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Reliability Evaluation of Resilient Safety Culture Using Fault Tree Analysis

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Abstract: Safety culture is a collection of the beliefs, perceptions and values that employees share in relation to risks within an organisation. On the other hand, a resilient safety culture (RSC) means a culture with readiness of the organisation to respond effectively under stress, bounce back from shocks and continuously learn from them. RSC helps organisations to protect their interest which can be attributed to behavioural, psychological and managerial capabilities of the organization. Quantification of the degree of resilience in an organisation's safety culture can provide insights about the strong and weak links of the organisation's overall health and safety situation by identifying potential causes of system or sub-system failure. One of the major challenges of quantification of RSC is that the attributes that determine RSC need to be measured through constructs and indicators which are complex and often interrelated. In this paper, we address this challenge by applying a fault tree analysis (FTA) technique which can help analyse complex and interrelated constructs and indicators. The fault tree model of RSC is used to evaluate resilience levels of two organisations with remote and urban locations in order to demonstrate the failure path of the weak links in the RSC model.

Keywords: fault tree analysis, resilient safety culture, safety, reliability, resilience

1. INTRODUCTION

Modelling and analysis of RSC provides opportunity for understanding the mechanism of building a strong safety focus within an organisation so that lessons can be learned, and weaknesses can be addressed to prevent any future health and safety hazard. In an earlier study, the authors developed a RSC model and used it for identifying how remoteness of job location can impact the RSC [10]. In that model, RSC is defined as a function of psychological, behavioural and managerial factors. In the context of RSC, the psychological/cognitive capabilities of an organisation enable it to notice shifts from standard safe operational procedures, interpret unfamiliar situations, analyse options and figure out how to respond. Similarly, behavioural capabilities comprise of established safety behaviours and routines that enable an organisation to learn more about the situation, implement new safety routines and fully use its resources [3]. Managerial/contextual capabilities are a combination of interpersonal connections, resource stocks and supply lines that provide a foundation of quick safety actions [4].

Contribution of these factors within an organisation has been measured separately through combination of qualitative and quantitative methods but have never been used for estimation of RSC as part of a combined model [1, 2]. These three factors, on the other hand, are dynamic and always evolve with time because of updates in the operational procedures, adoption of new technologies, changes in organisational structure etc. This also makes RSC dynamic over time [5]. Thus, often it becomes difficult to capture RSC of an organisation using a deterministic model. To address this issue, this paper develops and applies a probabilistic RSC model using a system fault analysis concept. Fault analysis techniques are generally used in systems safety and reliability assessment in order to provide a probabilistic estimation of the reliability of the system. We adopted this concept for modelling RSC so that a probabilistic estimation of RSC can be made.

There are many methods for system fault analysis including inductive and deductive approaches. In an inductive approach, failure states are examined and analysed. Examples of inductive approaches are Preliminary Hazard Analysis (PHA), Failure Mode Effect and Criticality Analysis (FMECA), Fault Hazard Analysis (FHA), Failure Mode and Effect Analysis (FMEA), and Event Tree Analysis (ETA) [7]. Drawback with inductive approaches is that the number of partial failure states tends to be too large, which makes it hard to determine all the possible causes of failures [8]. By contrast, a deductive analysis shows which failure modes has caused a system to fail [8]. Therefore, this deductive analysis would be better suitable for estimation of RSC as it would allow identifying major factors that are contributing to RSC. Quantitative FTA is a deductive risk analysis technique that effectively detects failures and quantifies probabilities of failure in a complex system [9]. Other advantages of using FTA is that it shows logical relationships between event and causes that lead to failure. It visualizes and helps quickly understand the results and pinpoint weaknesses in design and identify the errors. The FTA priorities issues since the fault paths can be understood and thus the user can choose where the resources need to be allocated. It also can be used for quality tests and maintenance procedures easily.

In this approach, it links a systems failure to all its subsystems and basic events that contribute to failure. Using FTA for the RSC model enables quantifying the overall probability of failure or inversely resilience level in an organization's safety culture but also relative probabilities of individual indicators, sub constructs and constructs.

Further, we first briefly present the RSC model and the FTA method highlighting its key features relevant to our analysis. Second, we present our RSC as a form of FTA model. Third, we applied this model to estimate RSC of two companies. Finally, we discuss implication of this model in increasing safety culture within an organisation.

2. RESILIENT SAFETY CULTURE MODEL

As mentioned before, the RSC model is based on three constructs: 1) Psychological/cognitive capabilities 2) Behavioural capabilities and 3) Managerial/contextual capabilities to anticipate, monitor, respond and learn in order to manage risks in a resilient organization. These three constructs are then divided into various Sub-constructs and indicators. In total there are 42 indicators in the whole RSC model. Details of our RSC model including these indicators and sub-constructs can be found in an earlier paper [6]. Figure 1 is the RSC model proposed in earlier publications [6, 10]. Figure 1 shows the RSC model where the resilience helps the system deflect any uncertainty or hazards which effect the system and thus enhancing the system performance.

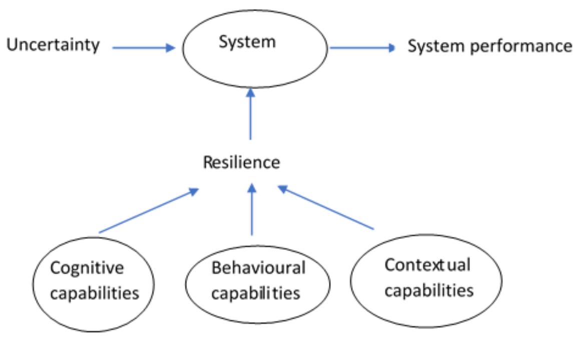

Figure 1: RSC model

Earlier studies proved that the psychological capability should be addressed then behavioural and then managerial for good functioning of the system [6]. In this paper, we use the FTA methodology to find the strengths and weaknesses of the linkages between indicators, sub-constructs and constructs and thus any weaknesses are addressed in the priority defined in earlier studies. Table 1 shows the relationships between constructs and sub-constructs. These sub-constructs further have indicators which shows the bottom most level in this pyramid model.

Table 1: RSC model with constructs and sub-constructs

Construct group#	Constructs	Sub-Construct Group #	Sub-Constructs
1	Psychological capability	1	Conceptual orientation
		2	Constructive sense making
2	Behavioural capability	3	Learned resourcefulness
		4	Counterintuitive agility
		5	Practical habits
3	Managerial capability	6	Behavioural preparedness
		7	Deep social capital
		8	Broad resource network
		9	Psychological safety
		10	Diffused power and accountability

3. FAULT TREE METHODOLOGY

A fault tree is a model that graphically and logically represents the various combinations of possible events, both at fault (i.e. when something goes wrong) and normal situation, occurring in a system that lead to the top event [11]. One distinguishing feature of the FTA is its visualised representation of logic sequences. Every logical operation is represented as a logic gate and connected to express the failure sequence of the system. Example of various gates is shown in figures 2 and 3. The event is denoted using a rectangle that results from the combination of events through the input of a logic gate. The circle denotes a basic fault event. The OR gate denotes that an output happens if one or more of the input event occurs. The OR gate provides a true (failure) output if one or more inputs are true (failures). On the other hand, the AND gate provides a true (failure) output if all the inputs are true (failures) [12].

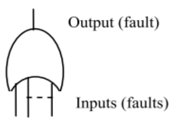

Figure 2: OR gate

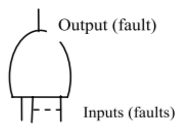

Figure 3: AND gate

The probabilities of occurrence of the OR gate are given by equation 1 and 2 [12], [13].

$$P(E_0) = 1 - \prod_{i=1}^{n}\{1 - P(Ei)\} \qquad (1)$$

Where P (E_0) is the probability of occurrence of the OR gate output event, E_0, n is the number of independent input fault events, and P (E_i) is the probability of occurrence of the input fault event E_i for i=1, 2, 3…n.

The OR gate corresponds to set union and probability of OR gate can also be written as follows:

$$P(A\ or\ B) = P(A \cup B) = P(A) + P(B) - P(A \cap B) \qquad (2)$$

The probabilities of occurrence of the AND gate are given by equation 3 and 4 [12],[13].

$$P(Y_0) = 1 - \prod_{i=1}^{n} P(Yi) \qquad (3)$$

Where P (Y_0) is the probability of occurrence of the AND gate output event, Y_0 and P (Y_i) is the probability of occurrence of the input fault event Y_i for i=1, 2, 3…n.

The AND gate represents a combination of independent events. This is equivalent to intersection of the input event set and probability of AND gate can also be written as follows:

$$P(A\ and\ B) = P(A \cap B) = P(A)P(B) \qquad (4)$$

4. FAULT TREE ANALYSIS OF RSC

As discussed in the previous section, FTA helps determining all possible situations that can result in the occurrence of undesirable event. We make analogy of this concept with RSC 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 which is discussed in section 4.2. Figure 4 shows the proposed fault tree for RSC which includes 3 constructs and 10 sub constructs of our 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 [2]. This is assumed that resilience level can only be achieved if employees can perceive about safety (psychological) and also have behavioural 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 are 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 ‘Behavioural capability’ (which is a construct) within an organisation is possible to achieve even 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. This is the limitation and assumption of this study. Further work need 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.

Behavioural capability construct is used as an example to show the breakdown of FTA in more detail towards the events level. Figure 5 shows illustration of the construct “Behavioural capability” denoted by B0 [15]. After OR gate, B1, B2, B3, B4 are its sub constructs namely “Learned resourcefulness”, “Counterintuitive agility”, “Practical habits”, Behavioural preparedness”. X10 to X24 are the basic events or indicators [6], [10]. 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 organisation.

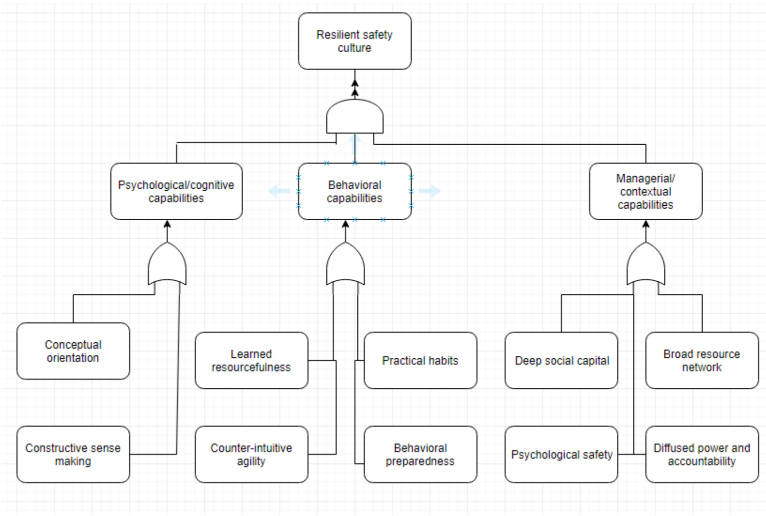

Figure 4: Proposed fault tree for resilient safety culture

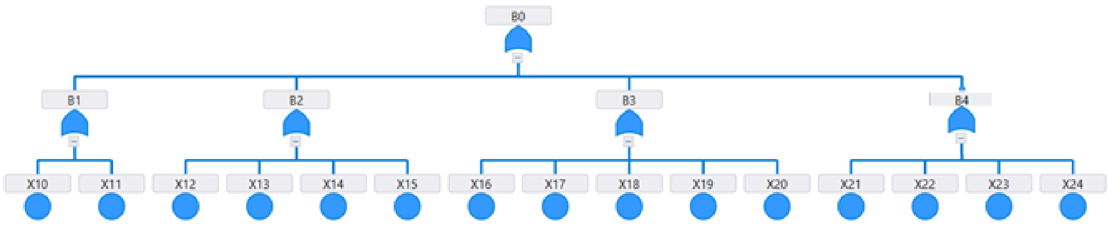

Figure 5: Proposed fault tree for "Behavioural capability" B_0.

Equation 5 shows the construct's probability which is calculated using summation of weighted sub constructs.

$$P = \sum_{i=1}^{n} a_i p_i \qquad (5)$$

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 4. 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 5 and 6 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 6 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 [14]. This is the construct level where no weights are assigned.

$$P_{BO} = a_1p_1 + a_2p_2 + a_3p_3 + a_4p_4 \qquad (6)$$

$$p_1 = a_{10}p_{10} + a_{11}p_{11}$$

$$p_2 = a_{12}p_{12} + a_{13}p_{13} + a_{14}p_{14} + a_{15}p_{15}$$

$$p_3 = a_{16}p_{16} + a_{17}p_{17} + a_{18}p_{18} + a_{19}p_{19} + a_{20}p_{20}$$

$$p_4 = a_{21}p_{21} + a_{22}p_{22} + a_{23}p_{23} + a_{24}p_{24}$$

Finally, using equation 7, 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 5 is used to calculate RSC.

$$P = \prod_{i=1}^{3} p_i \tag{7}$$

4.1. Model application

In order to test the applicability of the FTA model of RSC, a survey was conducted using relevant items listed and discussed in the RSC model [6] and was given to employees working in two organizations X and Y. Both organizations have sites in rural and urban areas which show varying resilience levels in these organizations [10]. This variation thus gives a good case study to show how resilience level can be gauged and what probability of occurrences are for various constructs and sub constructs. This paper proposes a tool through which resilience levels of organizations can be gauged using the RSC survey and FTA methodology and thus help in comparison, resource allocation and weak paths. The importance of FTA is showing the weak paths and thus nodes which have low resilience levels from the indicator to the construct level. Unidirectional approach from indicators to subcontracts to RSC is taken while the resilience information is disseminated. It should be noted that once the weaknesses are visualized and calculated, the RSC model defined in earlier studies prioritizes the resource allocation. A flow chart in further sections will help understand the whole sequence in more detail.

4.2. Survey

. The location of surveyed sites thus helps in the variation in the resilience levels and helps in comparison and resource allocation studies. The surveys were completed by different employees including engineers, supervisors, managers. There was no limitation on who could fill the survey since the goal is to gauge the perception and other indicators of all employees working in these organizations about the safety culture. There were 42 items in the survey. Nine items were for "psychological capability", fifteen items were for "behavioural capability" and eighteen items were for "managerial capability". A total of forty two items were inferred using the various indicators of resilient safety culture model [6]. 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. An example of one of the questions asked in the survey was "Does your organization have a strong sense of purpose, core values and a genuine vision? The higher the Likert scale response better it is for the company since the resilience level is higher in that organization and so forth. For comparison to see the difference in resilience levels between remote and urban sites, data was first analysed using t-test.

4.3. Un-paired T test

Unpaired t test was performed for companies X and Y which provided comparable sample size data for urban and remote sites. The unpaired t test is used if the population means estimated by two independent samples differ significantly. For unpaired t test for company X, the two tailed P value is less than 0.0001 showing extremely statistically significant results. For the unpaired t test of company Y, the two tailed P value equals 0.0023. Similarly, showing this difference is considered to be highly statistically significant. Thus, the companies X and Y data can be used to decipher conclusions based on t test significance [10]. Hence, this data was further used as input for the FTA.

4.4. Analysis of results

The survey generated data which informed about each indicator or items present or absent in the various sites of both organizations. The higher the Likert scale probability the better the resilience level as previously explained in the earlier section 4.2. Tables 2, 3 show relative probability of occurrence for these sub constructs and constructs along with final organizational resilience levels. This resilience level (RL) can be seen by equation 8. It states that this data interprets probability of occurrence at indicators or event levels and this resonates to its resilience capability. So, if probability of failure is calculated for any event or any failure mode at any sub construct or construct level, it can be seen through equation 8.

$$\text{Failure probability (Top event)} = 1- \text{resilience level (RL)} \quad (8)$$

Table 2 shows the company X and company Y resilience levels for urban and remote sites for all the sub constructs. These sub constructs fall under the three main constructs psychological, behavioural and managerial as shown in figure 4. For example, in table 2, probability of resilience for "Conceptual orientation" sub construct is 0.721 for remote sites which means the probability of failure is actually 0.279 for company X in remote site. This probability is purely based on the survey inputs. This can be a limitation for this type of study, the more the data better are the results and interpretation but since we are comparing two companies, it generally gives a good comparison trend.

Table2: Company X and Y remote and urban relative probability data for sub constructs

Sub-Construct Group #	RSC sub constructs	Remote	Urban	Remote	Urban
		Company X		Company Y	
1	Conceptual orientation	0.721	0.813	0.585	0.755
2	Constructive sense making	0.649	0.683	0.604	0.628
3	Learned resourcefulness	0.636	0.767	0.670	0.700
4	Counterintuitive agility	0.482	0.621	0.600	0.590
5	Practical habits	0.489	0.820	0.652	0.592
6	Behavioural preparedness	0.614	0.700	0.610	0.610
7	Deep social capital	0.649	0.804	0.611	0.714
8	Broad resource network	0.604	0.688	0.640	0.665
9	Psychological safety	0.621	0.663	0.595	0.625
10	Diffused power and accountability	0.614	0.742	0.625	0.745

Table 2 shows that "Conceptual orientation" has highest failure probability for remote sites for company Y whereas "Counterintuitive agility" for urban sites "Conceptual orientation" refers to company's sense of purpose, direction, values and vision which motivates employees and helps allocate resources where needed [16].

Table 2 also shows "Counterintuitive agility" in both urban and remote sites as the failure mode for company X. This is because it is having the least resilience level (RL) of all the sub constructs listed and so Company X needs to enhance this sub construct and its corresponding indicators to increase its total resilience levels. "Counterintuitive agility" refers to the ability to follow dramatically different action from what is the norm in the organization. An organization which adopt unexpected and timely responses to environmental changes impacting the organization [2].

It is interesting to note that this study is about understanding the failure modes of safety culture or trying to quantify the reliability of safety culture in organizations even though there is no physical downtimes are in play. Table 3 shows the three constructs resilience levels (RL) compiled together using equation 6 and 7.

Table 3: Company X and Y remote and urban relative probability data for constructs

Construct Group #	RSC constructs	Remote	Urban	Remote	Urban
		Company X		Company Y	
1	Psychological capability	0.685	0.748	0.595	0.692

2	Behavioural capability	0.555	0.727	0.633	0.623
3	Managerial capability	0.622	0.724	0.618	0.687
	Total resilience probability (RL)	**0.237**	**0.393**	**0.232**	**0.296**
	Comparison percentage increase		**65.8**		**27.5**

It shows "Behavioural capability" having higher probability of failure at remote sites for company X. As seen earlier in table 2, "Counterintuitive agility" is a sub construct of "Behavioural capability" thus the failure mode for remote sites. Table 3 shows "Psychological capability" which has higher failure rate in remote sites as compared to "Behavioural capability" in urban sites in company Y.

Figure 6 illustrates the whole methodology giving an example the calculations carried out for the remote site for company X

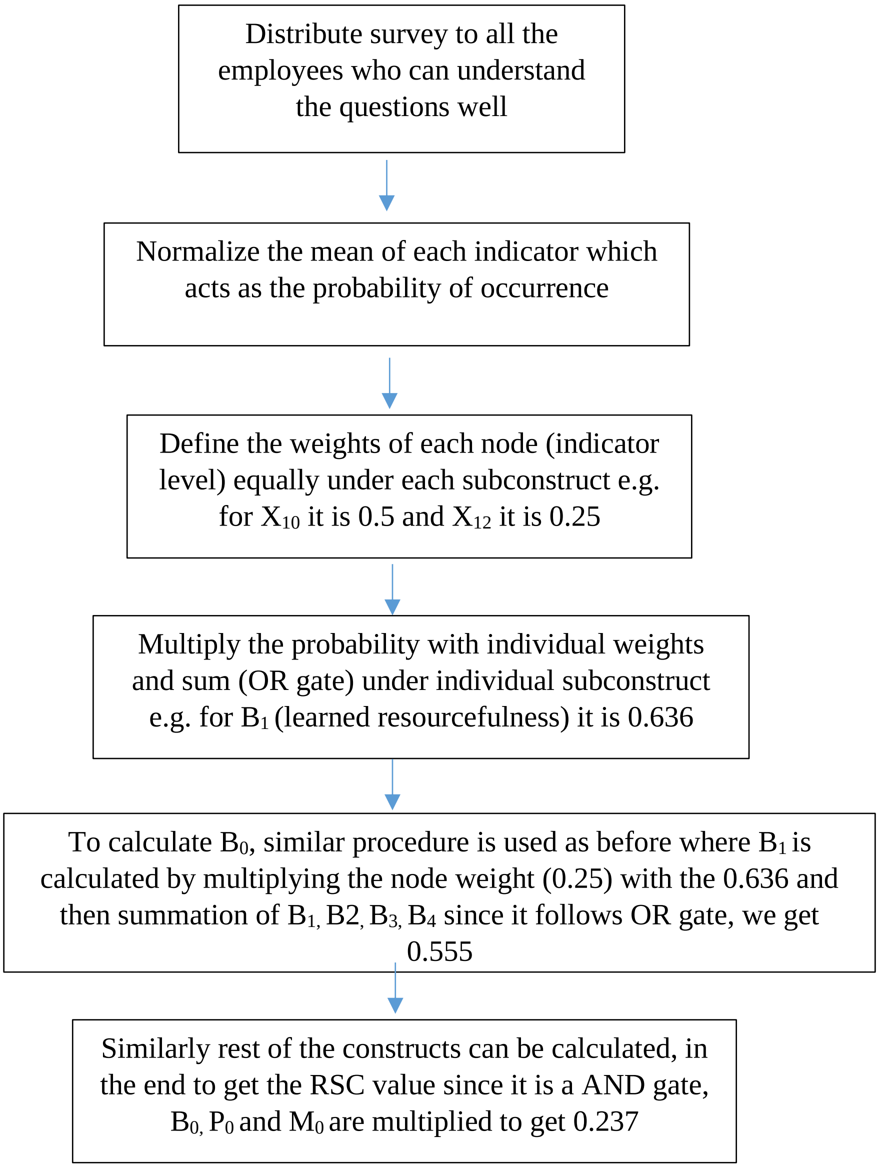

Figure 6: Flowchart showing steps to calculate the relative probability for RSC

5. DISCUSSION AND CONCLUSIONS

FTA detects weak points and unforeseen failure modes which is a strong feature of this methodology. This study thus finds resilience levels for remote sites less then urban sites. As seen in table 3, for company X, 65.8% resilience increase in urban sites as compared to remote sites. For company Y, 27.5% higher resilience levels in urban sites then remote sites.

Company X “Behavioural capability” shows the highest failure probability in remote sites and for company Y it was “Psychological capability” in remote sites. Comparing both companies, we find company Y was less resilient then company X both in remote and urban sites. Failure path for company X was through “Counterintuitive agility” and for the company Y was through “Conceptual orientation” in remotes sites. If using this methodology, it is found that two indicators in two different subconstruct category and two different construct category needs resource allocation, the rule followed is first satiate the psychological capability, then behavioural capability and then managerial capability. If it is just under one construct but two different subconstruct, then priority is given to the lowest subconstruct.

The reliability of this RSC system is the probability that this system operates for a certain period of time without failing. This reliability is the resilience level of the RSC system. It will be of interest to the researchers to find out how much machine down time is responsible for each of the sub constructs of the RSC system. It is seen that the resilience levels are not very high in the remote and urban sites and this study shows which indicators or sub constructs create a failure mode which is responsible for this downtime. Further research need to quantify this downtime with respect to each of the sub constructs or failure modes. On positive note, it can also be concluded that even though the resilience levels were low in both remote and urban sites for both companies, the maximum RL was 0.393, there is lot of scope for improvement and this can impact greatly on the performance of the companies. Good resilient safety culture can enhance the output of the company greatly and thus companies should focus on not just physical machine downtimes but also resilience levels in their safety cultures.

In conclusion, this study shows how RSC can be captured quantitatively through this model and how this model can give pointers where the resources need to be added for enhancing resilience in an organization. It also shows the failure path in weak links of the RSC model. The limitation however is the information collected and used in the model is dependent on the amount of survey questions and number of surveyors.

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