

# Equipment redesign feasibility through maintenance-work-order records using fuzzy cognitive maps

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**Abstract** Initiation of maintenance-work-order (MWO) by maintenance-planning unit drives maintenance activities, as it authorizes this work to be carried out. The MWO contains information on resource requirements besides specifying the time-frame for work completion. On conclusion of the maintenance actions, it is experienced that these and other maintenance parameters vary appreciably from their envisaged values. These deviations and the status of dismantled equipment are recorded in the MWO. The objective of this paper is to identify the parameters, which have a *potential for design-change*. It demonstrates the use of fuzzy cognitive maps to extract the desired knowledge from the MWO records. The study concluded that the MWOs, which recorded a high degree of cognitive values for *surface/material failure*, *deviation in equipment settings* and the *extent of repairs* carried out on the equipment do have a high degree of *potential for redesign*. The analysis also concluded that a high degree of *time to maintain* and *quantum of spares* used may not be critical for immediate design modifications. This will help to identify the MWOs, which should be sent to the designer for redesign of the equipment.

**Keywords** Maintenance-work-order · Redesign · Maintenance feed-back · Fuzzy cognitive map

## 1 Introduction

Knowledge and management of knowledge processes are critical to the survival of organizations. It is imperative for organizations to remain competitive by extracting the most from the resources at their command. Pricing of equipment, its quality and features, etc. make the organizations competitive. The customers use life cycle costing (LCC) as a means to evaluate the best that their money can buy. Therefore, the market forces demand that the equipment is constantly improved upon as regards to its reliability, availability and maintainability (RAM) attributes. Efficient management of knowledge processes can lead to such improvements. Maintenance-work-order (MWO) is one such knowledge process.

It is a general practice in the industry to use the MWO for the purpose of providing written instructions detailing the work to be carried out (BS 3811: 1984). It acts as a work request, a planning document, a work allocation document, a history record or as a notification of modification work completed (Kelly 1991). Traditionally, MWO serves the purpose of planning, scheduling and control (Duffuaa et al. 1999). The maintenance planners design the MWO to monitor the work and generate management information system (MIS) reports. The format of MWO is usually designed by the organizations to suit their individual needs. However, the maintenance planners need to realize that the data in the MWO, if recorded in an appropriate format, is precious and holds the potential of being a valuable input to the designer and the maintenance analyst. It helps the designer for design improvements, while the maintenance analyst benefits by improving the equipment availability. An attempt has been made in this paper to demonstrate that the structured observations recorded in the MWO can accomplish these objectives.

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The maintenance function is strategic to organizations that have significant investments in their production assets (Tsang 2002). The maintenance of assets and technologies is increasingly becoming challenging (Swanson 1997) due to advancement in technologies and complexities of the assets. Maintenance has also taken a strategic role due to safety and environment issues (Cooke 2003) and managing the assets has become a discipline by itself (Shrivastav 2005). Therefore, theoretical models that aim at practical applications will be needed in this functional area (Simões et al. 2011).

It is well recognized that the maintenance function is central to the profitability of any organization. The users are concerned with the functionality of the equipment whereas the maintenance team, through its close proximity to the equipment, keeps it in a functional state. The maintenance costs are high e.g., varying between 1 and 25 % of the plant turnover (Komonen 2002) and between 12 and 23 % of the total factory operating costs (Cross 1988), etc. Therefore, extracting the most out of this function will enhance the profitability of the organizations and justify the expenditure on maintenance.

Maintenance activities are conducted on instructions recorded on maintenance-work-orders. However, during execution of such works several ideas run through the minds of persons involved in the maintenance activities. Some ideas are related to improvement in maintainability attributes, which are born out of the difficulties experienced by the maintenance personnel. Other ideas germinate when the maintenance activities are carried out to resolve the failures that take place repeatedly with the mean time to failure (MTTF) much less than the expected value. In case of such failures the maintenance personnel resort to on-site changes in the equipment. This is accomplished through analytical skills of human intelligence, which is a component of knowledge base (Liang 2012). Heisig et al. (2010) mentioned that such failures should be recorded in the MWO and fed back to the design. The information related to reasons of design failure, the failure mode, times, ages of failed parts, rate and trends should be recorded as an appropriate knowledge process by incorporating these in the maintenance-work-order. These maintenance inputs are useful for the equipment designer and help in evolution of design besides adding to the knowledge bank for future product development and for use by the maintenance analysts to resolve field problems.

It is experienced that equipment do fail no matter what care is taken during the design phase, which includes simulated design decisions based on downstream factors (Sandberg et al. 2013). Assuming that the manufacture and installation of equipment are as per design, the equipment failures are either due to age related wear and/or design deficiency. Improper design manifests itself in the form of several time dependent variables, which should be recorded

in the MWO during the preventive or corrective maintenance activity on the equipment. These dynamic variables have a causal relationship amongst them, which eventually culminates into decision variable i.e., *potential for redesign*.

The study of relevant literature revealed that criticality of MWO records has not been modeled and analyzed to identify factors responsible for design lacunae. Fuzzy cognitive maps (FCM) can conveniently model the cognitive aspects of human perception based on human knowledge and experience, with respect to the values of the variables and their causal inter-relations. MWO can, therefore, be designed to contain all the relevant information but one does not know as to which ones should be given adequate importance. This paper will attempt to achieve the objective of uncovering the critical variables based on which the MWO should be sent to the designer for evaluation. The nomenclature, 'concepts' is used in this paper to describe the dynamic variables.

Fuzzy cognitive maps is used in this paper to represent the knowledge and experience because crisp mathematical numbers cannot describe human perceptions. It considers the dynamic state of the variables influencing the failure process that is similar to the real world. The FCM has not been applied in this area earlier. Zhou et al. (2006) described the fuzzy cognitive map as a signed digraph that captures the cause/effect relationships in a system. The nodes are the dynamic concepts of the system under consideration. The directed edges show causal relationship between the concepts. This structural map of the system stabilizes to specific concept values based on the initializing vector imposed on the FCM (Kosko 1986).

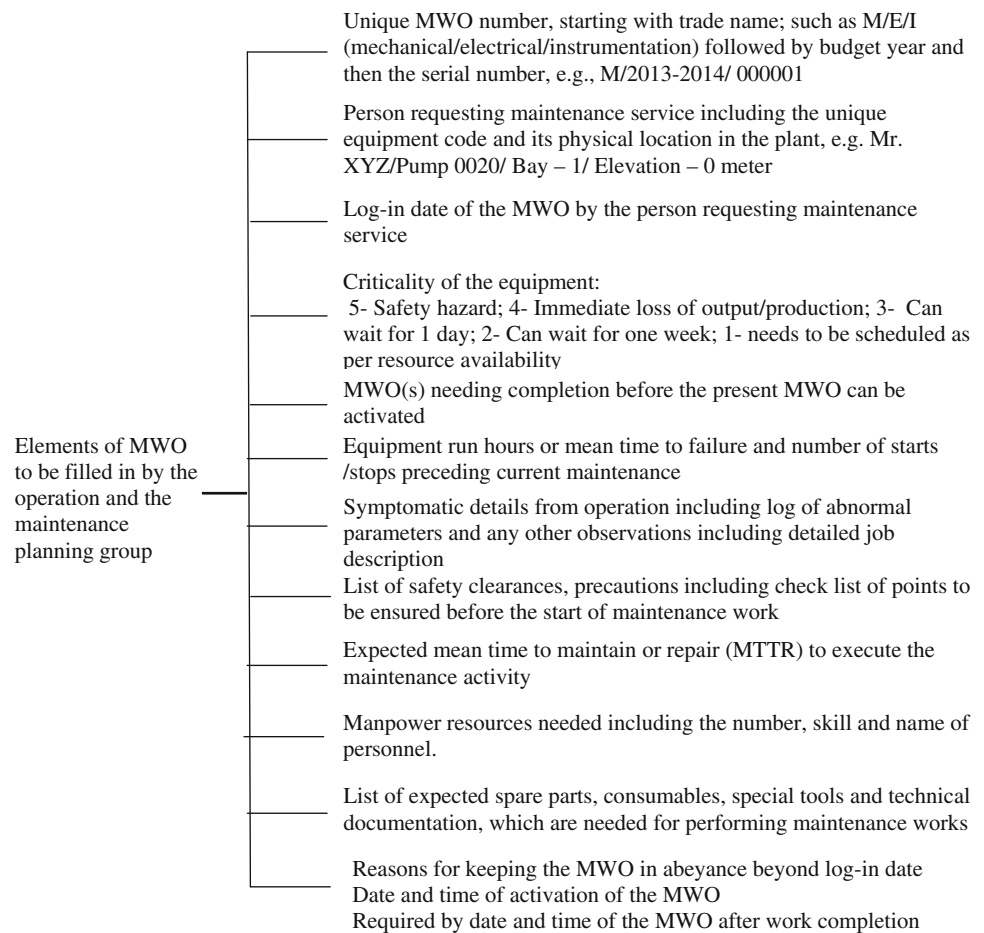
In this paper an attempt has been made to specify the relevant elements, which should be recorded in the MWO and a methodology has been described to analyze the recorded data using FCM with an objective to give feed-back to the designer for design improvisation. The input concept-vector and the edge matrix of causal relations have been perturbed to analyze the sensitivity of the feed-back decision.

The paper is organized in seven sections. Section 2 details the MWO contents, which should be recorded. Detailing of the FCM model along with the implementation methodology is discussed in Sect. 3. Section 4 uses the model to identify the factors that indicate *potential for redesign*. A case study for a turbine maintenance work demonstrates the implementation of the inference mechanism of the FCM, in Sect. 5. Section 6 discusses the utility of the model and finally, the last Sect. 7 concludes.

## 2 Maintenance-work-order contents

Some of the information typically included in the MWO are: Inventory number, unit description and site, person requesting

**Fig. 1** Elements of maintenance work order fields to be filled by maintenance planning department



for the job, job description and time standard, job specification and code number, date required and priority, trades required and the coordinating foreman, spares required with store number and location, special tools and lifting tackles required, safety procedure document and finally the drawing and manual number. It also contains control information like cost code for work type and trade, downtime, actual time taken, cause and consequences of failure and actions taken. However, the structured data, which should be recorded in the MWO, is shown in Figs. 1 and 2 (BS EN 13460: 2002).

It is experienced that more than 90 % of the failures occurring in equipment are on account of *material/surface failure* (Collins et al. 1976), which signifies the importance of this concept for consideration of design-change. Any such field-failure calls for *repairs* of components or change in design to prevent the root cause of such failure. The eventual failures are preceded by *deviations observed in the settings* of the equipment or *change in clearances* between the components. Such deviations usually take place because of overstressed components, heat influenced deformations, creep, sinking of foundations, erosion, corrosion, change in material property (grain growth), release of machining and fabrication stresses, etc. It is imperative to keep the designer in the

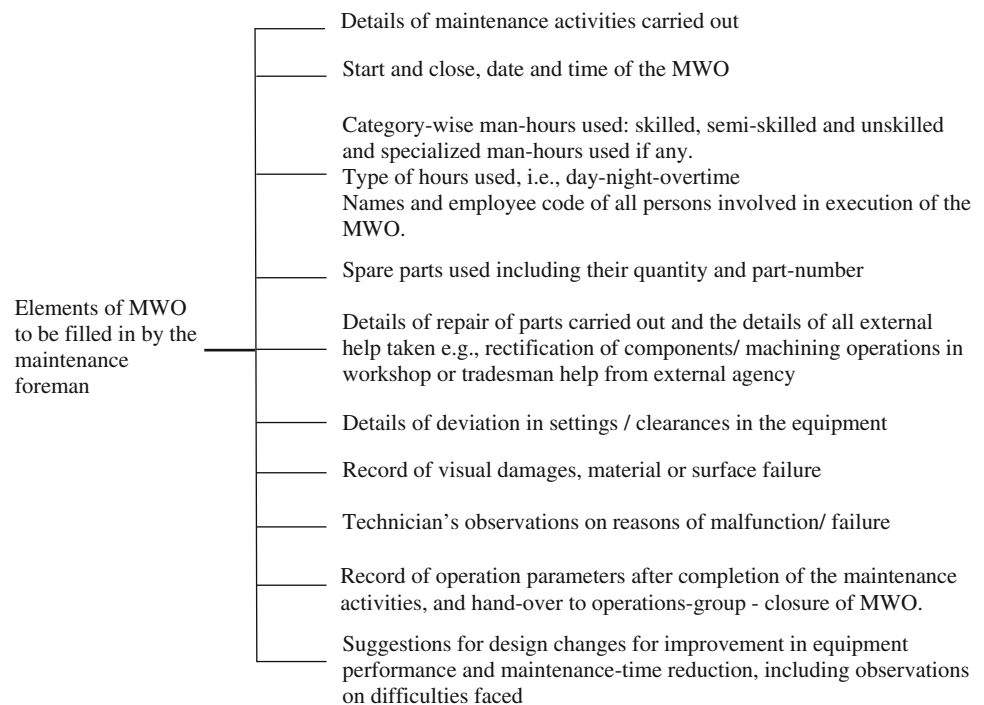
decision-making-loop for any unusual increase in *time to maintain*, which reduces the availability of the equipment. Unusually high *spares consumption* is a trivial sign of problem area in the equipment.

Based on the above discussions and Fig. 2, five critical concepts are chosen, These are modeled with an objective to analyze the criticality of the concepts and to assess whether the MWO should be fed-back to the designer for design re-evaluation. These are: (1) *time to maintain*, (2) *deviation in settings and clearances* in the dismantled equipment, (3) *material failure including surface failures* (Collins et al. 1976), (4) *quantum of spare parts used* and (5) the *extent of repairs* carried out. The cognitive values of these are recorded on the MWO after completion of the maintenance activities. Each of these concepts may have causal relations among themselves, which influences the target concept, *potential for redesign* of the equipment that is taken up for maintenance.

### 3 Fuzzy cognitive model

The concepts and their state, which is recorded in the MWO may be a manifestation of the design deficiency but

**Fig. 2** Elements of maintenance work order fields to be filled-in by the maintenance foreman



they cannot be hierarchically listed with respect to their redesign potential due to complex interactions and causal dependence among these. Nonetheless, their influence on the target concept can be analyzed using a structured network such as cognitive maps. The accumulated human knowledge of the system can be used to construct its map using nodes that represent the variables (concepts) and the edges representing the causal relationships between them.

Axelrod (1976) was the first to introduce and apply cognitive maps to decision making in social and political systems. Subsequently by using methods of fuzzy logic, Kosko (1986, 1992) gave crisp numbers to the concepts and their causal inter-relations in the cognitive maps, which enabled its use in engineering applications. Some of these applications are: maximizing the utility of a route (Kandasamy and Indra 2000), failure mode and effect analysis (Enrique and Bowles 1996) and modeling supervisory control systems (Stylios and Groumpos 1998), etc. FCM has, therefore, emerged as a powerful modeling and simulation technique, however, its potential has not been exploited fully in modeling engineering design space.

Traditional models are deficient in evaluating dynamic systems, which are typical of any operating equipment (Taber 1991). This is not so with the FCM, which allows evaluation of the effects of changes in the system. The FCM structure operates on a systematic causal reasoning and seeks answers to questions such as, “what if?”. It is dynamic and evolves over time due to excitation by an initializing vector consisting of specific values of concepts in a given state. Therefore, FCM can be used to model and

simulate dynamic environment, such as the real time condition of the equipment under maintenance. The record of the state of the equipment in the MWO can be modeled using FCM to prevent catastrophic failures and improvement in equipment design.

The FCM methodology primarily concerns with domain identification and mapping it with respect to concepts, mathematical representation, inference and thereby, creating knowledge base (Taber 1991). The next sub-sections describe the FCM representation and the inference mechanism.

### 3.1 FCM representation

Fuzzy cognitive maps represent real-world dynamic systems, which correspond to perception of human beings (Papageorgiou, 2011). These are drawn to illustrate the entire system as a combination of: concepts, represented by nodes ( $C_1, C_2, \dots, C_n$ ) and causal beliefs shown by directed edges ( $e_{ij}$ ), which represent the interrelationships between two nodes ( $C_i, C_j$ ). As discussed, the value of concepts characterize the behavior of the dynamic system and the state in which it exists at any instant of time. Interconnections ( $e_{ij}$ ) between the concepts are characterized by weight  $w_{ij}$  that describes the degree of influence of  $i$ th concept on the  $j$ th concept, while the direction of edge shows the direction of influence. Weights take values in the interval  $[-1, 1]$ . The +ve sign of the weight indicates a positive causality between concepts  $C_i$  and  $C_j$ , which means that an increase in the value of the concept  $C_i$  will

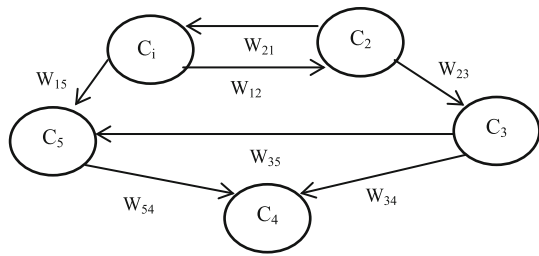


Fig. 3 A typical fuzzy cognitive map

cause an increase in the value of the concept  $C_j$  and vice versa. The negative sign of the weight indicates a negative causality, implying that the values of concepts will move in opposite directions. The value of  $w_{ij} = 0$  implies that no causal relation exists between the concepts. A typical diagram of a fuzzy cognitive map consisting of five node concepts is shown in Fig. 3. For example,  $W_{12}$  signifies that the concept  $C_1$  influences the concept  $C_2$  to a degree  $W_{12}$  with a positive causality, while  $W_{21}$  indicates the degree to which  $C_1$  is influenced by  $C_2$ .

Fuzzy cognitive map of a system having  $n$  concepts, has a weighted edge matrix  $W$  with order  $n \times n$  and is given by matrix Eq. (1). The diagonal elements of the matrix are all zeroes because it is presumed that no concept influences itself.

$$W = \begin{bmatrix} 0 & w_{12} & \dots & \dots & w_{1n} \\ w_{21} & 0 & \dots & \dots & w_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ w_{n1} & w_{n2} & \dots & \dots & 0 \end{bmatrix} \tag{1}$$

There are several approaches available to assign fuzzy weights to causal relations in the FCM. One way is to assign a real number belonging to the interval  $[0, 1]$  for each interrelation. To facilitate this, the linguistic variables, which are easier for humans to express their perceptions, are used. These are then converted to corresponding fuzzy numbers on eleven point scale (Rao 2008) and are given in Table 1.

It has already been discussed that, FCM represents the dynamic system under study, at any point in time “ $t$ ”. Therefore, the state of the system has specific values of

each concept at time “ $t$ ” and is given by,  $C_i^t$ . The system will equilibrate corresponding to the initializing state concept-vector  $C(t)$  under the action of edge matrix  $W$ . The state vector at time “ $t$ ” is given by Eq. (2). It may be noted that the concepts ( $C_i$ s) are also assigned fuzzy values initially based on the perceptual belief of their state of existence by the domain expert(s).

$$C(t) = [C_1(t), C_2(t), \dots, \dots, C_n(t)] \tag{2}$$

It is relevant to note that the dynamic values of the concepts given by the concept-vector, undergo change at every time- step under the action of the edge matrix and this is discussed in the next sub-section.

### 3.2 Inference from FCM structure

Once the fuzzy cognitive map of the system under study is formulated, it can be simulated to draw inference. The value of each concept  $C_i(t)$  is calculated (Stylios and Groumpos 1999) based on the influence of other concepts onto the  $i$ th concept, by using Eq. (3).

$$C_i(t) = f \left[ \sum_{\substack{j=1 \\ j \neq i}}^n C_j(t-1)w_{ji} + C_i(t-1) \right] \tag{3}$$

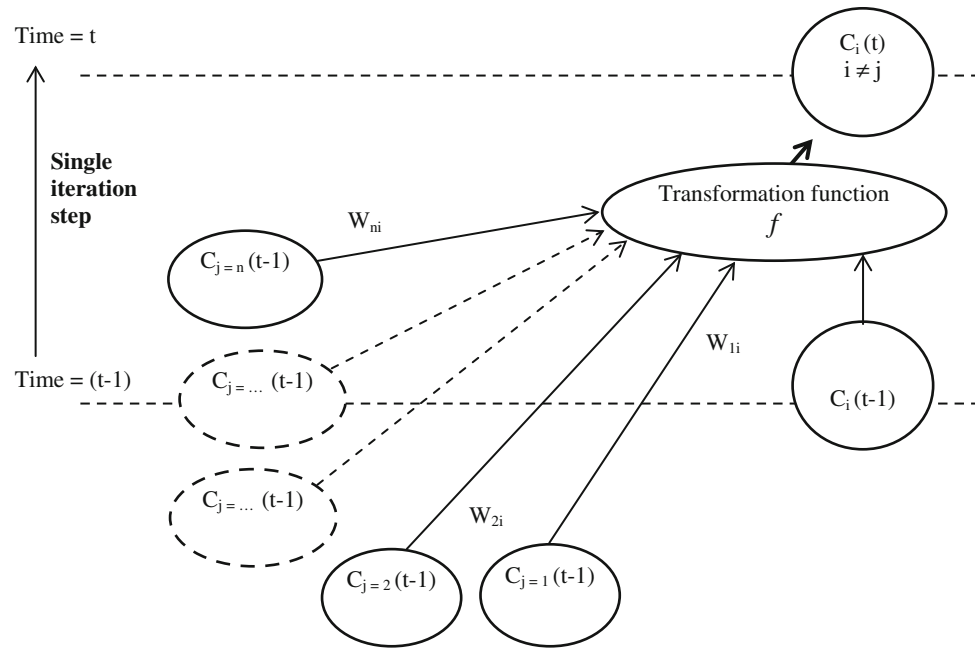
where,  $C_j(t-1)$  is the value of the concept  $C_j$  at time  $(t-1)$ ,  $w_{ji}$  is the weight of the inter-connection between concept  $C_j$  and concept  $C_i$  and  $f$  is the transformation function. The functions, such as sigmoid,  $\tanh(x)$  and  $\tanh(x/2)$ , etc. are usually used as transformation functions to enable the concept values to lie within the fuzzy intervals  $[0, 1]$  and  $[-1, 1]$ . The first and the second dependent terms of the Eq. (3) represent the values of the interconnected concepts and the concept  $C_i$  at the immediately preceding time instant  $(t-1)$  respectively. Figure 4 shows the single iteration process of the concept-vector.

It is experienced that the natural processes e.g. equipment degradation, including those of complex systems exhibit a progression from small changes that accelerate and approach a stable-climax over time. Therefore, besides

Table 1 Linguistic variables and their corresponding numerical values (Rao 2008)

| S. no. | Description of linguistic variables | Assigned values | S. no. | Description of linguistic variables | Assigned values |
|--------|-------------------------------------|-----------------|--------|-------------------------------------|-----------------|
| 1      | Exceptionally high                  | 0.955           | 7      | Below average                       | 0.410           |
| 2      | Extremely high                      | 0.865           | 8      | Low                                 | 0.335           |
| 3      | Very high                           | 0.745           | 9      | Very low                            | 0.255           |
| 4      | High                                | 0.665           | 10     | Extremely low                       | 0.135           |
| 5      | Above average                       | 0.590           | 11     | Exceptionally low                   | 0.045           |
| 6      | Average                             | 0.500           |        |                                     |                 |

**Fig. 4** Pictorial representation of change in concept values at each iteration step



restricting the fuzzy range the use of sigmoid or the hyperbolic tangent function as transfer functions are appropriate to model the fuzzy cognitive maps.

The FCM is excited by the initialization concept-vector each of whose elements are assigned crisp values by the experts. The revised vector  $C$  of the concepts, at each iteration step is derived from Eq. (3) through simulation. It shows the change in the initializing concept-vector state after its interaction with the edge-matrix representing the causal effects between concept nodes. The process of iteration continues till the concept vector equilibrates or else goes into a non-deterministic mode, e.g. trapped in a loop for a specified program execution time or exhibits multiple and random values.

#### 4 Identifying the MWO elements for design change

The previous section described the FCM while in this section the FCM is applied to identify the factors recorded in the MWO, which will decide the need for sending the specific MWO to the designer for considering design changes in the equipment. The process of FCM involves: (1) domain mapping through system study, (2) identifying the factors or the concepts recorded in the MWO, (3) drawing the FCM by determining the relationships between the concepts and assigning appropriate signs and weights, (4) mathematical representation of the map in the form of an edge matrix, (5) simulating the domain scenario by exciting the edge matrix with the concept-vector values recorded in the MWO, (6) drawing inferences and finally, (7) creating the knowledge base.

As a first step, a typical maintenance-work-order issued for doing maintenance on a steam turbine journal bearing is considered. The parameters recorded are as shown in Figs. 1 and 2.

In the next step, i.e. Step 2, a limited number of critical concepts as described in Sect. 2 are considered. It is experienced that these concepts are dynamic in nature with respect to time and are contextual too. The target concept in this case is the *potential for design-change* because the steady state value of this concept decides whether the specific MWO will be fed back to the designer or not.

The inter-relations between the concepts along with their linguistic degree of causation are determined in Step 3 and these are shown in Fig. 5. For example, on dismantling the equipment assembly *deviation in settings* ( $C_2$ ) are observed. Any discrepancies in these do indicate some inherent design defects. It is experienced that this concept does have a 'high' (assigned fuzzy value = 0.665) influence on the *potential for redesign* ( $C_6$ ), a 'low' (assigned fuzzy value = 0.335) influence on the *surface failure* ( $C_3$ ) of the mating components, an 'exceptionally low' (assigned fuzzy value = 0.045) influence on the *quantity of spares* ( $C_4$ ) used and a 'below average' (assigned fuzzy value = 0.410) influence on *time to maintain* ( $C_1$ ) and an 'extremely high' (assigned fuzzy value = 0.865) influence on the *extent of repairs* ( $C_5$ ) that are likely to be carried out to restore the settings. Similarly, the relations between other concepts are established. The degree of inter-relations is decided by a group of experts having the domain knowledge. Initially the degree of influences are collected in linguistic terms, after which they are converted to crisp values based on the fuzzy conversion scale discussed

earlier and given in Table 1. It may be noted that concurrence among experts with respect to the degree of influences does indicate a high level of expertise and, therefore, gives credibility to the constructed FCM (Taber and Siegel 1987).

The fuzzy cognitive map of the domain shown in Fig. 5 is a visual representation of the concepts and their causal relations, which is then converted into the equivalent edge matrix; Equation (4) for drawing subsequent inferences. This weighted edge matrix developed as Step 4 is used in the simulation of FCM, which is the next Step 5, to arrive at the steady state values of the concepts in the form of a row vector from which inferences can be drawn.

$$W = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.865 \\ 0.410 & 0 & 0.335 & 0.045 & 0.865 & 0.665 \\ 0.865 & 0.745 & 0 & 0.865 & 0.335 & 0.955 \\ 0 & 0 & 0 & 0 & 0 & 0.410 \\ 0.590 & -0.500 & 0.045 & 0 & 0 & 0.745 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

The dynamic change in values of the concepts at each simulation step is based on Eq. (3) and the transfer function used is  $\tanh(x)$ , which limits the concept values in the range  $[-1, 1]$ .

The objective of this paper is to evaluate the importance of the various concepts and their equilibrated values, which will indicate the *potential* of these concepts individually for *redesign*. In order to achieve this, the equilibrated concept vector needs to be evaluated. As a next Step 6 towards the inference process, the edge matrix is excited by assigning values to each element of the concept-vector  $C$  within the interval  $[-1, 1]$ , based on the state in which each concept existed on conclusion of the maintenance activity as recorded in the MWO.

In order to achieve the objective mentioned above, the edge matrix is excited by changing the value of one concept at a time. Table 2 shows the converged concept-vector as a function of excitation concept-vector for concept initializing level of average ( $C_i = 0.500$ ), one at a time.

The second column of the Table 2 shows the number of iterations required for the dynamic concepts to achieve equilibrium. For example, initialization of the fuzzy cognitive map of the MWO system, assuming an ‘average’ value of *time to maintain* ( $C_1$ ) recorded in the MWO, while keeping the value of other concepts at zero is given by the input concept-vector  $[0.500, 0, 0, 0, 0, 0]$ . After initial perturbation in the concept values, the simulation converges in 704 steps and the concept values stabilize at  $[0.0459, 0, 0, 0, 0, 0.4693]$ . This output concept-vector

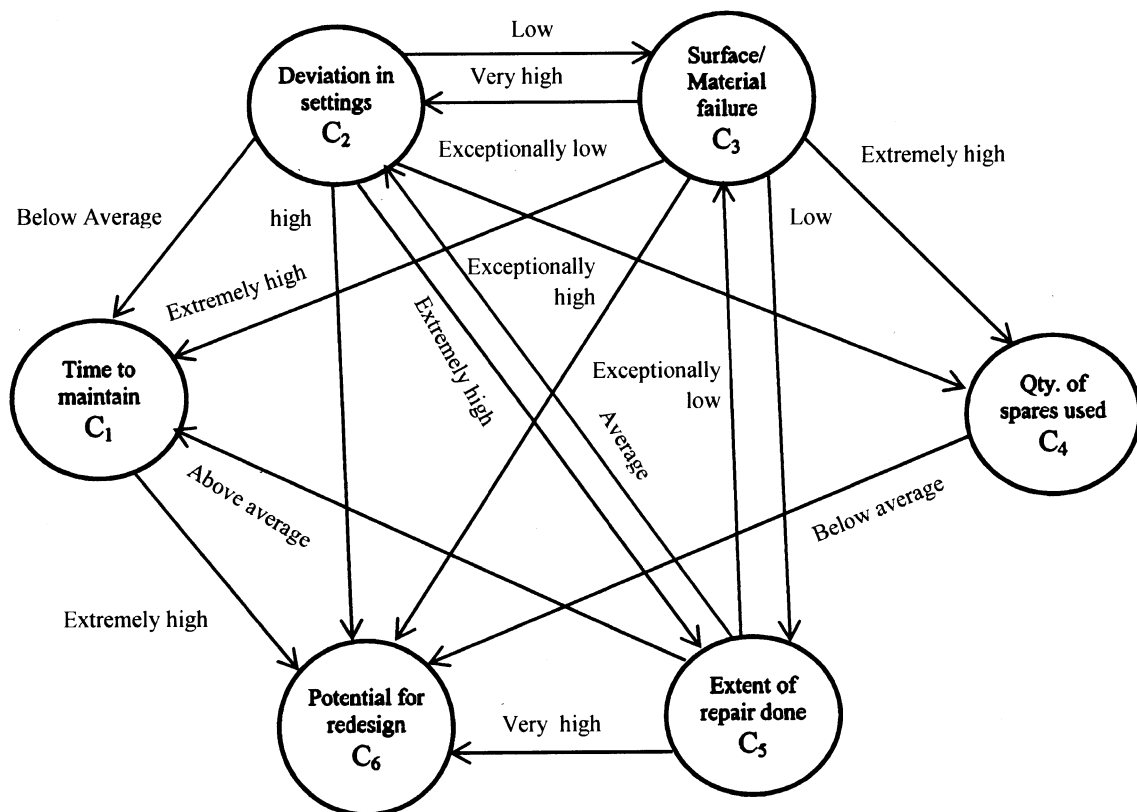


Fig. 5 FCM of the MWO influencing the target concept—potential for design

**Table 2** Output convergence vector as a function of initialization by state vector

| Initial-state vector of concepts for excitation [ $C_1$ $C_2$ $C_3$ $C_4$ $C_5$ $C_6$ ] | Number of simulation steps    | Output convergence vector of concepts       |
|---|-------------------------------|---|
| [0.500 0 0 0 0 0]   | 704                           | [0.0459 0 0 0 0 0.4693]                     |
| [0 0.500 0 0 0 0]   | 42                            | [0.9854 0.6172 0.7691 0.9242 0.9391 0.9994] |
| [0 0 0.500 0 0 0]   | 26                            | [0.9854 0.6172 0.7691 0.9242 0.9391 0.9994] |
| [0 0 0 0.500 0 0]   | 597                           | [0 0 0 0.0498 0 0.3829]                     |
| [0 0 0 0 -0.500 0]  | 34                            | [0.9854 0.6172 0.7691 0.9242 0.9391 0.9994] |
| $C_1$ = Time to maintain  | $C_2$ = Deviation in settings | $C_3$ = Surface failure/material failure    |
| $C_4$ = Extent of sparesconsumption   | $C_5$ = Extent of repairs     | $C_6$ = Potential for redesign              |

shows that though the excitation of the MWO system map was done by assuming an ‘average’ value of *time to maintain* ( $C_1$ ), yet it eventually stabilized at 0.0459, which is ‘exceptionally low’ as per the linguistic scale chosen. This implies that the value of the concept *time to maintain* ( $C_1$ ) recorded in the MWO was due to other contextual factors in the plant (Gupta et al. 2013) and cannot be attributed to severe design deficiency in the equipment because the converged value of *potential for redesign* ( $C_6$ ) was evaluated to be 0.4693, which is between ‘average’ and ‘below average’.

Similarly, it is also observed that if the values of other concepts are zero, an increase in ‘*quantity of spares used*’ ( $C_4$ ) to an average level (0.5000) has no cause for concern, because potential for redesign ( $C_6$ ) value is noted to be 0.3829 as shown in row 4 of the Table 2. On further simulations, it was also observed that change in value of spares consumption ( $C_4$ ) from ‘exceptionally low’ to ‘exceptionally high’ resulted in change of values of *potential for redesign* ( $C_6$ ) from 0.3659 to 0.3855. This again implies that, spares consumption does not have any significant impact on the *potential for redesign*.

However, the equilibrated values of the other concepts, when excited one at a time by the ‘average’ value of the other three parameters i.e. *deviation in settings*, *surface/material failure* and *extent of repairs* indicated a very high degree of *potential for redesign*, as is evident from column 3 of Table 2.

As discussed earlier in Sect. 3 and referring to Eq. (3), it is observed that each simulation step is proportional to a time step and hence the decreasing order of criticality in terms of *potential for redesign* is  $C_3$ ,  $C_5$  and  $C_2$ . This is based on the number of simulation steps it takes to achieve the equilibrated values of the concepts. It is noted that, lesser the number of simulation steps for the excitation concept-vector to converge, faster will the equipment attain a state based on which inferences are drawn, provided the convergence vector is identical.

The above discussions complete the last step 7 of the FCM process, i.e. creation of the knowledge base.

#### Sensitivity analysis:

In the above analysis, the edge matrix of the FCM was considered as fixed, implying that the weights of the relations do not change. This is not always the case, as the contextual conditions play a strong role in deciding the inter-relations. Therefore, sensitivity analysis should be performed to determine the effect of change in linguistic values assigned to the causal relationships and their combined effect on the inferences made above. Two different contextual conditions are considered for different rotating equipment, e.g., journal bearings of the steam turbine and the axial flow compressor. Unlike steam turbine, the compressor bearings are not prone to heat related changes. The edge matrix of the FCM as shown in Eq. (4) is indicative of maintenance activities on steam turbine. In the case of compressor, the pedestal supporting the journal bearing is not affected by heat related deformations and movements. In such a scenario, the edge matrix  $W$  varies and is shown in matrix Eq. (5).

$$W = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.665 \\ 0.410 & 0 & 0.335 & 0.045 & 0.500 & 0.500 \\ 0.665 & 0.665 & 0 & 0.865 & 0.335 & 0.955 \\ 0 & 0 & 0 & 0 & 0 & 0.410 \\ 0.500 & -0.500 & 0.045 & 0 & 0 & 0.745 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

The simulation results corresponding to the new edge matrix after a similar excitation as before are given in Table 3.

It is evident from Tables 2 and 3 that there is no significant difference in the qualitative results of the converged concept-vectors. But, the quantitative value for the concept *potential for redesign* ( $C_6$ ) did indicate a minor downward change. This is on expected lines because the air compressor journal bearings are not subjected to heat stresses. The results of Table 3 re-emphasized the criticality of the observations recorded in MWO for the concepts: *surface/material failure* ( $C_3$ ), *extent of repairs done* ( $C_5$ ) and *deviation in settings* ( $C_2$ ). On the other hand,



**Table 3** Output convergence vector as a function of initialization by state vector interacting with edge matrix of Eq. (5)

| Initial-state vector of concepts for excitation [ $C_1$ $C_2$ $C_3$ $C_4$ $C_5$ $C_6$ ] | Number of simulation steps | Output convergence vector of concepts       |
|---|----------------------------|---|
| [0.500 0 0 0 0 0]   | 704                        | [0.0472 0 0 0 0 0.4370]                     |
| [0 0.500 0 0 0 0]   | 56                         | [0.9709 0.5027 0.7379 0.9185 0.8808 0.9986] |
| [0 0 0.500 0 0 0]   | 11                         | [0.9709 0.5025 0.7378 0.9185 0.8808 0.9986] |
| [0 0 0 0.500 0 0]   | 597                        | [0 0 0 0.0498 0 0.3829]                     |
| [0 0 0 0 -0.500 0]  | 18                         | [0.9710 0.5039 0.7384 0.9186 0.8810 0.9986] |

**Table 4** Simulation results using excitation state-vector [0, 0, 0.335, 0, 0, 0]

| Iteration | Time to maintain | Deviation in settings | Surface/material failure | Qty. of spares used | Extent of repairs done | Potential of redesign |
|-----------|------------------|-----------------------|--------------------------|---------------------|------------------------|-----------------------|
| 1         | 0.2819           | 0.2445                | 0.3230                   | 0.2819              | 0.1118                 | 0.3094                |
| 2         | 0.6215           | 0.4047                | 0.3884                   | 0.5171              | 0.4066                 | 0.8406                |
| –         | –                | –                     | –                        | –                   | –                      | –                     |
| –         | –                | –                     | –                        | –                   | –                      | –                     |
| 30        | 0.9854           | 0.6171                | 0.7690                   | 0.9242              | 0.9391                 | 0.9994                |
| 31        | 0.9854           | 0.6172                | 0.7691                   | 0.9242              | 0.9391                 | 0.9994                |

time to maintain ( $C_1$ ) and quantum of spares ( $C_4$ ) used had no significant influence on the concept, *potential for redesign* ( $C_6$ ).

The analysis here considered only five critical factors recorded in the MWO. However, in actual practice the *potential for redesign* is influenced by numerous other factors, which were listed in Figs. 1 and 2, given earlier in Sect. 2. A comprehensive fuzzy cognitive map relating all the MWO concepts may be made by incorporating all such factors. A specific state of the equipment dismantled for maintenance and recorded in the MWO, can be used to excite the constructed edge matrix in order to arrive at the equilibrated state of the equipment. This implies that based on the observed state of the equipment after conclusion of the maintenance activity, one can have an idea of the final state of the equipment. This will help the decision makers.

## 5 Case study

A case study is taken from the paper by Gupta and Gandhi (2013) for routine inspection check of 120 MW steam turbine. The HP rotor shaft journal (towards the generator end) was found to have adhesive wear marks accompanied with the dulling of its journal surface. On inspection, the bottom half of the bearing was also found to carry similar symptoms. The shaft alignment between the high pressure/intermediate pressure (HP/IP) rotors was checked. The shaft catenary was checked as per the furnished design

values by verifying the shaft journal levels with respect to the reference journal i.e., the LP rotor (generator end) bearing journal. The bearing oil clearances were also checked. However, no abnormality was observed. The bearing was re-assembled and put back into service. The observed state concept-vector was [0, 0, 0.335, 0, 0, 0] because minor surface damage was observed in the journal bearing. On running the simulations for the FCM model as shown in Fig. 4 and exciting the edge matrix given in matrix Eq. (4) by the observed state concept-vector, the concept values equilibrated to [0.9854, 0.6172, 0.7691, 0.9242, 0.9391, 0.9994] after 31 iterations. The high value of the concept, *potential for redesign* i.e. 0.9994 indicates that the MWO must be fed back to the designer. This was in-fact done (though not in accordance with the FCM output). The analysis inferred that the bearing pedestal was expanding in the vertical direction due to exposure to excessive heat and, therefore, the bearing was getting overloaded and needed redesign. It was decided by the maintenance analyst to shield the bearing pedestal from heat and the designer was informed so that the future designs could incorporate reduction in the vertical expansion of the bearing pedestal. The results of simulation are shown in Table 4 and the plot is shown in Fig. 6.

## 6 Observations and utility of the proposed methodology

The methodology of fuzzy cognitive map is able to model complex and dynamic systems, such as mechanical

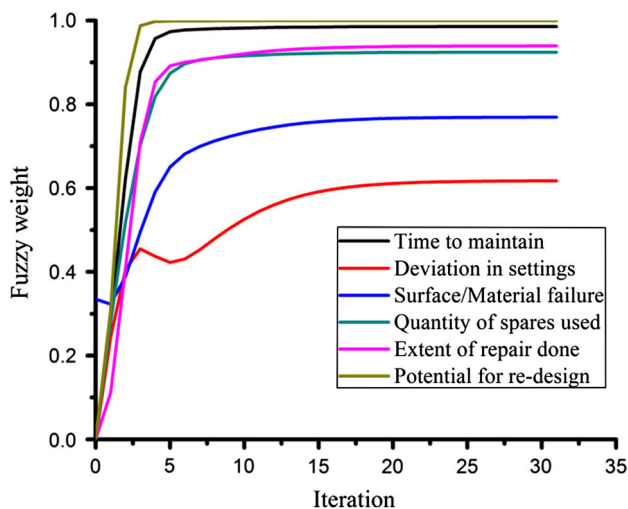


Fig. 6 Simulation results for the case-study

equipment. It introduces concepts and thereby identifies the elements of the maintenance-work-order document, which helps in the decision making process, i.e. whether to send the MWO to the designer for analysis or not. FCM simplifies the process of human reasoning through the approach of causal effect of one concept with the other—one at a time, using human experience and knowledge and, therefore, making the analysis of the complex system simple and convenient. The implementation of FCM is feasible for quantitative and qualitative systems, which involve innumerable inter-related factors or concepts. It enables the unique state of the equipment under maintenance to interact with the MWO causal map and simulates, to predict the eventual status of the system. This enables both the designers and the users to take timely corrective actions, before costly equipment failures take place. It is observed that the parent structure for all the elements of the MWO enumerated in this paper can be made and the causal relation weights must be evaluated accurately, by adopting techniques as mentioned by Taber (1991).

## 7 Conclusion

Traditionally, maintenance-work-order record is used by the finance department of the enterprises for cost control. On the other hand, the maintenance planners use the historical record of the MWO for estimation of resources for subsequent maintenance activities. However, in this paper the potential points of MWO are identified through FCM, for redesign considerations.

There are several qualitative techniques to analyze structured problems. Fuzzy cognitive map has been used in this paper to isolate a few critical parameters, whose record must be furnished to the maintenance analyst and the

designer for improving equipment design and therefore, availability. The study showed that the record of *deviation in equipment settings*, *surface/material failure* and the *extent of repairs* carried out during the maintenance activity on the equipment are critical observations, which should be accurately recorded and fed-back to the concerned personnel. However, the concepts, *time to maintain* and the *quantity of spares* used were found to have low significance with respect to *their potential for redesign* of the equipment. It is suggested that MWOs having record of the above significant observations should be color coded and routed to the designer. The authors opine that the users of the equipment would be happy to share the maintenance feedback with the equipment manufacturers because by doing so, they can expect better service support.

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