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Risk Quantification and Evaluation Modelling

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ABSTRACT

In this paper authors have discussed risk quantification methods and evaluation of risks and decision parameter to be used for deciding on ranking of the critical items, for prioritization of condition monitoring based risk and reliability centered maintenance (CBRRCM). As time passes any equipment or any product degrades into lower effectiveness and the rate of failure or malfunctioning increases, thereby lowering the reliability. Thus with the passage of time or a number of active tests or periods of work, the reliability of the product or the system, may fall down to a low value known as a threshold value, below which the reliability should not be allowed to dip. Hence, it is necessary to fix up the normal basis for determining the appropriate points in the product life cycle where predictive preventive maintenance may be applied in the programme so that the reliability (the probability of successful functioning) can be enhanced, preferably to its original value, by reducing the failure rate and increasing the mean time between failure. It is very important for defence application where reliability is a prime work. An attempt is made to develop mathematical model for risk assessment and ranking them. Based on likeliness coefficient β_1 and risk coefficient β_2 ranking of the sub-systems can be modelled and used for CBRRCM.

Keywords: Risk coefficient, likeliness coefficient, CBRRCM, condition, monitoring

NOMENCLATURE

β_1	Likelihood coefficient
β_2	Risk coefficient
Nd	Number for decision making
$f(x)_i$	Fuzzy number between 0 and 1
G.M.	Geometric Mean
n	Number of maintenance significant precipitating factor (*i*)
λ_{Ov}	Overall failure rate
Si	Risk scenario
Pi	Probability of occurring of risk element (*i*)
N	Total number of critical units above the Threshold unit
Xi(*u*)	Consequences of risk elements (*u*) which is a function depending on uncertainty (*U*)

1. INTRODUCTION

It is essential to have product specific data (PSD), based on which the product could be maintained so as to have a substantive residual life during the residual product life cycle. Every system has a number of subsystems and each subsystem may have a number of maintenance significant precipitating factors (MSPF), whose in-depth analysis into risk and potentiality of failure may give necessary feedback to the reliability centered maintenance (RCM) logic to determine appropriate preventive maintenance (either periodic or predictive) tasks. There are considerable numbers of systems, where the failures may involve risk or hazard. This is more seen in the case of defence products. In such cases, it is necessary to follow a systematic methodology to identify and prioritize the risks. In the literature, there is no such research paper giving research work in this area of risk quantification. In this paper, a new quantitative method has been suggested to estimate the characteristic criteria of risk.

Fonseca and Knapp[1] in their work and as reported by Basu[2], related to expert system for reliability centered maintenance (RCM), advocated the uses of model, likelihood index (LI) for the equipment or product, being considered , for prioritization of critical failure modes. Criticality Analysis of various units or subsystems, comprising the entire system, as stated earlier is done through failure mode effects and criticality analysis (FMECA) using risk priority number (RPN).

2. A CASE STUDY

The case study is carried out for road mobile launcher (RML) vehicle[3] and the methodology of risk assessment is adopted. Using the RPN values of various units or sub-systems of the total system as shown in Table 1, it is possible to get a guide into the systematic method of analysis of the algorithm.

The authors, in servicing the present system under consideration have tried to know the preference amongst the critical items, for product specific servicing based on the RCM logic. This needs identifying and analyzing, for each Hyper Critical unit or subsystem, the possible maintenance significant precipitating factors (MSPF) and subjects them to a quantitative analysis to obtain likelihood coefficient (LC). Each MSPF may have upper and lower level for malfunctioning, known as

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Table 1. Name of units of system with their RPN values[3]

Sl No.	Name of unit /Subsystem	RPN value	Rank	Remark
1	P.T.O.	72		Since values of RPNs in the table show Extremely asymmetrical probability distribution, the median approach which is a realistic one is used in determining threshold value. Here in this case study, the Threshold RPN number is 96. *classified as Critical items.
2	Pump	90		
3	Pressure line filter	120*	IV	
4	DCV1	168*	I	
5	Tilt cylinder	144*	II	
6	Outrigger cylinder	90		
7	DCV2	144*	III	
8	Pump	96	Threshold	
9	Motor	80		

Upper bound and Lower bound for specific attributes of failure. While, appropriating the critical units, involved in a system, to the RCM logic, it is necessary to decide if the system needs

(i) Predictive preventive based reliability centered maintenance or
(ii) Periodic preventive based reliability centered maintenance and for this purpose, it is essential to evaluate the specific cases through a quantitative decision making equation as given in Eqn. (1)

$$|Nd|_j = (RPN)_j \sum_{i=1}^{n} f(x)_i.(factor\ x_i) \quad (1)$$

For the system considering all critical items the equation is written as Eqn. (2)

$$|Nd|_{System} = \sum_{j=1}^{N} [(RPN)_j \sum_{i=1}^{n} f(x)_i.(factor\ x_i)] \quad (2)$$

where *Nd* is the number for decision making considering all hyper critical units or subsystems A, B, C and D.

j - Number of critical items above the thresholding item, in the FMECA study.

$f(x)_i$ - Being quantified by the fuzzy number between 0 and 1

n - Number of maintenance significant precipitating factor (*i*)

N - Total number of critical units above the threshold unit obtained through statistical analysis of all RPN values in system.

The number evaluated $[Nd]_j$ from the Eqn. (1) is the outcome of approximate reasoning algorithm consisting of fuzzy mathematical formulation, relating to one or more factors, justifiably called maintenance significant precipitating factors (MSPF). With the relative weights as given by RPN values, it may be found out for specific values appearing in the j^{th} failure mode. Let us assume that the precipitating factors denoted by $f(x)$ (i.e. a,b,…etc.) are quantified by the fuzzy number between 0 and 1. Each $f(x)$ mode may have several factors to estimate its failure. Failure of each one of the above items, classified, may depend on some precipitating factors. All identified precipitating factors involved in any failure mode, say i^{th} mode, and are expressed as trapezoidal or triangular fuzzy numbers so that their contribution to the specific failure mode could be quantified as fuzzy numbers between 0 and 1. Based on the 75 percentile into the range of RPN values, we find the critical units as classified in Table 2. Normalized relative worth of the subsystems A, B, C, D and E have been shown in the last column of the Table 2. Table 3 shows the maintenance significant precipitating factors (MSPF). For DCV1, the cost of re-engineering done for bringing the contamination level and proper operation of spool functioning within permissible limit is shown in term of Loss (in rupees) in terms of expenditure. Similarly loss for other critical units in terms of expenditure in rupees is obtained and shown in Table 3. The cost is estimated on the basis of materials involved and the cost of the time taken in investigation measured by man hour spent expressed in rupees.

3. DECISION IN REGARD TO PERIODIC OR PREDICTIVE PREVENTIVE MAINTENANCE

Both periodic and predictive preventive maintenance (PPPM) may be followed depending upon the feasibility to reduce the failure rates of the few identified critical elements or subsystems and thereby increase the mean time between failure (MTBF). This consequently helps us in determining the residual life of the system as a whole. For each of the critical unit or subsystems, there are again various Maintenance significant precipitating factors (MSPF), which are having upper and lower bounds.

Systematic flow diagram shows the specific detailed procedure involved in determining the typical PPPM to be involved at the appropriate level of RCM. Depending upon the ratio of *Nd* (obtained from Eqns. (1) and (2) and the threshold RPN, we can perfectly rank each of the critical sub-systems.

Table 2. Name of units of system with their criticality category

S/n from Table 1	Designated by	Name of unit /Subsystem	Category	RPN Value	Rank	Relative worth
4	A	DCV1	Super critical	168	I	(168/672)=0.25
5	B	Tilt cylinder	Hyper critical	144	II	(144/672)=0.21
7	C	DCV2	Hyper critical	144	III	(144/672)=0.21
3	D	Pressure line filter	Hyper critical	120	IV	(120/672)=0.18
8	E	Pump	Threshold	96	-	(96/672)=0.15
				∑=672		

Table 3. Maintenance significant precipitating factors (MSPF) of the system

Maintenance significant precipitating factor	Observed value at test	Unit	Name of unit	Loss (in Rs) in terms of expenditure
Improper flow of oil due to oil contamination level Oil flow ranges from 100 (lpm) to160 (lpm)	120	A	DCV1	25000
Spool not working due to improper power supply ranges from 18 V to 24 V	20			
Leakage through seals (Improper oil flow) High value 160 (lpm), Low value 100 (lpm)	120	B	Tilt Cylinder	200000
Improper pressure of oil High value 200 (bar) and Low value 100 (bar)	150			
Pressure not properly maintained High value 160 (bar) and Low value 100 (bar)	120	C	DCV2	25000
Filter clogging due to contamination of oil Pressure ranging from 1-3 bar (Pressure drop)	2 bar	D	Pressure line filter	10000

$$\left[\frac{\sum_{j=1}^{n} |Nd|_j}{(RPN)_{Threshold}}\right] = \left[\frac{\sum_{j=1}^{n} |Nd|_{System}}{(RPN)_{Threshold}}\right] = \lambda \tag{3}$$

It may be stated that if $\lambda > 1$, it would be judicious enough to have the total system on a condition monitoring based predictive preventive maintenance in the reliability centered maintenance (RCM) Logic.

Figure 1 shows flow chart for reliability analysis on the basis of MTBF and CBMTBF. λ_{Ov} is the overall failure rate of the system and as such λ_{Ov} is the reciprocal of $(MTBF)_{Overall}$. By CBFTA is meant the fault tree analysis of the system using condition based monitoring.

Now it is also possible to designate the ratio of

$$\left[\frac{|Nd|_j}{|Nd|_{Threshold}}\right] = \beta_1 \tag{4}$$

Figure 2 shows the information flow diagram for using the effect of maintenance significant precipitating factors of a unit in the system, in the RCM logic for determining the type of maintenance.

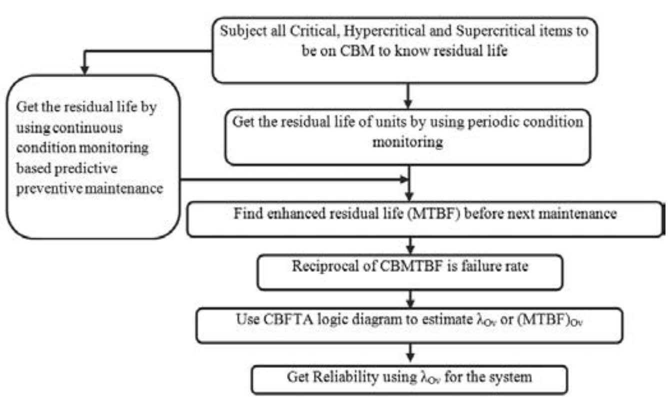

Figure 1. Reliability and condition based predictive preventive maintenance.

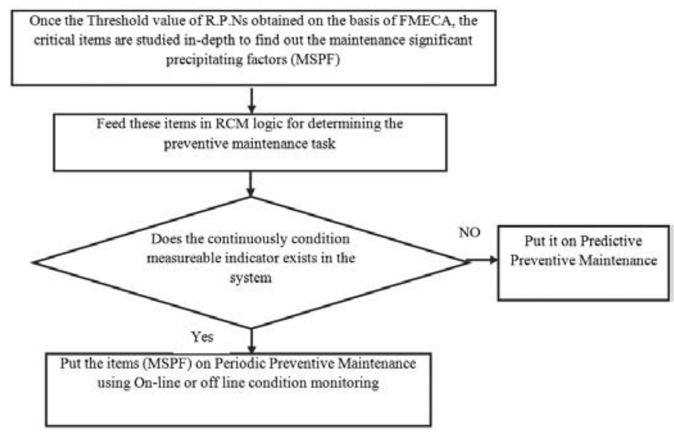

Figure 2. MSPF Items on PM (Periodic or Predictive).

Using fuzzy method for evaluating the precipitating factors in each mode and using the RPN value as weightage for each mode of failure, a quantified decision making equation for likelihood coefficient could be developed to find out if any failure mode, out of the critical modes should be put on condition based continuous monitoring. The author has been trying this as a new methodology while considering the evaluation of the residual life of the equipment.

4. RISK QUANTIFICATION AND CLASSIFICATION

Risk to be denoted by (R) can be described as a set of (i) risk elements. According to Kaplan and Garrich[4] the risk is given by Eqn. (5) .

$$[R] = \{Si, Pi, Xi(u)\} \tag{5}$$

where Si is risk scenario, which is multidimensional; Pi is probability of occurring of risk element (i); and $Xi(u)$ – Consequences of risk elements (u) which is typically a function depending on uncertainty U.

This has also been advocated by Bindel[5], *et al*. According to Shelab[6], *et al.* uncertainty generates risk and is founded on poor or missing information or lack of appropriate database.

Functioning of every critical item in a system depends on some degree of uncertainties and every uncertainty generates risk. Each risk faces a challenge or threat, normally indicated quantitatively by losses. These losses may be classified into main four categories as shown in Fig. 3. These four losses are the prime threats involved, whenever a failure or malfunctioning of any critical system or subsystem occurs.

Selvik and Avent[7] have advocated in their paper the usefulness of using risk and reliability centered maintenance. Risk, as it is seen, is dependent on both (i) event and consequences of the events and (ii) uncertainties involved. Uncertainties involved may result in a drastic change of time schedule and the target objectives, as well as loss of reputation. Such uncertainties, though can't be assessed quantitatively, researchers try to evaluate qualitatively, by giving the scale of high, low, and medium (H, L, and M), respectively, to ascertain (i) The degree of uncertainties (ii) degree of sensitivity (iii) degree of importance and (iv) overall impact.

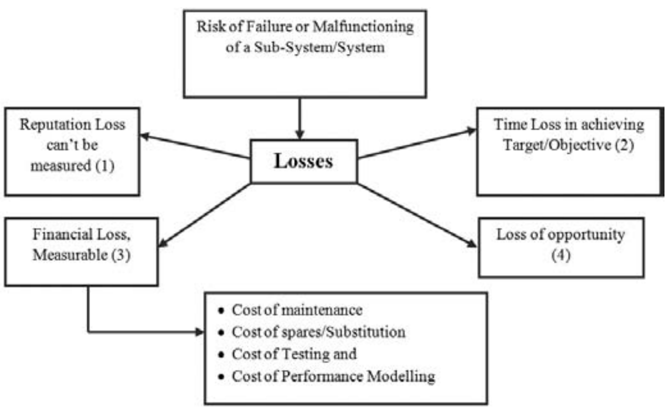

Figure 3. Losses threatened by risk.

5. QUANTITATIVE EVALUATION OF RISK

Usual method for assessing the risk is through potential losses (financial) in terms of expenditure for servicing, repair, maintenance including cost of materials, spare parts, etc for each maintenance significant precipitating factor (i) of a hyper critical item or sub-system J. Total risk involved may be expressed by the relationship:

$$Risk\ of\ J^{th}\ Critical\ Subsystem = |Risk|_J = \sum_{i=1}^{n} \pi_{ij}(W_i)_j \qquad (6)$$

where i, is the attribute of the risk. Here it is the characteristic probability of MSPF, as shown in Table 3. $\pi_{1J}, \pi_{2J}, ...\pi_{iJ}$ are the total monitory losses, while W_{1j}, W_{2j} .. are the precipitating factors i of j^{th} critical subsystem. Since, in most of the cases MSPF of each subsystem vary with upper and lower bound, it may be worthwhile to use the probability based on fuzzification of variation of each parameter between upper and lower bound as between 1 and 0. The Eqn. (6) gives the risk of J^{th} subsystems, but since it may be worthwhile to find out the risk involved in total failure of system considering all the J subsystems, the author prefers to access the same from the overall equation involving risk; by using quantified decision making equation given by Eqn. (7).

$$|Risk|_{System} = \sum_{j=1}^{N} W_j (Risk)_j \qquad (7)$$

where N is the total critical subsystems, principally responsible for the failure of the system.

For each precipitating factor MSPF, the relative worth r_{ij} is dependent on (a) degree of uncertainty (b) degree of sensitivity (c) degree of importance and (d) Overall impact to be assessed by using analytic hierarchy process as shown below.

Matrix I							Matrix II	
Risk Criteria		**a**	**b**	**c**	**d**		**G.M.**	**Worth**
Degree of uncertainty	a	1	4	6	2		2.632	0.491
Degree of sensitivity	b	1/4	1	2	1/4		0.594	0.111
Degree of importance	c	1/6	1/2	1	1/5		0.359	0.067
Overall impact	d	1/2	4	5	1		1.778	0.331

$G.M. = \left(\prod_{i=1}^{n} a_i\right)^{\frac{1}{n}} = \sqrt[n]{a_1.a_2.a_3...a_n}$ where G.M. is Geometric Mean

Multiplying Matrix I by Matrix II , we obtain Matrix No. III as shown hereunder.

$$[\textbf{Matrix III}] = \begin{pmatrix} 1.999 \\ 0.449 \\ 0.269 \\ 1.355 \end{pmatrix}$$

Dividing Matrix III by Matrix II, we get Matrix IV, the values being known as λ.

$$[\textbf{Matrix IV}] = \overset{\lambda}{\begin{pmatrix} 4.071 \\ 4.045 \\ 4.015 \\ 4.093 \end{pmatrix}}$$

From Matrix IV, $\lambda_{avg.}$ = 4.056, N - Number of criteria used, Viz. 4

Consistency index $(C.I.) = \dfrac{\lambda_{avg.} - N}{N-1} = \dfrac{4.056-4}{4-1} = 0.019$

Now the consistency ratio C.R. is given as (C.I.)/(R.I.), where the values of R.I. are to be obtained from the following Table given by Saaty[8], based on N.

CR=0.0019/0.90 = 0.021 which is much less than 0.1, hence the assumptions, based on test and practices, reflected in Matrix I, which evaluates the relative worth of each of the significant criteria for risk are justified.

N	1	2	3	**4**	5	6	7	8
RI	0	0	0.58	**0.90**	1.12	1.24	1.32	1.41

Quantitative equation for risk evaluation, may be modified as

$$|Risk|_J = \sum_{i=1}^{n} \pi_{ij}(W_i)_j = \pi_{aj}.r_{aj} + \pi_{bj}.r_{bj} + \pi_{cj}.r_{cj} + \pi_{dj}.r_{dj} \qquad (8)$$

Now the Eqn. (7) is modified by substituting in it the Eqn. (8), derived above to obtain the new Eqn. (9) including both attributes of risks (a,b,c,d) and the relative worth of every subsystem A,B,C,D as per Table 2.

Total risk of the system is :

$$|Risk|_{System} = \sum_{i=1}^{n} W_i[\pi_{aj}.r_{aj} + \pi_{bj}.r_{bj} + \pi_{cj}.r_{cj} + \pi_{dj}.r_{dj}] \qquad (9)$$

The Eqn. (9) gives the value of risk in terms of monetary loss. In the event of failure, in terms of expenditures involved in repair, maintenance, administrative logistics, etc. It is seen that pump (having serial no. 8) in Table 1 is the thresholding subsystem. In the event of failure of this thresholding unit, the financial expenditure (or monetary loss) for the same may be found out from equation of cost based risk in the form shown below

$$|Risk|_{Threshold} = \pi_{Th} \times W_{Th} \quad (10)$$

where π_{Th} is the expenditure in the event of failure or manufacturing of the thresholding unit

W_{Th} -the relative worth

Risk number for the system $|RN|_{System}$ based on the failure of the critical units above threshold value is given by Eqn. (11)

$$|RN|_{System} = \frac{|Risk|_{System}}{|Risk|_{Thewshold}} \quad (11)$$

$$|RN|_{System} = \frac{\sum_{i=1}^{n} W_i[\pi_{aj}.r_{aj} + \pi_{bj}.r_{bj} + \pi_{cj}.r_{cj} + \pi_{dj}.r_{dj}]}{\pi_{Th} \times W_{Th}}$$

where *i* stands for units A, B, C, D, respectively.

The value of unit A can be obtained as given in Eqn. (12)

$$|RN|_A = \frac{W_A[\pi_{ajA}.r_{ajA} + \pi_{bjA}.r_{bjA} + \pi_{cjA}.r_{cjA} + \pi_{djA}.r_{djA}]}{\pi_{Th} \times W_{Th}} \quad (12)$$

Similarly, for units B, C, D the Risk number can be obtained. This gives an importance Index based on the risk attributes of each sub-unit (A or B or C or D) as given in Eqn. (13).

$$\frac{|Risk|_j}{|Risk|_{Thewshold}} = \beta_2 \quad (13)$$

Using Eqn. (4) and Eqn. (13) we get $(\beta_1 + \beta_2)$ as the decision parameter to be used for deciding on ranking of the critical items, for prioritization of CBRRCM as suggested by Singh[9].

Based on the data obtained from the history of costs involved in repairing the units A, B, C, D failing, and costs involved in the various types of attributes of risk for each one of the units, Viz. a, b, c, and d as shown, while analyzing through AHP (See matrix I), the detailed data are presented in Table 4.

Sample calculations based on data in Table 4 and Table 2 are given as:

$$|Risk|_A = 20000 \times 0.491 + 10000 \times 0.111 + 15000 \times 0.067 + 20000 \times 0.331 = 18555$$

$$|Risk|_B = 50000 \times 0.491 + 25000 \times 0.111 + 25000 \times 0.067 + 150000 \times 0.331 = 78650$$

$$|Risk|_C = 20000 \times 0.491 + 10000 \times 0.111 + 15000 \times 0.067 + 20000 \times 0.331 = 18555$$

$$|Risk|_D = 5000 \times 0.491 + 2000 \times 0.111 + 5000 \times 0.067 + 5000 \times 0.331 = 4667$$

Table 4. Relative Worth's and cost data based on risk criteria

Unit	Sub-system	Critical rank	Relative worth	Financial loss due to risk factor (Rs)	
A	DCV-1	I	0.25	a	20000/-
				b	10000/-
				c	15000/-
				d	20000/-
B	Tilt Cylinder	II	0.21	a	50000/-
				b	25000/-
				c	25000/-
				d	150000/-
C	DCV-2	III	0.21	a	20000/-
				b	10000/-
				c	15000/-
				d	20000/-
D	Pressure Line Filter	IV	0.18	a	5000/-
				b	2000/-
				c	5000/-
				d	5000/-
E	Pump	Threshold	0.15	a	5000/-
				b	2000/-
				c	5000/-
				d	5000/-

$$|Risk|_{Threshold} = 5000 \times 0.491 + 2000 \times 0.111 + 15000 \times 0.067 + 20000 \times 0.331 = 10302$$

Using Eqn. (9), we can obtain $|Risk|_{System}$ as

$$|Risk|_{System} = 0.25 \times 18555 + 0.21 \times 78650 + 0.21 \times 18555 + 0.18 \times 4667 = 25891.86$$

Using Table 3, the functions are plotted for DCV-1, tilt cylinder, DCV-2 and pressure line filter as shown in Figs. 4-7 respectively. The maintenance significant precipitating factors (MSPF) are considered and specified limiting range is used to represent X-axis. The function line graph is drawn as straight line with minimum to maximum values of control parameters with function value 0 to 1. The observed value during tests is represented with marking which represents functional value as in Fig. 4 which is $f(x_{A1}) = 0.33$. This value is obtained by formulation as:

$$Function\,Value = \frac{Observed\ Value - Min.\ Limiting\ Value}{Maximum\ \ Value - Min.\ Limiting\ Value} = \frac{120-100}{160-100} = 0.33$$

This value is to be controlled for the MSPF hence it should be less than observed test function value. On similar basis all other function values are obtained and are represented in Figs. 4-7.

The *j* values of $\left|Nd_j\right|$ are obtained using Eqn. (1)

$$|Nd|_A = (RPN)_A[(f_{xA})_1 + (f_{xA})_2 = 168(0.33 + 0.33) = 110.88$$

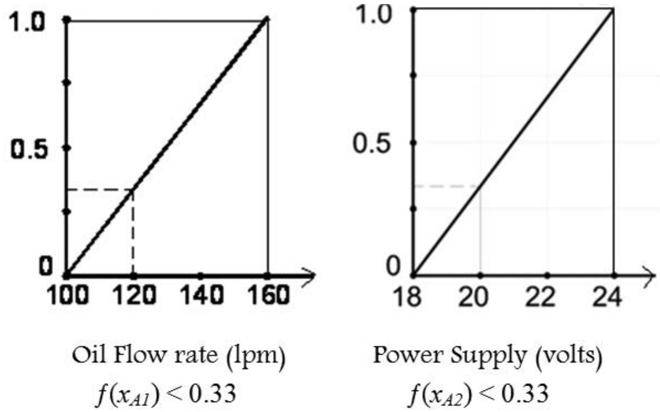

Figure 4. Factor X_A (DCV-1).

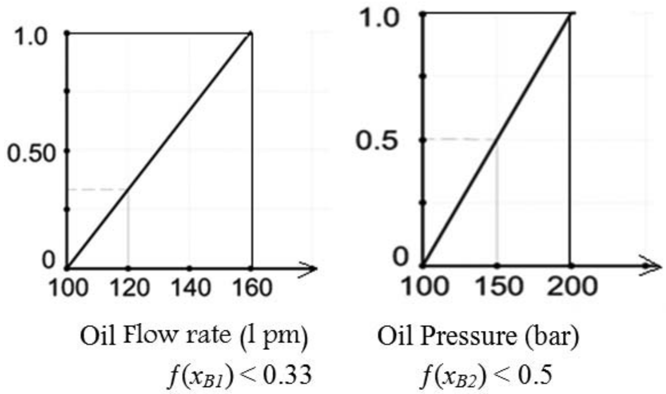

Figure 5. Factor X_B (tilt cylinder).

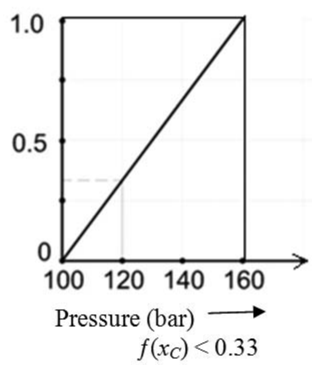

Figure 6. Factor X_C (DCV-2).

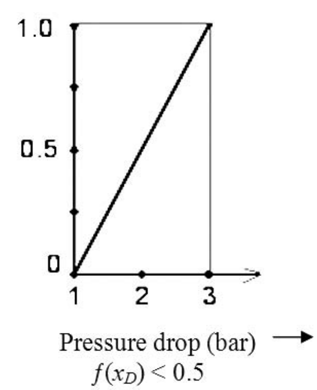

Figure 7. Factor X_D (filter clogging).

$$|Nd|_B = (RPN)_B[(f_{xB})_1 + (f_{xB})_2 = 144(0.33 + 0.5) = 118.58$$

$$|Nd|_C = (RPN)_C[(f_{xC})_1] = 144(0.33) = 47.52$$

$$|Nd|_D = (RPN)_D[(f_{xD})_1] = 120(0.5) = 60$$

$$|Nd|_{Threshold} = (RPN)_{Threshold}[(f_{xThreshold})_1] = 96(1) = 96$$

Using Eqn. (2) $|Nd|_{System}$ is obtained as

$$|Nd|_{System} = 110.88 + 118.58 + 47.52 + 60 = 336.98$$

The value of ratio $\lambda = \left[\frac{|Nd|_{System}}{(RPN)_{Threshold}}\right] = \frac{336.98}{96} = 3.510$

The values of β_1 for factors A, B, C, and D are obtained using Eqn. (4) as follows:

$$\beta_{A1} = \left[\frac{|Nd|_{A1}}{|Nd|_{Threshold}}\right] = \frac{110.88}{96} = 1.155$$

$$\beta_{B1} = \left[\frac{|Nd|_{B1}}{|Nd|_{Threshold}}\right] = \frac{118.58}{96} = 1.234$$

$$\beta_{C1} = \left[\frac{|Nd|_{C1}}{|Nd|_{Threshold}}\right] = \frac{47.52}{96} = 0.495$$

$$\beta_{D1} = \left[\frac{|Nd|_{D1}}{|Nd|_{Threshold}}\right] = \frac{60}{96} = 0.625$$

By using the Eqn. (11) risk numbers (*RN*) can be obtained as

$$|RN|_{System} = \frac{|Risk|_{System}}{|Risk|_{Thewshold}} = \frac{25891.86}{10302} = 2.513$$

Similarly we can find out the $|RN|$ number for each of the critical units by using the following equation

$$|RN|_A = \frac{|Risk|_A}{|Risk|_{Thewshold}} = \frac{18555}{10302} = 1.801$$

$$|RN|_B = \frac{|Risk|_B}{|Risk|_{Thewshold}} = \frac{78650}{10302} = 7.634$$

$$|RN|_C = \frac{|Risk|_C}{|Risk|_{Thewshold}} = \frac{18555}{10302} = 1.801$$

$$|RN|_D = \frac{|Risk|_D}{|Risk|_{Thewshold}} = \frac{4667}{10302} = 0.4530$$

Table 5 gives the Relative Worth's of the factors on the basis of combined effect of β_1 and β_2.

6. RESULT AND DISCUSSIONS

Reliability and risk centered analysis is done giving the details of quantitative equation developed for risk assessment. Steps are discussed to systematically evaluate the extent of risk involved by using a quantitative decision making equation.

Table 5. Relative Worth's of the factors on the basis of combined effect of β_1 and β_2

Critical sub-systems	β_1	β_2	$(\beta_1+\beta_2)$	Relative worth on the basis of $(\beta_1+\beta_2)$	Ranking on the basis of $(\beta_1+\beta_2)$
A	1.155	1.801	2.956	0.1944	II
B	1.234	7.634	8.868	0.5834	I
C	0.495	1.801	2.296	0.1510	III
D	0.625	0.453	1.078	0.0709	IV
			$\sum$=15.198		

By using the quantitative decision making equation developed, it is possible to prioritize the risk-based components in the system and rank them accordingly. Such a system of CMRRCM gives a glimpse into newer horizons of maintenance activity, hitherto far from practices in Indian Industries. But such a method, if used, will lead to improved reliability based design of the system with reduced failure rate and hence increased MTBF and hence residual life of the design.

Based on factors β_1 and β_2, suggested by the author, ranking of the sub-systems can be modeled and used for CMRRCM. Based on this, it may be possible for obtaining a quantifiable justification to consider the system (or some of the critical units of the system) on the basis of CMRRCM.

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