings for the single BE (basic event) must be aggregated to obtain a single opinion. This is done by linear opinion pool method given as follows.

$$M_i = \prod_{j=1}^{N_e} A_{ij} W_j \ \ (i = 1,2, \dots N) \quad (4)$$

Where N is the number of BE, N_e is the number of experts, W_j is the weighting factor of the expert j (in this case study, the weighing factor is kept same for all the experts which is the total factor sum to 1). A_{ij} is the linguistic expression (either a, b, c or d) of the i_{th} BE given by the expert j as seen in the tables 2 to 5. M_i is the aggregate resultant of the trapezoidal fuzzy number of the BE X_i. The values of the M_i (a, b,c,d) are shown in the following tables.

Table 2: Data of the basic events (BE) for company D

Indicator (BE)	a	b	c	d	P (Xi)
1	0.7992	0.8991	0.999	0.999	0.084766
2	0.7992	0.8991	0.999	0.999	0.084766
3	0.666	0.7992	0.8325	0.9324	0.030249
4	0.666	0.7992	0.8325	0.9324	0.030249
5	0.666	0.7992	0.8325	0.9324	0.030249
6	0.666	0.7992	0.8325	0.9324	0.030249
7	0.666	0.7992	0.8325	0.9324	0.030249
8	0.666	0.7992	0.8325	0.9324	0.030249
9	0.666	0.7992	0.8325	0.9324	0.030249
10	0.6327	0.7659	0.8325	0.8991	0.027002
11	0.5661	0.71595	0.74925	0.8658	0.018303
12	0.4995	0.666	0.666	0.8325	0.012791
13	0.6327	0.7659	0.8325	0.8991	0.027002
14	0.4995	0.666	0.666	0.8325	0.012791

15	0.666	0.7992	0.8325	0.9324	0.030249
16	0.5661	0.71595	0.74925	0.8658	0.018303
17	0.5994	0.74925	0.74925	0.8991	0.020487
18	0.5661	0.71595	0.74925	0.8658	0.018303
19	0.5661	0.71595	0.74925	0.8658	0.018303
20	0.4995	0.666	0.666	0.8325	0.012791
21	0.5661	0.71595	0.74925	0.8658	0.018303
22	0.4662	0.6327	0.666	0.7992	0.011377
23	0.3996	0.58275	0.58275	0.7659	0.008038
24	0.5661	0.71595	0.74925	0.8658	0.018303
25	0.666	0.7992	0.8325	0.9324	0.030249
26	0.7326	0.84915	0.91575	0.9657	0.047481
27	0.666	0.7992	0.8325	0.9324	0.030249
28	0.4995	0.666	0.666	0.8325	0.012791
29	0.4995	0.666	0.666	0.8325	0.012791
30	0.4995	0.666	0.666	0.8325	0.012791
31	0.666	0.7992	0.8325	0.9324	0.030249
32	0.666	0.7992	0.8325	0.9324	0.030249
33	0.5994	0.74925	0.74925	0.8991	0.020487
34	0.333	0.4995	0.4995	0.666	0.004985
35	0.4329	0.58275	0.58275	0.7326	0.008146
36	0.4329	0.58275	0.58275	0.7326	0.008146
37	0.333	0.4995	0.4995	0.666	0.004985
38	0.333	0.4995	0.4995	0.666	0.004985
39	0.5994	0.74925	0.74925	0.8991	0.020487
40	0.5994	0.74925	0.74925	0.8991	0.020487
41	0.5994	0.74925	0.74925	0.8991	0.020487
42	0.666	0.7992	0.8325	0.9324	0.030249

Table 3: Data of the basic events (BE) for company E

Indicator (BE)	**a**	**b**	**c**	**d**	**P(Xi)**
1	0.33	0.5625	0.5625	0.75	0.006767
2	0.33	0.5625	0.5625	0.75	0.006767
3	0.24	0.5	0.5	0.7	0.00466
4	0.24	0.5	0.5	0.7	0.00466
5	0.33	0.5625	0.5625	0.75	0.006767
6	0.51	0.6875	0.6875	0.85	0.014081
7	0.205	0.4375	0.4375	0.625	0.003225
8	0.205	0.4375	0.4375	0.625	0.003225
9	0.205	0.4375	0.4375	0.625	0.003225
10	0.24	0.5	0.5	0.7	0.00466
11	0.17	0.375	0.375	0.55	0.002127
12	0.17	0.375	0.375	0.55	0.002127
13	0.17	0.375	0.375	0.55	0.002127
14	0.24	0.5	0.5	0.7	0.00466
15	0.24	0.5	0.5	0.7	0.00466

16	0.205	0.4375	0.4375	0.625	0.003225
17	0.17	0.375	0.375	0.55	0.002127
18	0.205	0.4375	0.4375	0.625	0.003225
19	0.135	0.3125	0.3125	0.475	0.001308
20	0.17	0.375	0.375	0.55	0.002127
21	0.24	0.5	0.5	0.7	0.00466
22	0.24	0.5	0.5	0.7	0.00466
23	0.17	0.375	0.375	0.55	0.002127
24	0.17	0.375	0.375	0.55	0.002127
25	0.65	0.7875	0.8125	0.925	0.027446
26	0.56	0.725	0.75	0.875	0.01842
27	0.26	0.4375	0.4375	0.6	0.003306
28	0.205	0.4375	0.4375	0.625	0.003225
29	0.135	0.3125	0.3125	0.475	0.001308
30	0.205	0.4375	0.4375	0.625	0.003225
31	0.24	0.5	0.5	0.7	0.00466
32	0.17	0.375	0.375	0.55	0.002127
33	0.17	0.375	0.375	0.55	0.002127
34	0.17	0.375	0.375	0.55	0.002127
35	0.17	0.375	0.375	0.55	0.002127
36	0.1	0.25	0.25	0.4	0.000726
37	0.17	0.375	0.375	0.55	0.002127
38	0.17	0.375	0.375	0.55	0.002127
39	0.205	0.4375	0.4375	0.625	0.003225
40	0.135	0.3125	0.3125	0.475	0.001308
41	0.135	0.3125	0.3125	0.475	0.001308
42	0.135	0.3125	0.3125	0.475	0.001308

Table 4: Data of the basic events (BE) for company F

Indicator (BE)	**a**	**b**	**c**	**d**	**P(Xi)**
1	0.65	0.7875	0.8125	0.925	0.027446
2	0.51	0.6875	0.6875	0.85	0.014081
3	0.51	0.6875	0.6875	0.85	0.014081
4	0.42	0.625	0.625	0.8	0.009755
5	0.51	0.6875	0.6875	0.85	0.014081
6	0.65	0.7875	0.8125	0.925	0.027446
7	0.42	0.625	0.625	0.8	0.009755
8	0.33	0.5625	0.5625	0.75	0.006767
9	0.42	0.625	0.625	0.8	0.009755
10	0.33	0.5625	0.5625	0.75	0.006767
11	0.295	0.5	0.5	0.675	0.004816
12	0.205	0.4375	0.4375	0.625	0.003225
13	0.33	0.5625	0.5625	0.75	0.006767
14	0.17	0.375	0.375	0.55	0.002127

15	0.42	0.625	0.625	0.8	0.009755
16	0.385	0.5625	0.5625	0.725	0.007077
17	0.42	0.625	0.625	0.8	0.009755
18	0.24	0.5	0.5	0.7	0.00466
19	0.24	0.5	0.5	0.7	0.00466
20	0.17	0.375	0.375	0.55	0.002127
21	0.6	0.75	0.75	0.9	0.020569
22	0.385	0.5625	0.5625	0.725	0.007077
23	0.295	0.5	0.5	0.675	0.004816
24	0.33	0.5625	0.5625	0.75	0.006767
25	0.75	0.8625	0.9375	0.975	0.054326
26	0.7	0.825	0.875	0.95	0.037705
27	0.33	0.5625	0.5625	0.75	0.006767
28	0.295	0.5	0.5	0.675	0.004816
29	0.33	0.5625	0.5625	0.75	0.006767
30	0.205	0.4375	0.4375	0.625	0.003225
31	0.295	0.5	0.5	0.675	0.004816
32	0.205	0.4375	0.4375	0.625	0.003225
33	0.205	0.4375	0.4375	0.625	0.003225
34	0.295	0.5	0.5	0.675	0.004816
35	0.33	0.5625	0.5625	0.75	0.006767
36	0.26	0.4375	0.4375	0.6	0.003306
37	0.26	0.4375	0.4375	0.6	0.003306
38	0.33	0.5625	0.5625	0.75	0.006767
39	0.295	0.5	0.5	0.675	0.004816
40	0.33	0.5625	0.5625	0.75	0.006767
41	0.24	0.5	0.5	0.7	0.00466
42	0.205	0.4375	0.4375	0.625	0.003225

Table 5: Data of the basic events (BE) for company G

	Aggregate fuzzy numbers (M)				
Indicator (BE)	**a**	**b**	**c**	**d**	**P(Xi)**
1	0.56	0.725	0.75	0.875	0.01842
2	0.575	0.7	0.75	0.825	0.017822
3	0.51	0.6875	0.6875	0.85	0.014081
4	0.295	0.5	0.5	0.675	0.004816
5	0.51	0.6875	0.6875	0.85	0.014081
6	0.47	0.6625	0.6875	0.825	0.012639
7	0.47	0.6625	0.6875	0.825	0.012639
8	0.56	0.725	0.75	0.875	0.01842
9	0.42	0.625	0.625	0.8	0.009755
10	0.42	0.625	0.625	0.8	0.009755
11	0.56	0.725	0.75	0.875	0.01842
12	0.47	0.6625	0.6875	0.825	0.012639

13	0.56	0.725	0.75	0.875	0.01842
14	0.385	0.5625	0.5625	0.725	0.007077
15	0.65	0.7875	0.8125	0.925	0.027446
16	0.56	0.725	0.75	0.875	0.01842
17	0.385	0.5625	0.5625	0.725	0.007077
18	0.42	0.625	0.625	0.8	0.009755
19	0.33	0.5625	0.5625	0.75	0.006767
20	0.42	0.625	0.625	0.8	0.009755
21	0.7	0.825	0.875	0.95	0.037705
22	0.51	0.6875	0.6875	0.85	0.014081
23	0.38	0.6	0.625	0.775	0.008746
24	0.6	0.75	0.75	0.9	0.020569
25	0.56	0.725	0.75	0.875	0.01842
26	0.47	0.6625	0.6875	0.825	0.012639
27	0.435	0.6	0.625	0.75	0.00921
28	0.42	0.625	0.625	0.8	0.009755
29	0.47	0.6625	0.6875	0.825	0.012639
30	0.56	0.725	0.75	0.875	0.01842
31	0.61	0.7625	0.8125	0.9	0.024507
32	0.61	0.7625	0.8125	0.9	0.024507
33	0.47	0.6625	0.6875	0.825	0.012639
34	0.42	0.625	0.625	0.8	0.009755
35	0.475	0.625	0.625	0.775	0.01033
36	0.51	0.6875	0.6875	0.85	0.014081
37	0.385	0.5625	0.5625	0.725	0.007077
38	0.475	0.625	0.625	0.775	0.01033
39	0.7	0.825	0.875	0.95	0.037705
40	0.6	0.75	0.75	0.9	0.020569
41	0.56	0.725	0.75	0.875	0.01842
42	0.51	0.6875	0.6875	0.85	0.014081

3.4. Defuzzification process

This process converts a fuzzy number to fuzzy possibility score (FPS) which represents the possibility of BE. The defuzzification process that has been used here is the left and right fuzzy ranking method proposed by Chen and Hwang. The left and right utility score of a fuzzy number can be obtained with the help of figure 5 and the following expressions (5) and (6) for the left and right utility score are as follows.

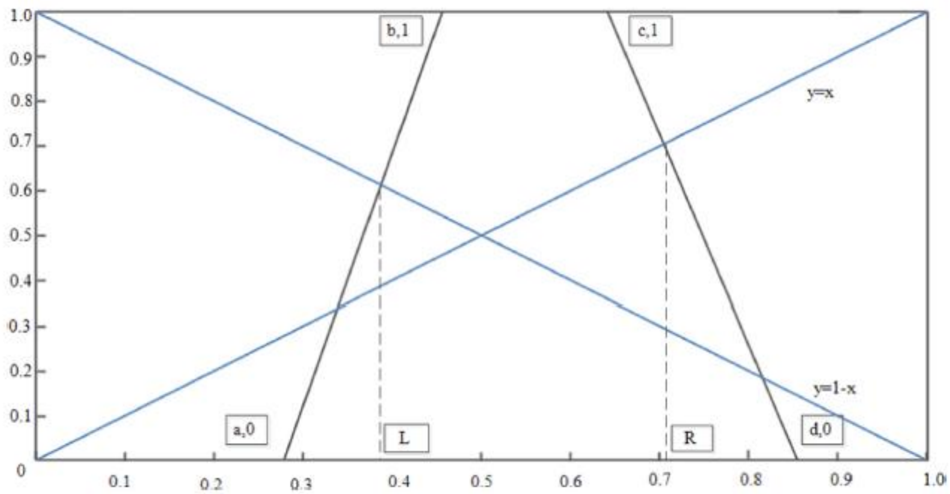

Figure 5: Representation of fuzzy number and its left and right utility score (Adapted from Cheliyan and Bhattacharyya 2018)

$$U_L = \frac{1-a}{1+b-a} \quad (5)$$

$$U_R = \frac{d}{1+d-c} \quad (6)$$

The FPS can be obtained by the following equation 7.

$$FPS = \frac{U_R+(1-U_L)}{2} \quad (7)$$

The defuzzification of the basic events lead to their FPS values

3.5. Converting fuzzy possibility score to fuzzy failure probability

The fuzzy possibility score of all BE needs to be converted to their fuzzy failure probability P(X_i). The fuzzy failure probability is defined as follows:

$$P(X) = \begin{bmatrix} \frac{1}{10^k} & for\ FPS \neq 0 \\ 0 & for\ FPS=0 \end{bmatrix} \quad (8)$$

$$k = 2.301 \left\{\frac{1-FPS}{FPS}\right\}^{\frac{1}{3}} \quad (9)$$

Table 2 to 5 gives the P(X)i values or the probability of basic events for all the four companies.

4.0. Discussion and Conclusions

Once the basic event probabilities are calculated, the relative probabilities are calculated using the FTA approach. Table 6 shows the relative probabilities of all the companies for the subconstructs and table 7 shows the relative probabilities of the constructs for all the companies.

Table 6: Company D, E, F, G relative probability data for sub constructs

Sub-Construct Group #	RSC sub constructs	Company D	Company E	Company F	Company G
1	Conceptual orientation	0.058	0.006	0.016	0.014
2	Constructive sense making	0.03	0.006	0.014	0.014
3	Learned resourcefulness	0.023	0.003	0.006	0.014
4	Counterintuitive agility	0.021	0.003	0.005	0.016
5	Practical habits	0.018	0.002	0.006	0.010
6	Behavioral preparedness	0.014	0.003	0.01	0.020
7	Deep social capital	0.024	0.009	0.019	0.014
8	Broad resource network	0.021	0.003	0.004	0.018
9	Psychological safety	0.007	0.002	0.005	0.010
10	Diffused power and accountability	0.023	0.002	0.005	0.023

Table 7: Company D, E, F, G relative probability data for constructs

Construct Group #	RSC constructs	Company D	Company E	Company F	Company G
1	Psychological capability	0.044	0.006	0.015	0.014
2	Behavioral capability	0.019	0.003	0.007	0.015
3	Managerial capability	0.019	0.004	0.008	0.016
	Total resilience probability (RL)	**1.55e-5**	**7.35e-8**	**8.20 e-7**	**3.36e-6**

Using the FTA approach as shown in earlier studies, we have found the resilience probability of all the four Australian construction companies. Looking at the data, in company D, to find failure mode or the weak resilience areas, it is seen that “Psychological safety” is the weakest subconstruct and thus the failure mode may pass through this subconstruct as seen in Table 6. The weakest construct is “Behavioral capability” and Managerial capability” out of these two the “Managerial capability” will have the failure mode pass through since the “Psychological safety” is subconstruct to “Managerial capability” construct. The total resilience probability for company E is lowest and company D is highest as seen in Table 7. Company E shows that less resilience is available to the whole network and less information is available which goes up the topmost level. In this methodology, it can be predicted what future failures can occur due to weak links associated with the hierarchy of the system. Looking at the results, we can conclude that prediction of failures can happen most in company E as compared to other companies. Subconstruct group 5, 9 and 10 in company E are the most susceptible.

It should be noted that the OR and AND gates are used in this study because it is assumed that the indicators, sub-constructs and constructs all follow the true relationships as defined. There is no cross relationship. This is the limitation and assumption of this study. Further work needs to be done to understand these relationships more using structural equation modelling and other techniques and other gates can be used once this concept is validated.

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