Developing a Decision Making Grid Using Fault Tree Analysis With a Case Study in Mobarakeh Steel Company

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Abstract

Decision Making Grid (DMG) is a tool where maintenance tactics are determined, and it is associated with the reliability and risk management of equipments. In this grid, decision making is performed based on the mapping of Mean Time to Repair (MTTR) against frequency of failures. A limitation of basic DMG is that the determined strategy based on these two indicators might not be an appropriate solution in all conditions, particularly when failures are interdependent. On this basis, the major aim of this research is to develop DMG using Fault Tree Analysis (FTA) in order to recognize the interrelationship and the impact of defects. The proposed method has been examined in eight equipments of casting unit of Mobarakeh Steel Company. Findings indicate different positions of equipments in the cells of the new grid compared to the basic grid.

Keywords: Decision Making Grid, Mean Time to Repair, Fault Tree Analysis**,** Reliability, Mobarakeh Steel company

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Introduction

Maintenance activities in the production process causes reduction of costs due to the operation loss of equipments, reduction of operating and service life, and lost profit because of failures. Because of using limited organizational resources, these activities are costly. For this reason, in maintenance processes, it is very important to omit unnecessary activities while system remains in the ideal condition.

Selecting and determining appropriate maintenance strategy based on the failure ratio of machineries to perform related activities is one of the ways to reduce unnecessary activities and reduces costs. Moreover, choosing appropriate maintenance policy based on the ratio of failures causes efficiency enhancement of machineries and increase of production in two quantitative and qualitative aspects. Maintenance has an important role in maintaining reliability, availability, quality of products, risk reduction, increase of output and equipment safety. Thus, maintenance and its strategies have strategic importance in industries. The increase of competitiveness enforces organizations to improve their overall business performance. For this reason, in maintenance topics, appraoches like, Reliability Centered Maintenance (RCM), and Total Productive Maintenance (TPM), and their relationship to Computerized Maintenance Management System (CMMS) have been proposed that are generally following a method at world class level to increase reliability (Labib, et al., 2004). According to Shahanaghi (2008) the most important strategies proposed in maintenance are corrective, preventive, and predictive maintenance.

Many researchers such as Cholasuke et al. (2004), Pinjala et al. (2006), Parida and Kumar (2006), and Reis et al. (2009) emphasized on the impact of effective and efficient strategic maintenance management on competitive advantage, continuous improvement, protecting productive activities, performance improvement, and protecting heavy industries with high investment through machineries and equipments in perfect performance condition. Shahin et al. (2013) in their research entitled "Determining Appropriate Maintenance System Based on Decision Making Grid (DMG), Sigma Level, and Process Capability Indicator for Machineries of Isfahan Steel Company" determined the appropriate strategy for equipments regarding reliability conditions and criteria, Mean Time between Failures (MTBF) and Mean Time to Repair (MTTR). Shahin et al. (2015) in their research entitled "Designing a Three Dimensional Model of Maintenance Decision Making Grid (DMG) Based on Failure Modes and Effects Analysis (FMEA) Approach -With a Case Study in the Mobarakeh Steel Company" proposed a three dimensional model of DMG based on FMEA. Regarding the comparison they made between the dimensions of the two models, it was assumed that the severity rate is the same as repair time, and failure occurrence is the same as frequency or the reverse of MTBF. On this basis, the fault detection coefficient dimension of FMEA approach, as the third dimension, was added to two dimensions of DMG to upgrade the strategies of the Grid. Aslam-zainudeen and Labib (2011) investigated the applicability and the application of DMG in the domain of maintenance of rotating components in rail industries. In their research, they concluded that applying DMG is valuable for prioritizing maintenance systems. Shahin and Attarpour (2011) in their research entitled "Estimating Overall Equipment Effectiveness (OEE) Indicator to Determine and Choose Maintenance Policy by Using Decision Making Grid", estimated OEE indicator by regression and proposed DMG based on MTBF and OEE. In their research by studying 30 equipments, a reasonable relationship was made between DMG and OEE. In the new grid, each maintenance policy appropriate for each of the equipments was specified and ultimately the approximate OEE indicator that justifies the application of TPM was determined.

With regard to the mentioned points and the importance of appropriate and desirable selection of maintenance system strategies and considering the importance of failures and downtime, DMG can be used as an effective guide. In this grid, decision making is performed based on the ratio of failures frequency indicators and MTTR, while compiling the strategy based on these two indicators cannot be an appropriate solution in all conditions. In the basic DMG, failure frequency is the same as equipments recorded downtime and DMG is formed based on the achieved data. In most of the researches performed, no discussion has been given concerning the role of failures effects and the interdependency of failures on DMG results. Such effect can also be related to as the mode of failure or a type of failure resulted from a part of a machine. On the other hand, the possibility of failure might influence choosing maintenance policy. Now, if the types of machine failures are investigated, and an analysis is made on the interdependencies and effects of failures, and its influence on MTTR, it might be effective in enhancing the application of this grid. The recorded value of MTTR can be exponentiated by the interdependency based effect of failures. In order to calculate the failure effect, the Fault Tree Analysis (FTA) and experts' viewpoint can be used. Finally, the proposed approach will be examined in one of the processes of Mobarakeh Steel Company, and the results obtained from DMG will be evaluated. Since the maintenance system existing in the Mobarakeh Steel Company is semi-centralized and maintenance function is at high level in respect of organizational importance, this company has been selected for case study.

Decision Making Grid

Although CMMS as one of the important and central components of maintenance function has been used in many organizations, these systems only provide facilities for data collection and cannot help managers in the analysis and decision making. Labib et al. (2004) called this lack as Black Hole and in order to remove this shortage suggested Decision Making Grid (DMG). DMG acts as a map that specifies the position of the worst machineries based on two criteria of downtime and frequency of downtime and proposes appropriate maintenance tactic as a basic solution for that problem. The major goal in applying DMG is to perform appropriate activities which push machineries towards condition improvement (Labib, 2004). As it is illustrated in Figure 1, five different maintenance tactics are defined which will be introduced in the following. DMG can also be used as a practical approach for obtaining continuous improvement.

In order to determine the position of machine in DMG cells, the recorded information in CMMS database is required.

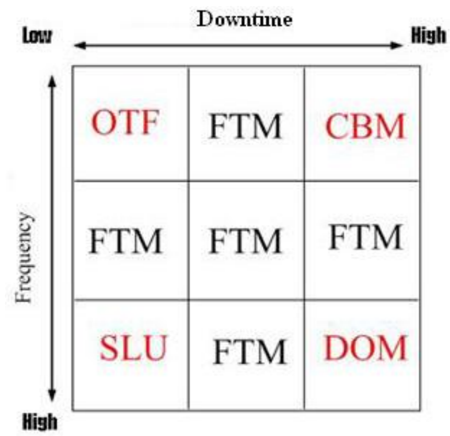

Figure 1. Decision Making Grid (Labib, 2004; Labib, 2008; Aslam-Zainudeen and Labib, 2011)

The important point about DMG is that this grid includes all three groups of mentioned maintenances in the maintenance management. It should be noted that the two indicators of MTBF and MTTR based on which Decision Making Grid is composed are the major indicators of reliability, and usually MTBF is more important than MTTR (Han, 2008). The point that how failure time can be reduced in order to maximize availability is the major concern of any organization (Jenna and Pazy, 2011). The maintenance tactics in DMG are introduced in the following:

- Fixed Time Maintenance (FTM): preventive maintenance is considered to prevent unplanned stoppages and planned stoppages and early equipment damage that will cause repair or corrective activities. This tactic of maintenance management is generally planned as scheduled or routine functions such as lubrication and adjustments which are for maintaining equipments at acceptable reliability and availability levels. Actions of scheduled preventive maintenance should generally be used in fixed time intervals for failures which cannot be discovered and reduced, or if it is essential due to production requirements.
- Operate to Failure (OTF): includess unscheduled activities which are performed when the equipments fail or unexpected failure outbreaks; in other words, it is referred to a series of repair actions on the machineries which suddenly fail. In OTF, after production staffs' request, repair actions are performed to normalize the quality and quantity of production. In facing with such failures, what is mostly important is to discover the place of failure and separating it from other parts, and provided that the repair unit is appropriately organized, it will succeed to repair, maintain, and restore the damaged part immediately after identifying the reason and place of failure. If the activity related to repairing the

failure is scheduled to perform at appropriate time, it is a corrective activity. But in emergency activity, the failure happens, but there is no time for scheduling.

- Condition Based Maintenance (CBM): is a kind of maintenance which is performed to supervise and take care of performance and technical condition of systems and specific sets of machineries which have effective role in the overall performance of system. Among the most important maintenance methods are the oil analysis and vibrations analysis. CBM is called “Economic Maintenance” too, because the maintenance activities are performed when they are required. As an example, instead of periodic oil changing, the actual time of oil changing can be specified. In the present era, all companies, organizations, and industries in all production and private sections need to manage their capitals which is the most important stimuli of capital management of economic, safety, and environmental interests in order to survive in the business competition arena or to perform assigned responsibilities optimally. Using a modern system of monitoring condition can result in acquiring benefits in each considered areas.
- Skill Level Upgrade (SLU): Masakatsu Nakaigawa, the counselor and promoter of TPM defines the skill as the people's capability in performing duties in a way that they perform reaction movements. One of the important goals of TPM and one of the important goals of industry in general is to promote staff's skill and knowledge level. By upgrading people's skill level, the quality and the condition of working environment would considerably improve.
- Design Out Maintenance (DOM): in order to reduce the need for maintenance, revision of the design of components is defined (Labib, 2008). The machineries and equipments which are employed for production or service affairs are themselves produced by other people, and there might be some defects and weaknesses in their design and production which are imported in the machineries and equipments intentionally or unintentionally, and the time spent to repair the failures due to such weaknesses not only imposes maintenance cost on the machineries and equipments, but it might also hinder the production process. The repetition of these incidents can lead us towards the change or modification of failure reason; in this case we would not actually need maintenance of this particular part. An example of such changes is the modification and replacement of bearings for which, because of locating at inappropriate places there is no possibility to access and lubricate them and are is constantly suffering from fatigue and failure. Such repairs are relatively existed in various industries and are named as maintenance for improvement, and have been performed in the framework of one of the methods of modification, change in the regulations, redesigning, and equipping with additional devices (Sayed Hosseini, 2014).

Fault Tree Analysis (FTA)

FTA can easily be regarded as an analytic method in which an undesirable condition of system (usually the condition which is critical in terms of safety) is specified and the system is analyzed in its environmental and operational context, so that all actual ways resulting in the outbreak of this undesirable event (top event) are discovered.

Fault tree is a graphic model of combinations of a series and parallel faults that cause unwanted and pre-defined events. The faults might be events related to hardware failures of parts, human faults, or any other events. Thus, the fault tree draws the logical relationship of basic events which result in top event. The considerable point is that fault tree is not a quantity model alone, but it is also a quality model that can be (and it is often the case that is) evaluated quantitatively.

The output of fault tree is actually a binary event, meaning that it is summarized in two modes of failure and success. Entities of fault tree are gates which specify the current logic in the tree. The gates show the logical relationship between downward (input of gate) and upward (output of gate) events. Figure 2 shows a simple fault tree.

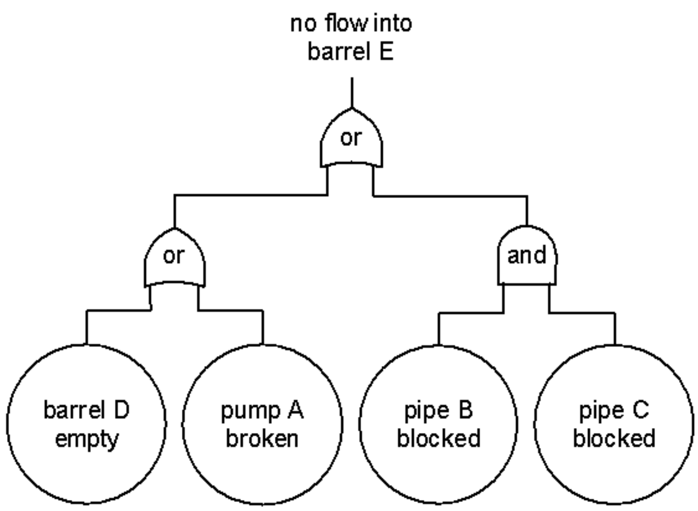

Figure 2. A simple example of a fault tree (Isfahani, 2010)

Various information is obtained from FTA that have considerable role in managers' decision making. Some of these features include:

1. Application of FTA in routing the logical way leading to top event occurrence.
2. Application of FTA in prioritizing events which have higher proportion in its occurrence.
3. Application of FTA as a proactive tool in preventing top event occurrence.
4. Application of FTA as a supervising tool of system performance.

5. Application of FTA in optimizing and minimizing the resources.
6. FTA as an auxiliary tool in system designing.
7. Application of FTA as a tool for identifying the causes of top event occurrence and its removal.

Analysis of fault tree has considerable role in decision making process. This analysis can be used in the whole lifecycle of system from design to development and production stage. When the design is progressed and more data is available, this method can fully be used for routing and reviewing faults and omitting or reducing their risk.

Research Methodology

As it was stated, the calculation in basic DMG is performed based on the previous events, and the ratio of failure in the performed researches is considered disregard of interdependency of failures. In this research, the types of failures of a machine are investigated and an analysis is performed on the impact of failures and their interdependencies. Then, the MTTR value is modified, respectively. For this purpose, the recorded value of MTTR is exponentiated by the fault effect. To calculate the fault effect, the Fault Tree Analysis and experts' viewpoints are used.

In order to perform the analysis, the Mobarakeh Steel Company which is the top ranked steel company of Iran and has strategically great importance for the country is chosen. In this research, the statistical population includes all machineries and equipments maintenance indicators in all units and workshops of Mobarakeh Steel Company at all times and all managers and staffs of maintenance unit of the company that are related to the selection process. The method of sampling is typically purposive and non-random. The recorded data of casting unit machineries with their failure times and working times, and the frequency of their failure are collected in a 12 months period (from September 2013 to September 2014) and for each one of the equipments, the mean time of working and repair times is calculated. In general, eight equipments from casting unit of Mobarakeh Steel Company are introduced for this research which include Motor, Tacho, Cylinder, Pinch Roll, Flexible Hose, Propeller, Gearbox and Bearings.

In this research, in order to analyze the data of the MTTR and failures frequency, descriptive statistics is used and their calculation is performed by Microsoft Excel software. For FTA, the comparative analysis is used and for drawing failure tree and DMG, Microsoft Visio software is used.

Findings

The data collected from casting unit of Mobarakeh Steel Company in a 12 months period includes eight equipments that had the highest emergency repairs. Hence, for each of the equipments, the data related to the description of failure type, cause of failure, number of failures, and the mean time of each failure was collected, separately. To summarize the data, the ratio of MTTR or stoppage time should be calculated. Thus, for each of the failures of investigated equipments, the “frequency” and “repair time” are calculated. Then, regarding the repair time and the number of failures for each of the under investigation equipments, the MTTR related to the cause of failure of these equipments is calculated which is addressed in Table 1.

Table 1. Primary information of equipments

Code and name of equipment	MTTR	Failure frequency
1. Motor	1.250	7
2. Tacho	1.500	10
3. Cylinder	1.833	8
4. Pinch roll	2.052	15
5. Flexible Hose	1.783	17
6. Propeller	2.083	5
7. Gearbox	2.466	5
8. Bearings	2.250	7

Basic DMG results

First, in order to choose appropriate maintenance strategy for the equipments under investigation, the basic DMG is used which is based on two indicators of MTTR and frequency of failures. For defining and dividing the horizontal and vertical axles of DMG which, the following method is applied (Fernandez, et al. 2003):

$$\text{Top scale} = \text{highest value}$$
$$\text{Middle to upward scale} = \frac{2}{3} \times \text{highest value}$$
$$\text{Middle to downward scale} = \frac{1}{3} \times \text{highest value}$$
$$\text{Low scale} = \text{lowest value}$$

MTTR values are used for the calculation of horizontal axis, and frequency values are used for calculation of the vertical axis.

According to Table 1, the scales of basic DMG are calculated based on the indicators which are addressed in Table 2.

Table 2. Scales of the basic DMG

	Mean Time to Repair	Frequency
Lowest value	1.250	5
Middle to downward value	1.655	9
Middle to upward value	2.061	13
Highest value	2.466	17

Then, in order to determine the appropriate maintenance tactics for each equipment, Table 3 should be used for developing the grid in Figure 3.

Table 3. Failure frequency and MTTR values of equipments based on the basic DMG

MTTR scale	Code and name of equipment	MTTR	Failure frequency scale	Code and name of equipment	Failure frequency
High	6. Propeller	2.083	High	4. Pinch roll	15
	7. Gearbox	2.466		5. Flexible Hose	17
	8. Bearings	2.25	Medium	2. Tacho	10
Medium	3. Cylinder	1.833	Low	1. Motor	7
	4. Pinch roll	2.052		3. Cylinder	8
	5. Flexible Hose	1.783		6. Propeller	5
Low	1. Motor	1.25		7. Gearbox	5
	2. Tacho	1.5		8. Bearings	7

As it is observed in Table 3, Motor has the lowest rate of MTTR, Gearbox has the highest rate of MTTR, Propeller and Gearbox have the lowest rate of failure frequency and Flexible Hose has the highest rate of frequency.

According to Figure 3, for equipment 1 (Motor), OTF; for equipments 2, 3, 4 and 5 (i.e. Tacho, Cylinder, Pinch roll and Flexible Hose), FTM; and for equipments 6, 7 and 8 (i.e. Propeller, Gearbox and Bearings), CBM are suggested.

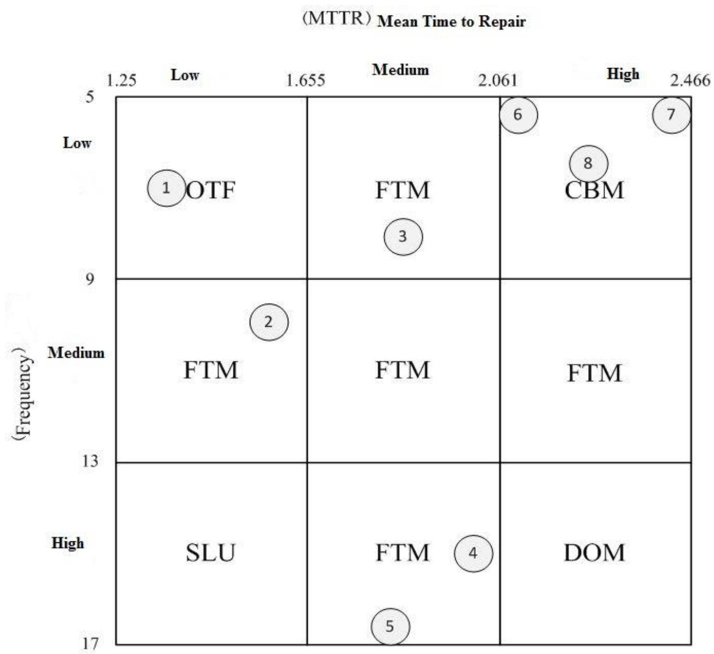

Figure 3. Positioning equipments based on the basic DMG

New DMG results considering interdependency and effects of the faults

As it was mentioned, the faults and failures occurred in equipments do not have equal impact on the system and all of them result in equipment failure, hence the intensity of fault effect of all sub-equipments cannot be regarded equal. In the basic DMG, all of the failures are considered with the same effect intensity. But, in the proposed approach, by using FTA, the interdependency of components and also the importance of failures in the sub-equipments of the segment are specified. In order to draw the fault tree, it is required to determine the relationship between failures. In the meetings and by using experts' viewpoints, structure of failures is identified and the relationship between failures to draw the fault tree is specified. The fault tree of the equipment segment is illustrated in Figure 4.

According to Figure 4, each of the sub-equipments of Pinch roll, Cylinder, and Flexible Hose alone results in segment failure, but the failures of other five equipments, i.e. Motor, Tacho, Bearings, Propeller and Gearbox do not occur in this way. The failure of each of these five equipments results in production quality fall or reduction of production volume, but do not cause production stop and line failure.

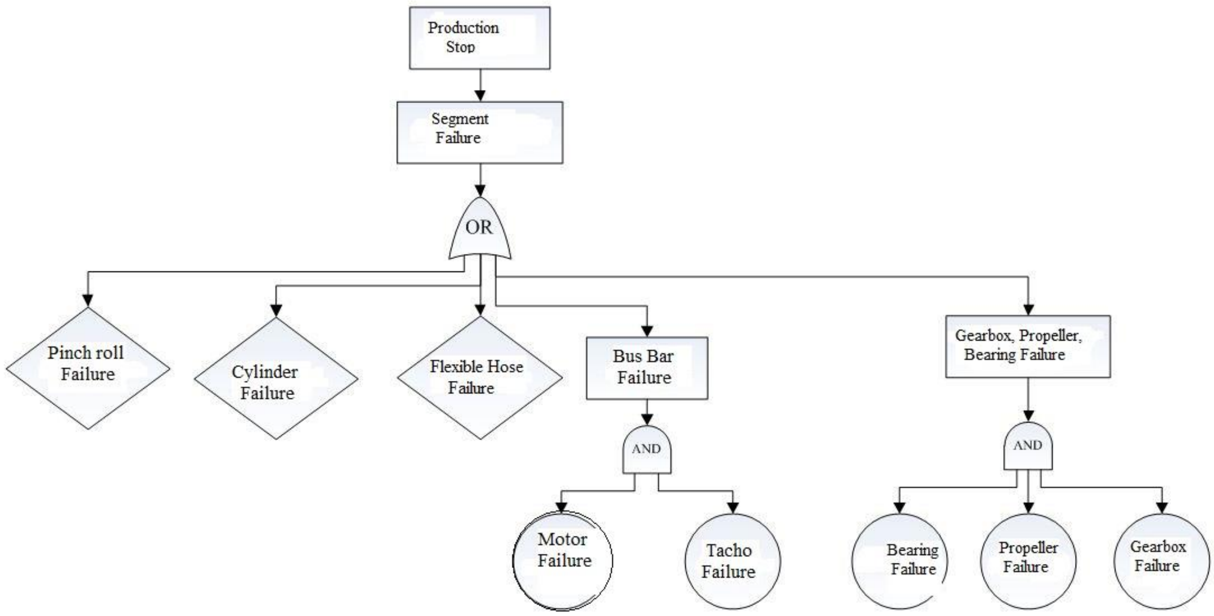

Figure 4. FTA of the case study

The Reliability Block Diagram (RBD):

The equivalent Reliability Block Diagram (RBD) to the FTA shown in Figure 4 is shown in Figure 5. The RBD is considered as a mental model (Labib, 2014; Labib and Harris, 2015) that is derived from the FTA model and it helps to visualise the relationship among causal factors and hence identification of vulnerable aspects of the model. In constructing the RBD the following two ules apply:
every OR gate in the FTA in Figure 4 is mapped into a ‘series’ structure in the RBD and,
every AND gate into a ‘parallel’ structure.

Based on the RBD, minimum cut set; which is least group of fault tree basic events that if all occur, will cause the top event to occur, is considered to be:
(4), (3), (5), (1), (8); (4), (3), (5), (1), (6); (4), (3), (5), (2), (8); (4), (3), (5), (2), (6)

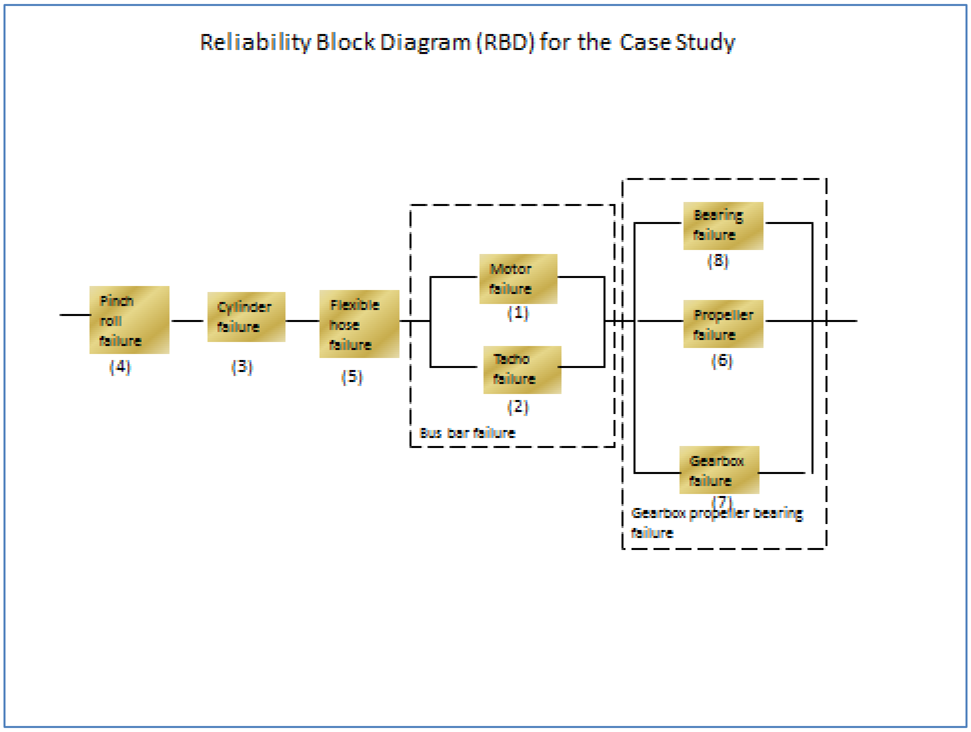

Figure 5. The Reliability Block Diagram (RBD) for the case study

In the two sub-equipments of Motor and Tacho, the failure of each one would not solely cause Bus Bar failure, but the simultaneous failure of these two equipments causes Bus Bar failure, and ultimately the failure of segment. Therefore, the gate "AND" is used for this relationship.

The failure of each of the three sub-equipments of Gearbox, Propeller, and Bearings would not solely result in segment failure, but the simultaneous occurrence of their failures interrupts production, hence these three sub-equipments are also denoted by the gate "AND". According to the drawn fault tree and the above interpretations, the failure effects of eight sub-equipments are not equal; because some of the failures directly cause segment equipment failure, but some other do not have this effect alone. Therefore, the failures effect should also be considered in the DMG. For this purpose, regarding the research performed by Shahin (2004) and based on Tan and Shen (2000), the dimension of MTTR is raised to the number 'k', so that it removes the intensity of the effect of each of failures from the equal mode. 'k' refers to the interdependency importance of failure. Here, by using the five point Likert scale, it is assumed that the middle number (i.e. 3) indicates a medium and usual effect and the highest number (i.e. 5) indicates the highest effect. Therefore, for the sub-equipments connected to the gate "OR" k=5, and for the sub-equipments connected to the gate "AND", k=3 are suggested. Finally, for reducing the diversity of the computed values, logarithm (Ln) is taken. In Table 4, the new computed values of the two dimensions of DMG are addressed.

Table 4. Values of the new DMG

Code and name of equipment	MTTR	Failure frequency
1. Motor	0.669	7
2. Tacho	1.216	10
3. Cylinder	3.030	8
4. Pinch roll	3.750	15
5. Flexible Hose	2.891	17
6. Propeller	2.201	5
7. Gearbox	2.708	5
8. Bearings	2.433	7

According to the process mentioned for drawing the basic DMG, the scales of the axes of the new DMG are computed based on the indicators addressed in Table 5.

Table 5. The scales of the new DMG

	MTTR	Frequency
Lowest value	0.669	5
Middle to downward value	1.696	9
Middle to upward value	2.723	13
Highest value	3.750	17

Based on Table 5, the new DMG is developed as illustrated in Figure 5. For equipment 1 (Motor) OTF is suggested; for equipment 3 (Cylinder) CBM is suggested; for equipment 2 (Tacho), equipment 6 (Propeller), equipment 7 (Gearbox), and equipment 8 (Bearings) FTM is suggested; and for equipment 4 (Pinch roll) and equipment 5 (Flexible Hose) DOM is suggested.

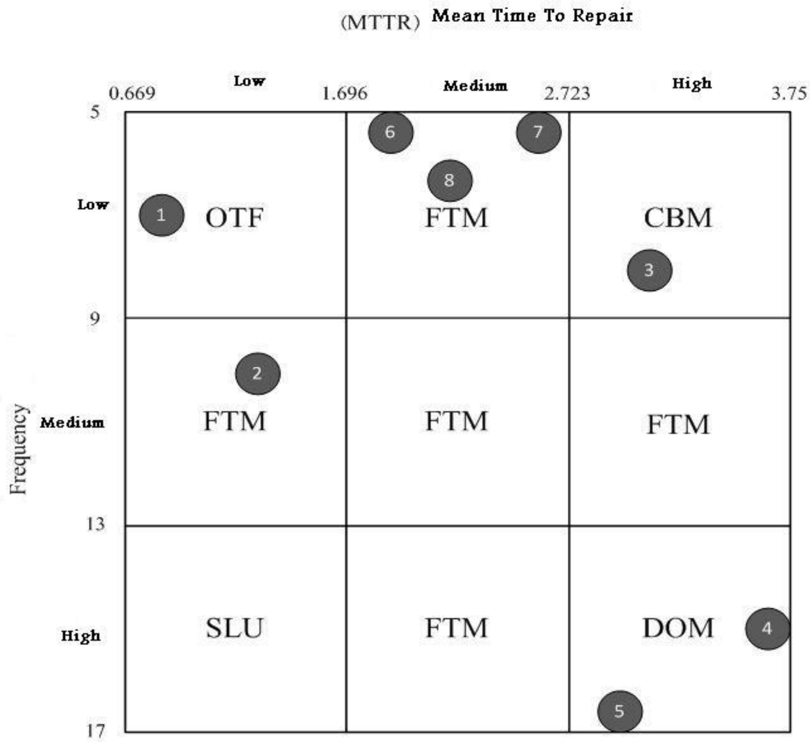

Figure 5. Positioning equipments based on the proposed DMG

Discussion and conclusions

In this research, an attempt was made to develop the basic DMG using FTA. For this purpose, the indicator of failure effect intensity was assumed the same as MTTR, and the indicator of failure occurrence was considered the same as failure frequency. In order to show the relationship and the effect of failures, FTA was used; then, the analysis related to the equipments under investigation was offered.

Motor: the proposed tactic for the equipment Motor in the new DMG is the same as the previous tactic, i.e. OTF. This is due to the low frequency of failure and the low MTTR of this equipment, and the point that the failure of this equipment does not result in segment failure alone.

Tacho: the proposed tactic for the equipment Tacho in the new DMG is the same as previous tactic, i.e. FTM. This is due to the low MTTR of this equipment, and the point that the failure of this equipment does not result in segment failure alone.

Propeller: the proposed tactic for the Propeller in the new DMG is FTM, while in the basic DMG, CBM is proposed. Regarding the effect of failure that this equipment has on the system and high cost of CBM compared to FTM, it is suggested to use FTM.

Bearings: the proposed tactic for the Bearings in the new DMG is FTM, while in the basic DMG, CBM was suggested. Regarding the effect of failure that this equipment has in the system and high cost of CBM compared to FTM, it is suggested to use FTM.

Gearbox: the proposed tactic for the Gearbox in the new DMF is FTM, while in the basic DMG; CBM was suggested. Regarding the effect of failure that this equipment has on the system and the high cost of CBM compared to FTM, it is suggested to use FTM.

Cylinder: the proposed tactic for the Cylinder in the new DMG is CBM, while in the basic DMG, FTM was suggested. Regarding the low failure times and the high failure effect that this equipment has, and in order to improve performance, and to increase reliability, and production productivity, and performing repairs when necessary, CBM is suggested.

Flexible Hose: the proposed tactic for the Flexible Hose in the new DMG is DOM, while in the basic DMG, FTM was suggested. Regarding the high effect of failure and high failure times that this equipment has and to justify and reduce the failures and repair times and also to reduce repair costs, DOM is suggested.

Pinch roll: the proposed tactic for the Pinch roll in the new DMF is DOM, while in the basic DMG, FTM was suggested. Regarding the high effect of failure and the high failure effect that this equipment has, and in order to justify and reduce the failures and repair times and also to reduce repairs costs, DOM is suggested.

The most important difference between the basic and new DMG is the difference of failure effects in the proposed grid; while in the basic grid, all failures have equal effect on decision making. Another difference made by the proposed approach is the tactics of six sub-equipments which are changed compared to the basic DMG. The equality of the frequency dimension in the two basic and new grids is one of the similarities of the two grids. Another similarity of the two grids is the equality of the proposed tactics for two sub-equipments of Motor and Tacho. In both grids, OTF was suggested. Another similarity is that based on the research findings, in both DMGs, the tactic of SLU was not suggested for any equipment, and that the scales of both DMGs have been calculated similarly.

Comparing the present research with similar previous researches of Fernandez et al. (2003), Aslam-zainudeenand and Labib (2011), Shahin and Attarpour (2011) and Shahin et al. (2013), this point can be mentioned that the major innovation of this study is the use of FTA for specifying the interdependency of the failures.

As it was mentioned, the value of 'k' is given by experts, hence this coefficient can be changed based on other people’s viewpoints. Therefore, it is conventional and is not a standard and predefined value, which can be one of the limitations of this research. Another limitation of DMG is that this grid is limited to two criteria of frequency of failures and MTTR values, and other criteria are not considered in this grid. Another limitation is that each of the two axes of DMG is divided into three sections and only five maintenance tactics are used in nine created cells. Another limitation of this paper is that in both basic and new DMGs cost analysis was not performed, which in turn could be an important indicator in selecting cost effective maintenance tactics.

As future study, it is suggested that based on decision making and weighting methods, a standard basis could be obtained for determining the value of 'k'. It is also suggested to consider additional maintenance indicators including cost indicators in analyzing DMG results. Furthermore, investigating the inclusion of other maintenance tactics in DMG in addition to the five regular tactics could add value to the literature.

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