Forecasting Machine Failure Using DMG and Weibull Analysis in an Automotive Industry: A Case Study

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ABSTRACT

In manufacturing or production setup, maintenance cost is one of the major portions of overall operating expenditure. It can vary between 15 to 60 percentage of overall cost for various industries including food related industries, iron, steel and other heavy industries. Such a high cost directly impacts manufacturing setup, profitability and sustainability in long run. In most of the industries, ineffective maintenance management can result in loss of capital and inefficient human resource deployment. This in turn affects the plants' ability to manufacture quality products that are competitive in the market. Various maintenance management strategies including Operate to Failure (OTF), Design Out Maintenance (DOM), Skill Level Upgrade (SLU), Condition Based Monitoring (CBM) and Fixed Time Maintenance (FTM) are used in industries for maximizing productivity. In recent years, Computerized Maintenance Management System (CMMS) has become an integral part of most of the industries so its importance and characteristics cannot be understated. While CMMS cannot live standalone, it requires some decision-making techniques to be equipped with. These techniques range from Failure Mode and Effect Analysis (FMEA) to Decision Making Grid (DMG). In this paper, concept of DMG has been applied to an automotive parts Manufacturing Industry in conjunction with Weibull analysis. Parallels are drawn between the results of DMG and Weibull analysis.

Keywords: Decision Making Grid, CMMS, Reliability, Weibull Analysis

1. INTRODUCTION

In recent times, majority of the companies emphasize on higher productivity, quality and reduction in maintenance cost for them to succeed in doing business. But with rising competition, other factors such as faster delivery, marketing and most importantly price has led to the development of industry 4.0 concept that combines automation, its integration and offers flexibility. More investment is made on the new and complex machines to get the product ready on time with the required quality. But with the increasing complexity of machines, maintenance of these equipment is getting tougher. Breakdowns and availability are the two main factors to be considered by the maintenance people. The real challenge of the modern era is to avoid unplanned and costly breakdowns and to increase the availability of the machines.

Maintenance can be defined as set of actions to identify and alleviate system degradation to an acceptable performance level after failure [1]. Current trends in manufacturing have two significant

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implications for maintenance management. First machine breakdowns not only cause the down machines to loose output, but also result in downstream machine production being lost. Second the gap has broaden between operators' technical competence and the machines' technological capabilities. This gap reduces operators' ability to adjust their own machines and do minor repairs [2].

Maintenance and Computerized Maintenance Management System (CMMS) are two widely discussed terms in industry these days. A computerized maintenance management system is mainly used to collect manual inspection lists such as measurement values and other relevant data. This data is further used in various types of trend analysis and studies. It also helps to manage various business activities such as inventory control, work orders, preventive and maintenance planning and economic analysis in companies.

CMMS provides tools for data capturing and data analysis, however, it also provide an opportunity for manufacturing managers for decision analysis based on maintenance practices in the manufacturing setup [3].

Several factors contribute towards the need of CMMS in the industry including ever increasing data regarding machines, shop floor activities and inventory control. It is pertinent to mention that use of CMMS is necessary to acquire real time data in addition to its historical data [4]. Trunk [5] has put forward many reasons for adopting CMMS software in an industry. Labib [6], and Travis and Casinger [7] have discussed about the characteristics and solutions which CMMS offers in their studies.

Suggested by Labib [6], DMG is a visual tool for decision support that monitors the performance of the worst machines based on two criteria, downtime and frequency of failures. The required data is obtained from the history stored in the CMMS's database. In the first step of applying DMG, two criteria are set: frequency and downtime. The objective of this step is to recognize the worst performing machines according to these two criteria. The worst machines in both criteria are sorted and grouped together into high,

medium and low sub groups. Once the worst machines for both criteria have been identified, the next step is to determine the boundaries in which each machine will lie. This stage is called decision mapping.

To calculate the boundaries of the decision-making grid following formulae is used.

High boundary	= highest value
Medium/High boundary	= highest value – 1/3(highest value)
Low/Medium boundary	= highest value – 2/3(highest value)
Low boundary	= lowest value

The resulting machines are then mapped onto the grid to classify machines in high, medium and low groups according to downtime and frequency of failures criteria. Based on the performance of different machines according to the grid placement, appropriate maintenance strategies are suggested [6]. Decision making grid contains nine sub grids, each point towards specific maintenance strategy. One should bear in his mind that these boundaries are not fixed. As soon as the frequency and downtime of the relevant machines decreases, new DMG is calculated. New maintenance strategies are suggested for the new or existing machines. The nine strategies in the decision-making grid are as follows [6]:

- **Operate to Failure (OTF)** The aim of DMG is to move the machines from their current location in the grid to the top left corner where equipment with both minimum frequency and downtime (OTF) is placed. This sub grid suggests that machine in this grid should not be considered on the top priority, but the machines should be operated until their failure.
- **Design Out Maintenance (DOM)** This sub grid shows which machines are the top priorities for maintenance department. In this category the machines fail too often and for long periods of time. Consequently, the strategy to apply is to redesign components and to structurally modify the machine.
- **Skill Level Upgrade (SLU)** This sub grid presents the skill level upgrade for the maintenance personnel. The machines which fall

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in this category are failing too often as compared to the other machines, but with the least downtime.

- **Condition Base Monitoring (CBM):** Machines in this category rarely fail, but with the highest downtime. As a result, it is necessary to monitor the condition of different components of the machine as a measure to prevent unexpected failures.
- **Fixed Time Maintenance (FTM):** The remaining five sub grids suggest strategies which can be considered a fine tuning of the maintenance function and the procedures. This is related to increase in the efficiency and effectiveness of maintenance function
- **FTM1:** Refers to when the maintenance function should take place and the procedures followed need to be checked.
- **FTM2:** Refers to Who will perform the maintenance task, the operator, the maintenance department or a sub-contractor.
- **FTM4 and FTM:** Refer to the what and how respectively. It basically should do with doing the things right and doing the right things.
- **FTM3:** Refers to the implementation of suitable scheduled maintenance strategies [8].

After identification of worst performing machines, related cost of maintenance action is ascertained.

In this way, DMG devises strategies according to the condition of the machine and the cost involved. This is a continuous improvement program. Burhanuddin *et al.* [9] applied decision making model using multiple criteria analysis for small and medium industries. The results were obtained from the maintenance strategies implementation in one of the SMI in Malaysia. Raw data was collected for whole year and later recommendations were given. Tahir *et al.* [10] implemented DMG with tri-quadrant clustering method and used an intelligent module in maintenance decision support system to identify maintenance strategies in SMI's. It was found out that not only there was reduction in the cost and machine downtime but also there was better reliability on daily operations and maintenance management. Shahin and Attarpour [11] developed decision making grid for maintenance policy making based on estimated range of Overall Equipment Effectiveness (OEE). Traditional DMG was modified to estimate the range of OEE and replaced by one of the grid's criteria. Burhanuddin *et al.* [12] analyzed the machine clustering for maintenance using decision making model. It was demonstrated how the downtime analysis can be conducted to cluster machines using DMG. The proposed decision model improved the accuracy of the maintenance activities for the production equipment. Aslam-Zainudeen and Labib [13] explored the applicability of DMG and its usefulness in the maintenance of rolling stock in railway industry. The advantages of using DMG in this practical application were discussed. Burhanuddin *et al.* [14] used Decision Making Grid model to identify strategies for maintenance decision. The basic model has limitation as it considers only two factors, that is, downtime and frequency of failures. Authors considered another factor of cost in their study to estimate maintenance cost. More recently, Tahir *et al.* [15] addressed the basic problem of applying DMG that is the unavailability of important data. Methods of genetic algorithms were implemented to generate optimal variable values of machine breakdown from a DMG process on observed small and medium industries to be processed into other related problematic small and medium industries.

When one talks about the maintenance of the machine, reliability factor also comes into play. The importance of reliability in the present world can never be overstated. An effective reliability program would be impossible without the collection of information and analysis. The history data of the machines helps in predicting the maintenance schedules for the machine. This not only results in good maintenance of the machine but also increase in the profit. To study the history data, statistics proves to be very helpful. Different types of statistical distributions are suggested by various authors. In the current study Weibull Analysis will be used to forecast the reliability of the machines.

Weibull distributions are used when the rate at which failures occur changes monotonically with the accumulation of service life. The Weibull model, or distribution, has two forms, a two-parameter form and

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a three-parameter form. The two-parameter distribution is more widely applied.

The Weibull distribution density function used is expressed as [16]:

$$f(t) = (\beta/\eta^{\beta})t^{\beta-1}\exp[-(t/\eta)^{\beta}], \quad t>0$$

where: $f(t)$ = fraction of parts failing
$\quad\quad$ t = failure time
$\quad\quad$ η = characteristic life or scale parameter
$\quad\quad$ β = slope or shape parameter

The parameter β is called the shape parameter and is positive. The parameter η is called the scale parameter is also positive; η is also known as the "characteristic life" and it provides a measure of the overall reliability. Whereas, the β is a dimensionless pure number [16].

The analyst can ascertain from the value of this parameter whether the failure rate is decreasing over time, constant, or increasing (Fig. 1). The shape parameter β indicates the pattern of deterioration of components in their life span.
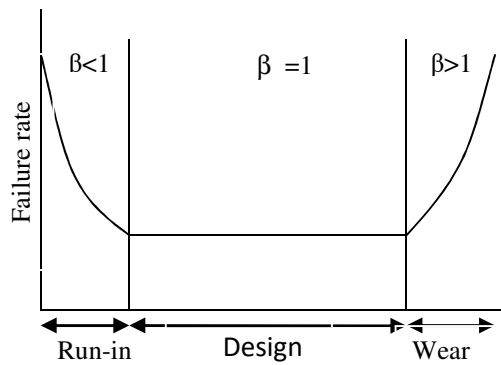

Fig. 1: Bath-tub curve

Fitzgibbon *et al.* [17] presented a method that combined Weibull analysis and statistical algorithms to forecast failures. The combined method output gave two possible dates for failure: one using the mean time to failure and the other using trend line extrapolation. The final probable date of failure was calculated using an interference probability method similar to stress-strength method. Rostum [18] performed statistical modelling of pipe failures in water networks. A computer code was developed to estimate the parameters of Power Law model and later comparison

of the results with modified Weibull proportional hazards model was done. Study of Pasha *et al.* [19] aimed at the Empirical analysis of the Weibull distribution for the Failure Data. Median rank regression for data fitting method was described and goodness of fit using correlation coefficient was applied. Singh and Suhane [20] focused their research on using Weibull analysis to know if centrifugal pump will be available for maintenance or not. Donglei *et al.* [21] proposed doubly truncated Weibull distribution for reliability analysis of NC machines.

From the literature survey there is no study that looks at the use of decision-making grid and application of Weibull Analysis to forecast the failure of machines together. In this study DMG and Weibull Analysis has been implemented in an automotive part manufacturer industry. The failure of different machines has been predicted by both techniques and similarity of the results are reported.

2. MATERIALS AND METHODS

From CMMS, ten worst equipment in terms of frequency of failure and downtime were picked as shown in Table 1.

Table 1: Ten Worst Equipment List			
Serial No.	Equipment No.	Frequency of failures	Downtime
1	016-253	627	453.90
2	016-264	383	255.28
3	158-155	340	449.10
4	254-053	353	512.03
5	165-351/7	354	400.57
6	165-352/7	430	557.94
7	252-154	392	415.21
8	252-155	333	367.79
9	254-041	299	391.74
10	252-156	338	380.01

To get more meaningful result from the application of DMG and Weibull analysis, equipment age with its corresponding name is shows in Table 2.

3. RESULTS AND DISCUSSION

Once the 10 worst machines for both criteria were identified, the next step was to determine the boundaries in which each machine would lie. Fig. 2 shows the placement of the ten identified machines in

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the DMG. Fig. 2 shows the placement of the ten identified machines in the DMG.

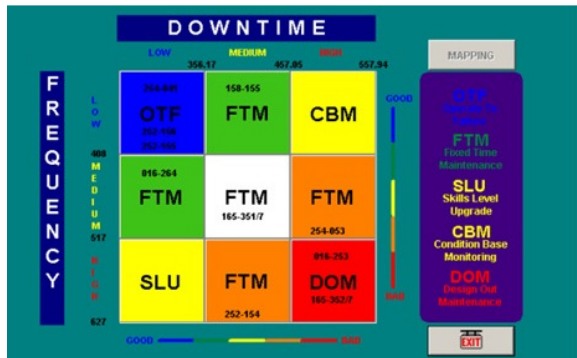| Table 2: Equipment Name and Age		
Equipment No.	Name	Age
016-253	Conveyor 1 – 6	17 years
016-264	Conveyor 7 – 12	17 years
158-155	Baltec 880	3 years
165-351/7	FPS 1 Feature grind	16 years
165-352/7	FPS 2 Feature grind	16 years
252-154	Baltec 2 (825)	6 years
252-155	Baltec 3 (825)	6 years
252-156	Baltec 4 (825)	6 years
254-041	Cell 3 press	19 years
254-053	Cell 11 press	16 years

Fig. 2: Placement of machines in the Decision-Making Grid

It was clear from DMG that the worst performing machines were 016-253 (Conveyer) and 165 – 352 / 7 (Feature Grind). To reduce the down time, it was suggested to redesign components and to structurally modify the machine. None of the machines were in CBM and SLU sub grid. Three machines were in the most ideal sub grid of OTF and those were 158 – 152 (U222 Baltec), 252 – 155 (Baltec 3) and 254-041 (Cell 3 Press). Those machines were to be operated till the failure. It is interesting to see that Cell 3 Press was 19 years old but still it was in the most desirable sub grid. It can be a case that this particular press might have been used less as compared to the other equipment of the plant. Rest of the machines were placed in FTM sub grids that require fine tuning in the maintenance procedures.

After the application of DMG, Weibull Analysis was carried out in order to see if there is any correlation between the two methods of predicting failures. The data obtained from CMMS was in very raw form. Some mathematical calculations and manipulations

were done in order to get the required parameters. For applying Weibull analysis, following assumptions were used.

- As, we are dealing with only one equipment at a time, so the sample size was taken to be the number of failures of that equipment.
- Equipment is considered to be new after the maintenance.
- The age of equipment was assumed to be average of maximum failures.
- As a datum point for time to next failure, first failure of that equipment was selected, and the next failure time is subtracted from the first failure time.

The Weibull analysis was carried out using the Reliasoft Weibull ++ Software. Fig. 3 shows the Weibull plot for calculating β and η values for Equipment number 016 - 253.
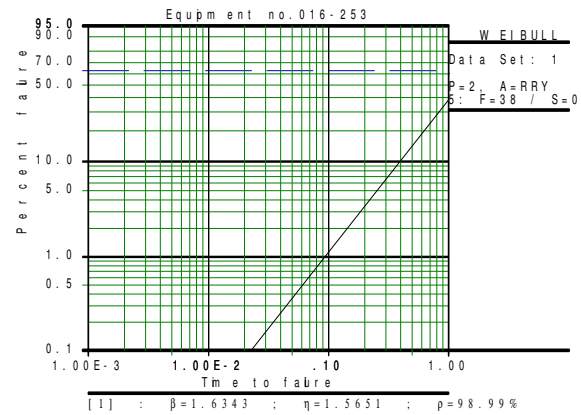

Fig. 3: Time to failure vs. percent failed

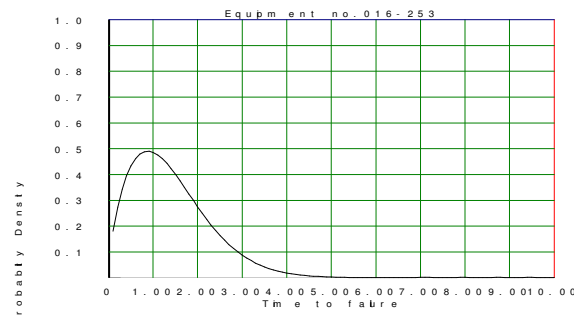Fig. 4 shows the Probability Density Function (PDF) for the equipment No. 016-253.

Fig. 4: The probability density for the equipment

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Fig. 5 gives the reliability curve of the equipment, indicating that the reliability of quipment No.016-253 is decreasing and eventually reaching to the zero value. Same software was used to get the values of β and η of other machines, which are tabulated below in Table 3.
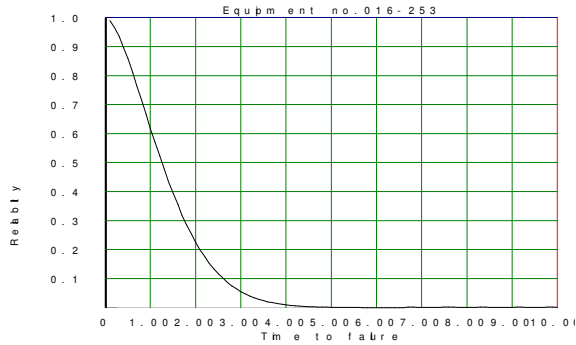

Fig. 5: Reliability curve

Table 3: β and η values of the machines		
Equipment No.	β	η
016-253	1.6343	1.5651
016-264	0.7121	29.5536
158-155	1.0271	4.3457
254-053	0.6658	31.0959
165-351/7	1.4340	3.3664
165-352/7	0.6659	25.1923
252-154	1.2662	5.8161
252-155	0.6287	31.3287
254-041	0.5857	41.4921
252-156	0.6740	32.0802

Equipment No. 016-253

The value of β is the highest in this case, which showed that it is in the wear out phase. This can be explained by working age of this equipment which is 17 years. The value of η gives the overall reliability which is the least among all the equipment. Weibull analysis for this value of β gives rise to a solution of replace policy. It is also important to mention that the same equipment was placed in the DOM sub grid of DMG.

Equipment No.016-264

This machine is same as conveyer 016-253, but the β value is less than one. The value indicates
that it is in infant mortality stage while its working age is about 17 years. This contrasting finding can be explained by the fact that it might have been redesigned with the course of time or the data set is incomplete. According to DMG this equipment is in the FTM2 sub grid with Low downtime and Medium

frequency (closer to OTF sub grid). This equipment can reach to the upper left corner of DMG grid by addressing the 'Who' issue. It has to do with, 'Who' will perform the maintenance task, the operator, the maintenance department or any sub-contractor. Minor changes to the maintenance schedules can prove its worth.

Equipment No.252-155

This is the same equipment as 252-154 but its β value is 0.6287, which tells us that this equipment is in the infant mortality phase. This is contrasting fact as compared to the equipment no. 252-154. The working age of the both equipment is about 6 years and the β values of both equipment suggest almost opposite fact. It is evident that equipment No. 252-154 is experiencing some wear out mode failures while equipment No.252-155 is in its infant mortality mode. The failure rate is decreasing with the age of the equipment. The repair only policy is useful for such kind of equipment. Similar result is seen on DMG where equipment 252 – 155 is in the most optimum sub grid *i.e.*, OTF. Weibull analysis shows that there is wear in equipment 252 – 154 and same result is obtained from DMG as well which is placing this equipment in FTM sub grid with High frequency of failure and Medium downtime.

Equipment No.254-041

Surprisingly the β value is less than 1 (0.5857), while its working age is about 19 years. It has been found out that some design changes have been made to this equipment to improve its working and reliability. Fig. 6 shows the changes done to the original design.
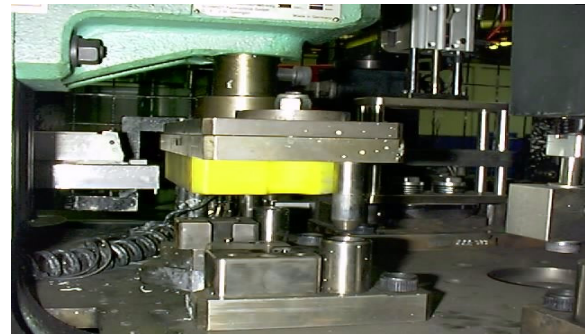

Fig. 6: Equipment No.254-041(Press)

This design change can be the reason for the lower value of β. The value of β suggests that this equipment

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is in its infant mortality region. Only reactive maintenance is a good answer to such kind of equipment. DMG is also placing it in the OTF sub grid.

Equipment No. 165-351/7

The β value is 1.4340 which is greater than 1 and the η is 3.3664. These values suggest that this equipment is in the wear out phase of its life. The η value tells us about the reliability of this equipment. As this equipment has already completed 16 years of working, so the higher value of β is expected. The Weibull analysis suggests the replacement policy according to the β value of the equipment. For the process in the plant, this equipment is very important as the overall production is decreased by quarter of the full if this equipment is down. This machine is placed in the FTM3 sub grid of DMG (Medium downtime and Medium frequency of failure) suggesting performing regular maintenance contrary to the Weibull Analysis of replacement altogether.

Equipment No.158-155

The value of β is almost equal to 1, which indicates the time independent failure. Nothing much can be done for this mode of failure. As the failure rate is almost constant. It is of no use to carry out any replacement policy for this equipment. The best practice may be to deal with the failures as they occur, because the failures are independent of time. Reactive maintenance may be regarded as a suitable policy for this equipment. DMG also suggests performing maintenance of this equipment as it is in the FTM1 sub grid. Regular Condition Monitoring can be a good option to monitor certain parameters for the equipment.

Equipment No.254-053

β is less than one (0.6658) with the η of 31.0959. Some necessary data is missing so we cannot predict the right behaviour of this equipment. DMG places this equipment in the sub grid of High downtime and Medium frequency (FTM4) that means if not maintained properly this equipment may move to the DOM sub grid (lowest leftmost corner) in the coming years of operation.

Equipment No. 165-352/7

This is the only major contradiction where the results from Weibull analysis and DMG do not match. The working life of this equipment is about 16 years and the value of β is less than 1. The value of β suggests that this equipment is in infant mortality mode whereas DMG rightly places it in the DOM sub grid. The part should be redesigned or modified in order to be operational. Insufficient data can be the main cause for such behaviour.

4. CONCLUSIONS

DMG along with Weibull analysis were carried out on data provided by CMMS of an automotive parts manufacturing industry. Ten worst machines in terms of failure and frequency of downtime were picked up from the computerized system. According to DMG result, out of the ten machines, Baltec, Baltec 3 and Cell Press were performing in the OTF (operate to failure) phase. Similar kind of result was indicated by the Weibull analysis. The β value was less than one for these equipment where-as the overall reliability η was the highest. It meant that these machines are in infant mortality phase and their failure rate will decrease with time. Conveyer and feature grind were the worst performing machines from the point of view of DMG and were placed in the lower right corner (DOM) of the grid. Again, Weibull Analysis was in agreement as it calculated the β to be greater than 1 (wear out phase) and the η to be the least than all the other machines. These machines were having failure rates that increase with time. This agreement of results using both DMG and Weibull Analysis is interesting. It can be said that from the maintenance point of view we may use any of the two methods for decision making. The main point is this to some-how bring the machines to the DMG's sub grid of OTF and to increase the overall reliability of machine. A routine regular maintenance can be useful in this kind of situation and in the worst-case scenario the machine must be replaced.

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