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Reliability Centered Maintenance Actions Prioritization Using Fuzzy Inference Systems

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Abstract— **Reliability centered maintenance (RCM) is a systematic maintenance philosophy/approach used to analyze system's performance in terms of the impact of a potential failure and select the most efficient maintenance tasks along with their timings in order to mitigate failures risks. In this paper, a comprehensive RCM actions prioritization method is proposed using four criteria: severity, benefit to cost ratio, customer satisfaction, and easiness of action implementation. The method utilizes fuzzy inference system (FIS) to incorporate subject matter experts feedback into the decision making process. The output of the FIS, which takes the form of a numerical weight that assesses the relative importance of each criterion, is then fed into a binary integer program (BIP) that selects the optimal maintenance actions out of a set of possible actions. A real life example of a hydraulic brake system is also provided to illustrate the proposed methodology.**

Keywords—reliability centered maintenance; action prioritization; optimization

I. Introduction

Reliability Centered Maintenance is a systematic maintenance program used to select the most efficient maintenance tasks and schedule to prevent a failure, or minimize the consequences of failures when occurs. Moubray [1] defined RCM as a methodology to determine what must be done to ensure that the asset is running and fullfiling its intended function. RCM programs are based on the traditional failure modes and effects analysis (FMEA) where the focus is on the ability of the system to deliver its primary functions. However, the focus of RCM is added value of maintenance scheme and activities rather than the hardware or design of the system. Although RCM had its origin in the commercial airline industry in the 1960's [1], it has been used in steel industries [2], railroad industry [3], power distribution [4], wind turbines [5], construction [6] among other industries. Rausand [7] presented a structured approach to RCM using twelve steps with a detailed explanation to each step.

Figure 1 depicts a graphical summary of the RCM methodology. The steps comprising the methodology are typically followed during a workshop where a cross functional team including maintenance crew representatives are the main participants. In the case of regional or global product distribution, multiple workshops might be needed in order to have specific RCM implementation plan to different regions. The team starts by defining the main functions of the system and potential failure modes. Next, potential causes of failures are listed, prioritized based on occurrence rate, and managed based on consequences of failures. An important step in RCM is the determination of whether a failure can be prevented or predicted and weather an investment should be done for either way. Based on the distinction of weather the failure mode can be predicted or prevented and consequences of such failure, a set of RCM actions are determined which shape out the new maintenance schemes.

Once actions are determined, an action implementation plan is needed which includes the following: prioritization of actions, determination of maintenance events and intervals, communication plan determination, and order of any special tools required by new actions.

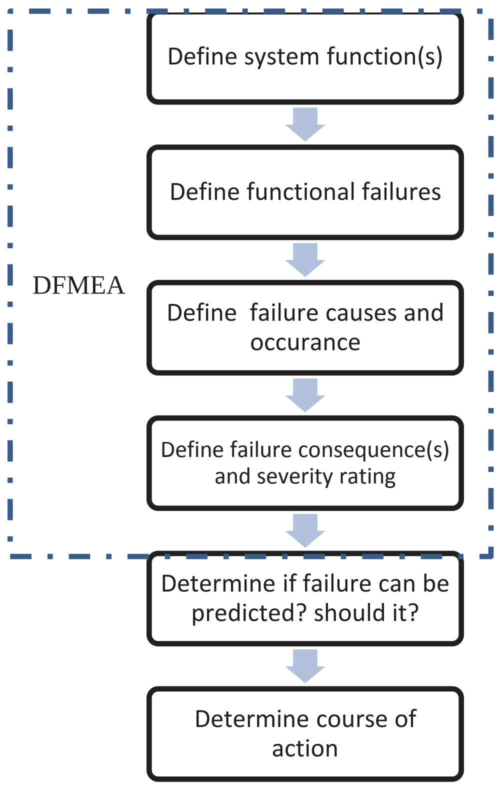

Figure 1. RCM methodology

Successful RCM implementation results in higher system availability and utilization, lower capital and recurring costs, and improved customer satisfaction. However, it is estimated that more than 60% of RCM programs initiated failed in the implementation stage due to multiple reasons [1]. Among these reasons are: assessment failures, poor communication, and failure to implement RCM actions. Selvik et al., [8] proposed an extension of the RCM where risk is considered as the reference of the analysis in addition to reliability and called it reliability and risk centered maintenance (RRCM).

Like any other intervention, over maintenance could lead to system failure which is counter intuitive to the purpose of maintenance. A great example of such situation is pinched wire resulting from electronic connections such as connectors and terminals. Mobley [9] indicated that one third of all maintenance cost is wasted as a result of unnecessary or improper maintenance activities. According to [6], up to 50% of unplanned downtime occurs in systems that were "serviced" within the previous seven days based on research done by Palo Alto electric power research institute and the U.S. Navy. A similar pattern is also present in oil and gas exploration assets. Despite implementation failures, RCM is proven to eliminate or reduce over maintenance and unnecessary maintenance activities.

In order to achieve RCM objectives, it is necessary to develop a maintenance plan that includes different schemes of maintenance tasks according to the criticality of each component in the system [10]. A good RCM implementation could lead to the following maintenance schemes:

1. Corrective maintenance (CM): maintenance or repair is performed once a failure occurs and it is typically used when consequences of failure are not costly or time consuming. Systems with redundancy, i.e. if subsystem one fails then switches to subsystem two and fix system one, are good candidates for CM scheme.
2. Preventive maintenance (PM): maintenance is carried out before any failure occurs based on a fixed schedule. Parts replaced may still have some remaining life which can be utilized to reduce cost. Moreover, PM activities may introduce unintentional failures referred to as maintenance induced failures with failure rates depending on how invasive these activities are and experience of maintenance personnel. Examples of PM activities are replacement of oil and filter of an engine or transmission after certain mileage.
3. Condition based maintenance (CBM): instead of replacing parts based upon a certain schedule, systems are inspected at predetermined events and a decision is made weather to replace faulty or near faulty parts or not. The frequency of inspection events may be driven by time (hours, days…), or usage (miles, cycles, jobs …), or both. In general, CBM is invasive; inspection tools are used to check the system condition such as volt meters and current measurements meters. Using such invasive tools may introduce additional idle time and maintenance induced failures. The data collected during CBM can be used to build trend charts with indicators of system degradation or wear out.
4. Prognostics health management (PHM) based maintenance: this is the most effective scheme of conducting maintenance where certain parameters are continuously monitored by the system itself and error messages are flagged in the case of near failures. A great example of PHM is the "check engine light" message in automotive when an emission related failure is about to happen. A more efficient way of utilizing these parameters is to predict the remaining life of the system, i.e. prognostics. Such systems require good infrastructure to enable data collections, communication, and processing.

Both CBM and PHM schemes have the advantage of lowering maintenance interference with assets which results in lower maintenance induced failures. It is not uncommon for a technician to pinch a wire, under torque, cross thread, miss an O-ring, and the list goes on and on during a regular preventive maintenance. As a result, the less time a technician spends during PM, the lower the chance to cause a failure. In a recent empirical study conducted on an electro-mechanical system used in oil industry, almost 20% of failures are due to human mistakes such as maintenance induced failures during PM and not following a procedure. Al-Najjar and Alsyouf [11] provided a list of factors that affect the quality of surveillance and maintenance activities.

II. PROBLEM STATEMENT

The final outcome of RCM is typically translated into actions aimed at failure impact (severity) reduction or failure frequency (occurrence) reduction or reduction in time to repair, and customer satisfaction improvement. Actions used in RCM analysis vary in terms of effect, financial implications, and effort. Hence it should be focused on either reducing the occurrence rate (likelihood of failure) or effect of failure (consequences).

In general, RCM actions can be classified based on failure management into four groups: maintenance, redesign, procedural, and training. Maintenance actions refer to rescheduling of some PM steps to make it either less or more frequent or eliminate it completely. Redesign is related to hardware such as adding a feature to enable access or change type of screws or seals to make design more robust and less sensitive to variations or environmental effects. In some cases, the system usage evolves to a stage beyond the system design capabilities and requires either re-design or decommissioning to keep up with demand. In some cases, maintenance procedures need to be updated due to design changes or to clarify some steps. Finally training modules could be established or updated based on technicians' ability to adhere to maintenance procedures. The four main RCM actions groups can be further broken down into subcategories as shown in

TABLE 1:

TABLE 1 RCM ACTIONS SUBCATEGORIES

ID	**Action Subcategory**	**Example**
A	Add a PM test/step	Cleaning of a groove, lubricate a thread
B	Develop CBM check	Check oil viscosity
C	Use continouse monitoring	1. Develop an automated self-diagnostic routine 2. Monitor temp./ humidity of an electronic board real time
D	Clairfy procedure in SWI	Toque specification
E	Re-design	Re-design groove, threads, or add a feature to grip a component

ID	**Action Subcategory**	**Example**
F	Upgrade component	Use of stainless steel bolts, high temp. seal
G	Corrective maintenance (CM)	Failure of a protective fuse due to abnormal voltage spike
H	Deploy/improve training	
I	Develop new SFT	O-ring installation, adjustment tool, Spring collapsing tool
K	Re-schedule PM interval	
L	Re-package spare parts	Use seal kits or fastener kits instead of individual
M	Delete PM step	Delete unnecessary wires wiggling test
N	Add redundancy	Use back up part/system
O	Increase spare part holding	Increase inventory lot size

Depending on the type of industry and complexity of system studied, the management of RCM actions can be challenging. The authors were exposed to several RCM activities in oil and gas industry where the number of actions generated ranges from 20 to 110. Such large number of actions imposes the challenge and need for action prioritization and execution management. Figure **2** shows an example of RCM actions breakdown by type for a simple hydraulic circuit used to deploy a mechanism in oil and gas tool. There are 45 actions varying in cost, benefit, and effort to implement.

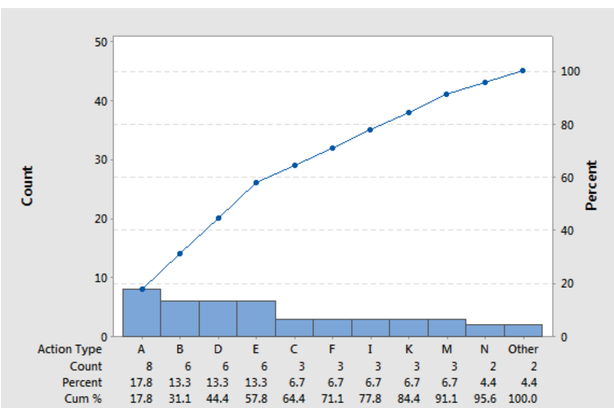

Figure 2. Example of RCM actions by type

The purpose of this article is to propose a method to prioritize these actions and select the most important subset of actions while meeting time and budget constraints. Many researchers discussed the problem of maintenance strategy selection for different machines in manufacturing firms [11] [12] or a mix of these strategies [13], but very little research, if any, discuss the RCM action prioritization problem. Moreover, the surveyed literature used multi-criteria decision making (MCDM) such as AHP which requires multiple pairwise comparisons among criteria and among maintenance strategies. These comparisons are typically time consuming and subjective in nature.

III. DECISION CRITERIA

A. Literature Review

One important subproblem of action prioritization is the definition of the prioritization criteria. Although there is little research on RCM actions prioritization if any, there is an extensive research done on similar problems such as reliability allocation. In reliability allocation, a reliability target is allocated to the *ith* subsystem such that the overall system reliability goal is achieved. Several approaches were proposed with different criteria. One of the earliest reliability allocation methods is based on a weighting factor w_i shown below in equation 1 [14]:

$$w_i = \frac{A_{i1}(A_{i2} + A_{i3} + A_{i4})}{\sum_{i=1}^{k}[A_{i1}(A_{i2} + A_{i3} + A_{i4})]} \quad (1)$$

Where

A_{i1} = state of present engineering progress
A_{i2} = subsystem complexity = f (no. of components)
A_{i3} = operating time factor
A_{i4} = externally applied effective stress

A modification of the above model in equation 1 called the feasibility of objectives (FOO) were included in the Mil-Hdbk-338B also considered similar factors and utilizes reliability experts assessment based on a 10-point numerical scale [15].

Wang et al., [16] proposed a method based on seven factors: frequency of failure, criticality of failure, maintainability, complexity, manufacturing technology, working conditions and cost. Their method utilizes the following weight factor:

$$w_i = \frac{\sum_{j=1}^{7} a_j A_{ij}}{\sum_{i=1}^{k}\sum_{j=1}^{7} a_j A_{ij}} \quad (2)$$

Where

a_j = the relative importance weight of factor *j*
A_{ij} = quantitative or qualitative rating of factor *j* for system *i*

B. Benefits gained from RCM

There are several ways to estimate benefits gained from RCM implementation, the authors suggest using the following categories:

- Reduction of severity: severity is typically assessed using a 10-point ordinal scale where 10 is used for failures with safety or failure to meet governmental regulations impact without warnings, and 1 for nuisance impact [17]. Using this ordinal scale for measuring benefits and subsequently actions prioritization is not reasonable because of the assumption that equal difference between scales has the same impact regardless of the location of the scale. For example, an action that will reduce the severity scale from 10 to 9 (safety effect without warning to safety effect with warning) is similar to an action that will reduce severity from 2 to 1 (low effect to very low effect) [18]. To avoid this shortcoming, Kim et al. [19] proposed transferring the linear severity to an exponential severity to distinguish impact of improvement efforts on reducing failure effect, see equation 3:

$$\widehat{S_{ij}} = \exp(\propto S_{ij}) \quad (3)$$

Where

$\widehat{S_{ij}}$ = transfered severity of failure mode j in subsystem i

$\propto$ = exponential parameter (typically 0.8)

S_{ij} = maximum severity effect of all failure causes

- Financial benefits: each of the RCM actions will incur a cost and provide financial benefits resulting from either failure prevention/reduction or a reduction in maintenance/repair time and cost. The following equation will be used tFigure **3**o quantify the financial benefits gained from i^{th} action implementation per tool per year:

$$B_i = c_i \Delta \lambda_j + c_l \Delta MTTR_j + c_l \Delta MTTM_j - C_{inv} \quad (4)$$

Where:

c_i = the cost of failure including down time, labor and material

$\Delta \lambda_j$ = failure rate reduction due to action j

c_l = labor cost

$\Delta MTTR_j$ = mean time to repair reduction

$\Delta MTTM_j$ = mean time to maintain reduction

C_{inv} = the annual investment cost per year per tool

It is important to point out that some actions may impact *MTTR* only such as design actions that improve time to diagnose, or accessibility of components. For example, development of a new special fixturing tool (SFT), or placing all seals and O-rings in a nice kit by PM service event will definitely reduce repair and maintenance time. Similarly, some actions may impact *MTTM* only such as increasing preventive maintenance interval. Failure rate λ, *MTTR* and *MTTM* are key variables in terms of determination of systems availability (A):

$$A = \frac{MTBF}{MTBF + MTTR + MTTM} \quad (5)$$

Where

$$MTBF = \frac{1}{\lambda} \quad (6)$$

Where $MTBF$ is mean time between failures

- Increased customer satisfaction: according to Kano model [20], customer needs can be classified as basic, performance, and customer delights. Meeting basic needs such as having a functional system will not increase customer satisfaction, however not meeting these basic needs will increase customer dissatisfaction. The higher the performance features of the system, the higher customer satisfaction is. Finally the presence of features that goes beyond customer needs (surprise and delight) will increase customer satisfaction substantially. As a result, customer satisfaction improvement credit will be considered only if performance or delights needs are improved. Fixing a maintenance induced failure will help in meeting a basic need, hence it will not change customer satisfaction. Based on authors experience and other subject matter experts (SMEs) feedback, customer satisfaction is strongly impacted by the usability of the system. For instance, the automation of several manual steps or having a self-diagnostic routine will boost the customer satisfaction even though such actions may have a limited impact on failure rate.

In addition to the categorization of the benefits gained by RCM implementation mentioned above, the effort needed for implementing the actions has to be considered as well. Some actions require very little effort such as checking oil level during PM maintenance, while other actions require great amount of effort such as adding an oil quality sensor which require a major redesign of the existing system.

IV. PROPOSED METHODOLOGY

The proposed methodology for RCM actions prioritization consists of the following four phases:

1. Ranking of the importance of each criterion: each SME will assess each criterion individually using a 1-10 point scale which will be transformed into a fuzzy linguistic terms such as (low, medium, high) scale as shown in Figure 5. Next all SME's assessments will be aggregated into one single linguistic term using a rule-based fuzzy inference system (FIS). Finally the aggregate term will be defuzzified by mapping it to a numeric weight using a membership function such as the one shown in Figure 3.
2. Actions assessment: in this phase a mixture of deterministic assessment using crisp data and fuzzy linguistic variables will be used to assess all RCM actions. The fuzzy linguistics will then be defuzzified to obtain a crisp value using the centroid method.
3. Develop a binary linear model for actions selection where an objective function of selected criteria is maximized with budget and time constrains consideration.
4. A sensitivity analysis is conducted to address any importance changes scenarios.

Considering all benefits mentioned in the decision criteria section along with the implementation effort, the problem of action selection and prioritization can be formulated as a binary integer program (BIP). In this model, a binary integer variable x_i is defined such that:

$$x_i = \begin{cases} 1 & if\ maintenance\ action\ i\ is\ selected \\ 0 & otherwise \end{cases}$$

Actions are selected by solving the following BIP model:

$$Max \quad Z = w_{SEV} \sum_{i=1}^{n} \widehat{SEV}_i . x_i + w_{BCR} \sum_{i=1}^{n} BCR_i . x_i + w_{SAT} \sum_{i=1}^{n} SAT_i . x_i + w_{EF} \sum_{i=1}^{n} EF_i . x_i$$

$$s.t. \quad \sum_{i=1}^{n} C_i x_i \le B$$

$$\sum_{i=1}^{n} t_i x_i \leq T$$

$$x_i \in \{0,1\} \qquad \forall i \tag{7}$$

Where SEV_i is the normalized transformed severity for action i, w_{SEV} is the weight of transformed severity, BCR_i is the normalized benefit-to-cost ratio for action i, w_{BCR} is weight of BCR, SAT_i is customer satisfaction gained from action i implementation, w_{SAT} is satisfaction weight, EF_i is the effort needed for action i implementation, and w_{EF} is weight for effort EF.

The BIP model seeks to maximize severity, benefit-to-cost ratio and customer satisfaction while minimizing the effort needed subject to budget and time constraints. The first functional constraint stipulates that the sum of the costs associated with implementing each action C_i has to be less than or equal to the dedicated budget B. The second constraint incorporates the total development time for these selected actions t_i which is limited to the allocated time window T.

The weight associated with each criterion is an indication of the importance of that criterion to the decision maker with respect to other criteria. This weight can change according to organization objectives setting which is heavily impacted by external environment and competition. Weight assessment is better achieved using a 1-10 scale point and a FIS where SMEs inputs are mapped to a weight output using fuzzy logic [21]. The following section provides more details on criterion weight selection using fuzzy logic theory.

V. FUZZY LOGIC

Fuzzy logic is a method where vague expressions and subjective relationships are translated into a mathematical function. It is not uncommon for a SME to express his/her view using fuzzy verbatim such as “not exactly, it is much more than that” or “it has a slight impact”. This view can be expressed mathematically using a membership function; a function that defines the extent to which each point in the input space belongs to a specific set based on a scale that extends between 0 and 1. Some of the most commonly used membership functions are triangular and trapezoidal functions [21]. Given three values a, b and m for the input variable x where $< m < b$, the triangular membership function can be defined as:

$$f(x) = \begin{cases} 0 & x \leq a \;\; or \;\; x \geq b \\ \dfrac{x-a}{m-a} & a < x \leq m \\ \dfrac{b-x}{b-m} & m < x \leq b \end{cases} \tag{8}$$

Similarly, given that $a < b < c < d$, a trapezoidal function can be described as:

$$f(x) = \begin{cases} 0 & x \leq a \;and\; x \geq d \\ \dfrac{x-a}{b-a} & a < x \leq b \\ 1 & b \leq x \leq c \\ \dfrac{d-x}{d-c} & c < x \leq d \end{cases} \tag{9}$$

The severity and financial benefits of maintenance actions can be assessed with high level of certainty based on the understanding of failure consequences, and historical records. However, the rating of actions with respect to customer satisfaction and implementation effort is highly subjective and is better assessed using feedback from SME through the selection of 7-point linguistic scale. Severity and BCR can be assessed numerically based on historical data and understanding of failure effect, however customer satisfaction and implementation effort will be judged based on experience and expectations of SMEs. Figure 3 depicts action rating fuzzy linguistic variable used for customer satisfaction. For implementation effort, a similar function with opposite scale is used since the lower the effort the higher the value should be.

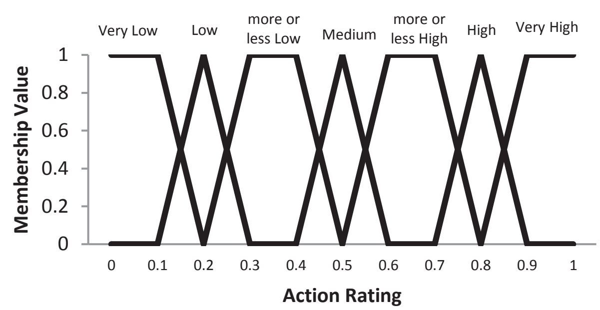

Figure 3 Action rating linguistic model

The adopted four criteria are not equally important necessitating the introduction of the weights shown in the objective function of the developed BIP model. The process of deciding on the appropriate weights is dependent on the period of the year, the nature of the industry and the financial health of the organization among other factors. Moreover, SMEs have different backgrounds which will impact their view of priorities. A fuzzy inference system (FIS) using MATLAB Fuzzy Logic Toolbox is usually developed to provide a reasoning mechanism of human expressions where input space is mapped to a numerical output value through a set of if-then rules. The most commonly used fuzzy inference technique is that of Mamdani as it is typically used in modeling the human expert knowledge. The complexity of the FIS is a function of the number of variables (input and output) and number of rules. Although it is important to design a FIS that adequately captures all aspects of the problem at hand, the robustness and easiness of the adopted system shall also be accounted for.

The last step after building the FIS is to decide on the defuzzification method to adopt towards attaining a crisp weight for each criterion. There are several defuzzificaion techniques that have been proposed in the literature, such as bisector, middle of the max, mean of the max, centroid, etc.

As pointed out in [11], the criteria used in determining the most appropriate defuzzification technique are disambiguity (i.e., the result is a single value), plausibility (i.e., it lies approximately in the middle of the area) and computational simplicity. The centroid was selected as it returns the center of the resulting aggregated area and it is simple to calculate. It is important to note that the resulting crisp weights for the four criteria need to be normalized so that they add up to one.

Once the crisp values for the ratings of all actions with respect to the different criteria along with the weights of those criteria are determined, they are plugged in the mathematical model which is now readily solvable using any commercial off-the-shelve packages such as Excel Solver, LINGO or ILOG CPLEX.

VI. NUMERICAL EXAMPLE: BRAKE CIRCUIT

Figure 4 depicts a simplified portion of a typical hydraulic circuit diagram used in construction equipment systems. The circuit is used as part of an emergency brake system activated manually using a parking brake and assisted with hydraulic pump. In the case of pump or hydraulic fluid loss, a warning is activated and a stored energy in the accumulators is next utilized to apply brake for several times and avoid any catastrophic incidents.

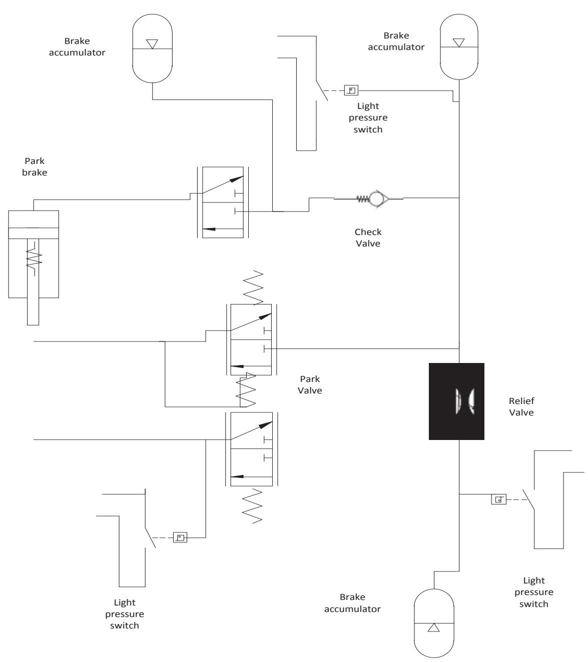

Figure 4 Hydraulic brake system circuit

A detailed RCM was conducted to the hydraulic brake system in attempt to reduce occurrence and severity of failures. A portion of the RCM output actions was changed significantly due to confidentiality reasons and depicted in the Appendix along with data needed to implement the proposed methodology. The actions generated cover a wide spectrum of typical actions for electro mechanical subsystems. The budget dedicated for improvement is limited to $100,000 while time is constrained to 1560 hours (one and a half full time employee time for a period of 6 months).

Following the proposed approach, the first step is to rank the four criteria based on their importance relative to organizational objectives. In this paper, we collect the input from four SMEs who were asked to express their opinion concerning the importance of each criterion using a 0-1 point scale where 1 is most important. Next each SME assessment was mapped into a linguistic term using a trapezoidal fuzzy linguistic model shown in Figure 5.

As there are four SMEs with fuzzy linguistic variables identical to that shown in Figure5, the fuzzy rule based inference system calls for the use of $3^4 = 81$ rules to obtain the fuzzy output linguistic variable called weights. These rules are summarized using Mamdani approach as shown in Figures 6 and 7.

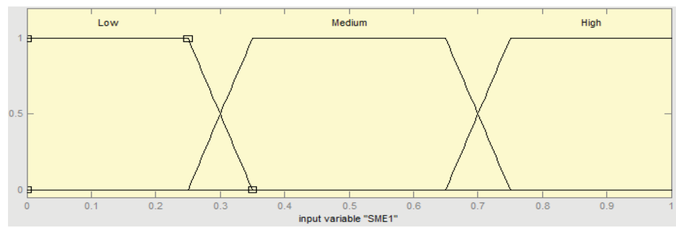

Figure 5 Fuzzy linguistic model for the input variable for SME 1

The obtained fuzzy linguistic model for the output variable involves 7 membership functions assuming either a triangular or a trapezoidal shape as depicted in Figure8.

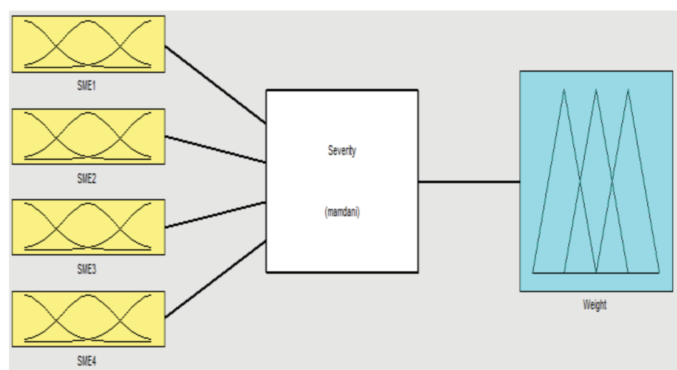

Figure 6 Fuzzy inference system for weight assessment

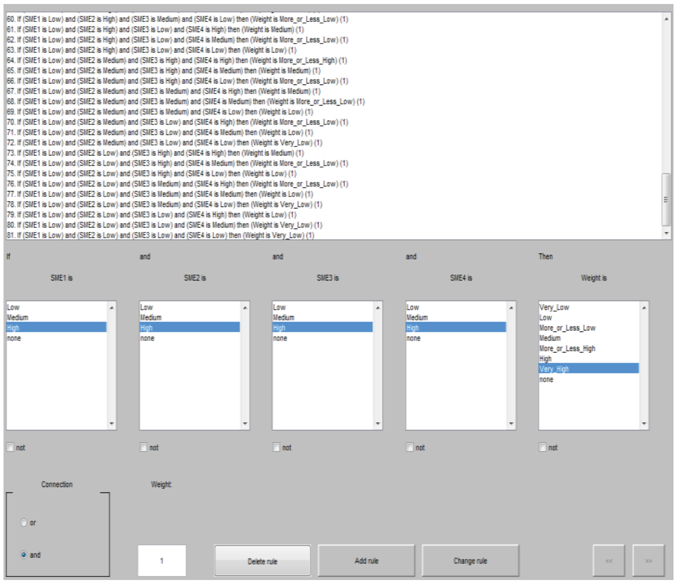

Figure 7 A partial set of the rules used in the FIS

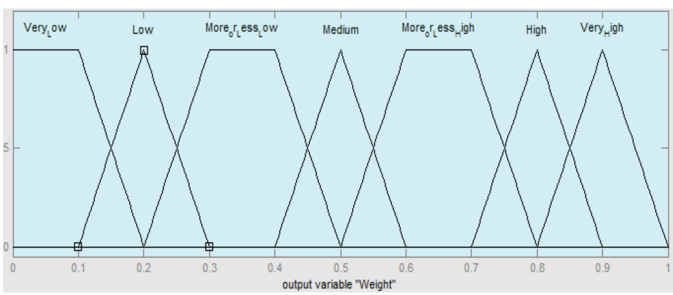

Figure 8 The fuzzy linguistic model for the weight output variable

The second step is to obtain SMEs assessment of RCM actions. In the case of severity an agreed upon number was easily obtained using a 1-10 scale since failure effect is known with great amount of certainty. Similarly, BCR was calculated for each action based on historical records. In the case of customer satisfaction and implementation effort, each SME was asked to select a linguistic term depicted in Figure 3. Next all of the ratings were presented to all SME's to trigger a discussion on the assessment and converge to one selected linguistic term. Once the term is selected, it will be mapped to the centroid of that term in Figure 3. The figures for each criterion are normalized so that all the scores are between 0.1 and 1. **Error! Not a valid bookmark self-reference.** summarizes SMEs' feedback on the importance of the selected criteria using the 0-1 scale. The agreed upon linguistic terms assessing the rating of each maintenance action with respect to customer satisfaction and implementation effort are shown in the Appendix.

TABLE 2 SME'S RANKING OF IMPORTANCE OF CRITERIA

SME	***Criterion***			
	Severity	***BCR***	***SAT***	***Effort***
SME1	10	9	8	4
SME2	9	7	6	4
SME3	8	3	7	4
SME4	8	8	9	7

VII. Results

Given the inputs of the SMEs and through implementing the FIS described above, the obtained weights are 0.9, 0.75, 0.85 and 0.6 for severity, BCR, customer satisfaction and efforts, respectively. Those weights need to be normalized, through dividing each by the total, before being fed into the BIP model which results in the normalized values of 0.290, 0.242, 0.274 and 0.194 respectively. Having those crisp weights coupled with the input data provided in the Appendix, the developed BIP was run and the result is to select actions 1, 2, 5-10, 12-14 with an objective function value of 3.48 and a budget of $ 96,115 and a total development time of 535 hours.

In order to shed more light and provide more insights on the impact of the criteria's weights, four additional scenarios were evaluated for the hydraulic brake example by varying the weights/importance of the four criteria in the objective function.. Results are summarized in TABLE **3**.

TABLE 3. HYDRAULIC BRAKE EXAMPLE RESULTS

	Weights				***Actions selected***	***Objective***	***Cost ($)***	***Time (hr)***
	SEV	***BCR***	***SAT***	***EF***				
1	0.25	0.25	0.25	0.25	1, 2, 5-10, 12-14	3.71	96,115	535
2	0.3	0.3	0.3	0.1	1, 5-11, 13, 14	3.13	94,075	495
3	0.4	0.2	0.2	0.2	1, 2, 5-10, 12-14	3.32	96,115	535
4	0.3	0.6	0.1	0.1	1, 5-11, 13, 14	3.25	94,075	495

The first scenario in Table 3 gives equal weights/importance to all terms and resulted in the selection of eleven actions out of fifteen actions. The budget was almost exhausted; however only one third of the budgeted development time was consumed. When severity was given higher priority (w_{SEV} = 0.4), optimal solution was not changed as shown by the third option. In the second scenario, less weight/importance was assigned to effort; inducing a change in the optimal solution which now calls for the selection of ten actions only with the budget almost fully consumed and major slack of development time. The results were not changed when higher weight is assigned to BCR on the expense of customer satisfaction and effort (Scenario 4 in the table).

VIII. Conclusion

RCM is a systematic approach that seeks to outline all functional failures along with their effects and potential causes. Typically, failures are ranked based on severity (i.e. consequences) of the effect. In principle, failures with high severity can be managed through actions aimed at probability of failure (occurrence) reduction (OR) and/or changing the consequence (CC) as shown in Table 4. It is from the author's experience that actions aimed at changing consequences (CC) are far more economical to implement than occurrence reduction (OR) related actions. This is particularly true when dealing with electronic hardware and firmware failure modes. In this paper, a model for the prioritization of RCM actions is proposed and demonstrated using a real life example of a hydraulic brake. The prioritization takes place based on several criteria where the model favors failure modes with the highest consequences (severity), highest benefit-to-cost ratio resulting from failure occurrence and maintenance time reduction, highest potential customer satisfaction, and least action implementation effort. The model developed also incorporates SMEs opinions in order to come up with linguistic ratings of the actions with respect to customer satisfaction and implementation efforts. In addition, the weights of the respective criteria are determined in consultation with the SMEs whose input is aggregated through the use of If-Then based fuzzy inference system to obtain a fuzzy linguistic variable that is then defuzzied to a crisp value using the centroid method. The computational results indicate that the selection of which maintenance actions to carry out is impacted by the relative importance (i.e. weight) of the considered criteria.

TABLE 4.RCM ACTIONS EXAMPLES BY IMPACT

Occurrence reduction (OR)	***Changing consequence (CC)***
Component re-design	Use of back-up component
Preventive maintenance	System duplication
Deploy/improve training	Fault isolation
Develop new SFT	Failure containment
Clarify procedure in SWI	
Condition monitoring	
Load sharing	

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APPENDIX: RCM EXAMPLE DATA

ID	*Category*	*Action*	**SEV**	*Transformed SEV*	*Development time (hrs)*	*(failures/year)*	*Cost of Failure ($)*	*TTR reduction*	*total cost ($)*	*B/C ratio*	*Customer Satisfaction*	*Impl. effort*	*Notes*
1	A	Add a thorough cleaning step in service level II	5	55	15	5	3,000		5,340	3.8	Low	Low	Use new accumulator for all production
2	L	Use of seal kit instead of individual o-rings	3	11	80	1	4,000	10	23,240	11.0	More or less low	Low	Supply chain effort, failure is due to missing step. Saving in installation time
3	I	Design new SFT for pump plate adjustment	5	55	80	3	300	5	65,240	5.3	High	More or less Low	Easy to adjust by clients based on load
4	E	Re-design hyd. tubes o-ring mounting cones	7	270	160	5	250		25,640	0.3	Very Low	More or less High	
5	B	Test cracking pressure of RV	7	270	40	3	12,000	25	2,040	34.0	Low	Low	
6	I	Design torque tooling for set plugs	9	1339	80	1	150	15	19,240	16.0	Low	Low	Safety related item
7	D	Use of e-SWI instead of hard copies (easier to update)	3	11	60	4	900	10	4,090	11.0	Very Low	Medium	
8	B	Develop set-up to test hydraulic gauges	5	55	40	6	250		4,365	0.4	Medium	More or less High	
9	F	Change material of seal (thermal resistant)	8	602	40	2	2,500		10,040	1.3	Medium	Medium	High visibility market
10	B	Monitor oil quality during PM (CBM)	7	270	80	2	6,000	30	12,240	33.0	More or Less High	High	CBM can be used by clients to decide when to replace
11	C	Develop a self-check SW program	3	11	120	3	250	70	34,440	72.0	High	Very High	Automatic self-check
12	H	Deploy training modules on gauges calibration	2	5	80			2,000	13,240	0.5	Medium	Medium	Minimize gages calibration frequency
13	M	Replace electrical wiring test from PM with less invasive one	7	270	20	9	700	70	1,440	72.0	Very Low	More or less Low	Use of special connector
14	K	Increase service 1 interval to 500 hrs instead of 250 hrs in regular markets	4	25	0			120	840	120.0	More or less High	Low	Annoyance, reduce trips to dealership
15	C	Add humidity sensor (PHM)	7	270	1200	1	9,000		36,840	2.3	Medium	Very High	Addition to tool