Optimizing Preventive Maintenance Frequency and Duration Using Mathematical Model and Fuzzy Logic in Flour Mills

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Abstract

Maintenance planning is one of the most important tasks carried out by a factory. Preventive maintenance is one type of maintenance that prevents major breakdowns from occurring. Increasing preventive maintenance duration reduces corrective maintenance duration. However, conduction of preventive maintenance causes downtime and incurs costs too. Several studies have been conducted to establish a tradeoff between these two types of maintenance to reduce the overall downtime. Models that minimize costs are preferred by industries. Besides, models requiring complex datasets are not readily adopted by most of the industries for regular use. This paper represents three different methods for optimizing preventive maintenance duration and frequency in a renowned flour mill factory of Bangladesh. The first method uses an established mathematical model which determines the optimum frequency of preventive maintenance per month, maximizing profit. This model is comparatively easier to adopt in flour mills since it does not use reliability concepts for different components, rather uses simple costs and downtime data, assuming constant failure rate. The second method modifies the existing model to optimize the duration of each PM inspection as well as frequency, which is an important parameter for flour mill maintenance. The third method uses three maintenance KPIs as inputs to determine the total duration of PM per month for the flour mills. The reason for not adopting PM models in factories is the lack of data availability and the difficulty in aligning the model with the existing maintenance plan. Besides, flour mills have components in continuous production lines which, if maintained separately, would not be profitable, rather a single PM activity should be carried out for some set hours, set by the maintenance department. The rationale behind this paper is to develop easily adaptable PM models for flour mills.

Keywords
Optimization, Flour Mill, Maintenance, KPI and Fuzzy

1. Introduction
Maintenance work is crucial for a factory. It is difficult to develop a maintenance plan and implement it that maximizes profit. The maintenance and operations departments are the largest, and each comprises 30 percent of the total manpower (Garg & Deshmukh 2002). Due to the inability to control the cost-based inputs, the consequent lack of planning and coordination may cause workers to wait for resources, incur additional material acquisition costs, or execute the work on an overtime basis (Weidner 2023).

Also, data in terms of manpower and materials employed for maintenance is exceedingly difficult to track. Maintenance scheduling is a challenging problem and distinguishes from production scheduling. About 15 to 70 % production cost is originated from maintenance activities (You et al. 2010) .

The paper is based on preventive maintenance frequency and duration optimization. Two types of maintenance are mainly conducted in industries, preventive maintenance and corrective maintenance. Preventive maintenance is conducted to prevent the probable breakdown which may result in loss of production and assets. Corrective maintenance is carried out after the fault has been recognized when the equipment faces breakdown (Stenstrom et al. 2015). On the other hand, preventive maintenance requires downtime and investment too. So, the maintenance plan is developed in such a way that it makes a tread off between these two types of maintenance. Before adopting a new strategy and plan, a factory performs a cost analysis, and the decision depends on the profit change from the plan.

Keeping all of it in mind, a mathematical model that maximizes profit by optimizing PM (Preventive Maintenance) frequency per month and duration of each activity and overall duration is best appreciated by the maintenance department. The model we used here requires downtime data and cost data corresponding to different types of maintenance, labor costs, equipment inspection costs and replacement costs, production, profit per unit output, etc. the modified model for optimizing duration of PM activity required some standard KPIs to be maintained by a specific factory which are set by the maintenance department of that particular factory.

A fuzzy based model has been used to calculate the three most used KPIs each month and then find out the optimum value of PM duration for the whole flour mill to be maintained in the following month. The KPIs used in this model are Unscheduled Downtime Percentage, Reactive work percentage and Maintenance cost percentage. By doing so, the factory can adjust the KPIs to the standard set values by adjusting the PM activities. For determining the overall PM duration, a mathematical model can result in inappropriate values. Therefore, a fuzzy based model is used in this case. The model is cost effective and user friendly. This research has three objectives, including, calculating optimal value of PM frequency per unit time using an already established model, calculating optimal frequency and duration of PM by modifying the model and calculating overall PM duration for three KPI values set by the maintenance department.

1.1 Objectives

The study aims at maximizing the profit earned by a renowned flour mill factory in Bangladesh by optimizing PM frequency and duration per month for mechanical maintenance. First, the inspection optimization model proposed by Dhillon, is used to calculate the optimal PM frequency. The objective is to optimize both frequency and duration by modifying the model with some constraints implied on the objective functions. The results should suggest that the modified model increases the profit. Another objective of the study is to develop a simple fuzzy rule-based model to determine duration for overall PM per month by using the three most used maintenance KPIs for the flour mills.

2. Literature Review

One of the first proactive strategies employed since the study of maintenance systems began was PM strategy. Artificial intelligence (AI), simulation, mathematical formulation, matrix construction, critical analysis, and multi-criteria technique have been used to examine efficacy in the majority of studies. While study trends on planning and strategies for PM reveal that there have been variances of methodologies employed over the years from the early '90s to the present, in practice, PM activities tend to be planned based on cost, time, or failure. After failure was recognized as something that needed to be prevented, preventive maintenance was introduced in the 1950s.

Xinlong Li used a hybrid hazard rate model of a multicomponent system having imperfect preventive maintenance, to develop an equal cycle preventive maintenance model (Li et al. 2021). The optimum replacement interval time for critical components and availability value for shifter machines in a flour mill was determined using goodness of fit test and reliability model (Wahyukaton 2020). A fuzzy logic model was used to select optimum maintenance strategies for the Jordanian food industry using statistical analysis for weight of importance (Meanazel et al., 2020). Angels proposed an original approach for determining optimal inspection intervals of mining equipment based on a reliability-based model instead of a typical physical age interval suggested by equipment manufacturers (Angeles & Kumral, 2020). A reliability-based and dynamic programming-based mathematical model was used by Percy (Percy & Kobbacy, 2000) and Vaughan (Vaughan 2005) in two papers to determine optimal PM interval. A reliability based mathematical formulation was used to determine optimal PM interval which minimized costs per unit time (Mijailovic, 2003). Fuzzy rules were used to optimize PM interval based on minimizing total PM cost (Khanlari et al. 2008).

We can infer from the past study that researchers aiming to achieve PM planning goals have given AI and mathematical formulation a great deal of attention. Theoretically, artificial intelligence (AI) and mathematical formulations involve sophisticated calculations that pose challenges for industrial practice. For instance, deploying AI calls for specialists and analysis software. Data issues in the real world will have an impact on the actual operational status of a process, and mathematical formulation is dependent on data (Basri et al., 2017). Therefore, a straightforward strategy that is also relatively simpler to create is required for usage in actual industries. Reliability-based models need a large amount of past data which is not easy to gather and can generate erroneous results. While some studies consider economic factors, such as maintenance costs, they may not fully capture the comprehensive cost analysis associated with maintenance optimization. They did not consider the cost of downtime, spare parts inventory costs and labor costs altogether (Murthy et al. 2002).

Most of the models are complicated, which deters factories from implementing them for everyday use. A component of the managerial perspective is PM planning, which calls for objectives, planning, and methodologies to be taken into account before PM is implemented on a system (Basri et al., 2014). It is important to have appropriate objectives, planning, and methodologies to assist the process of creating and refining PM planning by offering better knowledge and appropriate recommendations (Basri et al. 2017).

Even though some studies take economic considerations into account, such as maintenance expenses, they might not adequately represent the thorough cost analysis connected with maintenance optimization. They failed to take into account the total cost of labor, inventory expenses for spare components, and downtime.

3. Methods

3.1 Sequential Steps

The following steps were followed to carry out this research:

1. Going through research papers related to preventive maintenance and finding research gap
2. Developing models that are applicable in real life
3. Choosing appropriate data source required for our models
4. Analyzing existing maintenance policies and plans
5. Collecting data
6. Sorting data
7. Running models
8. Analyzing models

3.2 Inspection Optimization Model

Using this methodology, the optimal inspection frequency to optimize profit can be determined. The facility or equipment that needs maintenance will have no output, which will result in lower profit, according to the model. Additionally, there is a risk that excessive equipment inspections will result in costs that are higher than those caused by breakdowns owing to things like lost output, increased material costs, and wage costs.
This model assumes the following: –

The equipment failure rate is a function of inspections.
Times to inspection are exponentially distributed.
Equipment failure and repair rates are constant (Dhillon, 1983)
We can assume constant failure rate for our study because the mill components are in the flat part of the bathtub curve as they are in the useful life period. The equipment's life is long enough so consider this scenario (Alexandria, 1975). The following equation of profit is used in this paper to maximize the profit, where n is variable PM frequency per month for mechanical maintenance of the flour mill.

$$\text{Profit} = p - PL_i - PL_r - IC - RC$$

$$= p - \frac{pn}{\theta} - \frac{p\lambda(n)}{\mu} - \frac{nC_i}{\theta} - \frac{C_r\lambda(n)}{\mu}$$

$= p - \frac{pn}{\theta} - \frac{pfe^{-n}}{\mu} - \frac{nC_i}{\theta} - \frac{C_r fe^{-n}}{\mu}$

By differentiating with respect to n and then equating it to zero,

$$\frac{d\,\text{Profit}}{dn} = -\frac{p}{\theta} - \frac{p}{\mu}\frac{d\lambda(n)}{dn} - \frac{C_i}{\theta} - \frac{C_r}{\mu}\frac{d\lambda(n)}{dn} = 0$$

$$\frac{d\lambda(n)}{dn} = -\left[\frac{1}{\theta}\,(p + C_i)\right] \div \left(\frac{p}{\mu} + \frac{C_r}{\mu}\right)$$

Assuming the failure rate of a manufacturing system is,

$$\lambda(n) = fe^{-n}$$

$$-fe^{-n} = -\left[\frac{1}{\theta}\,(p + C_i)\right] \div \left(\frac{p}{\mu} + \frac{C_r}{\mu}\right)$$

The optimal value of n,

$$n^* = \ln\left[\frac{f\theta(p + C_r)}{\mu(p + C_i)}\right]$$

n = number of inspections performed per unit of time,

$1/\theta$ = mean of exponentially distributed inspections times,

p = profit at no downtime losses,

C_i = average inspection cost per uninterrupted unit of time,

C_r = average repair cost per uninterrupted unit of time,

λ = equipment failure rate,

μ = equipment repair rate,

PL_i = production output value loss per unit of time due to inspections.

PL_r = production output value loss per unit of time due to repairs.

IC = inspection cost per unit of time,

RC = repair cost per unit of time.

3.3 Modified Optimization Model

In this case, the optimal duration of a PM activity (inspection) is also calculated to maximize profit. The equation remains the same. In addition to that, some constraints are applied to the function. The constraints are related to the minimum duration to be maintained for a single inspection and the maximum total downtime percentage; not to be crossed. Both values are set by a particular maintenance department. is a KPI (Key Performance Indicator) of the maintenance conducted by the industry's maintenance department. It can be applied to a particular organization. It can also maximize the profit, giving an optimal value. Solving this optimization problem will give us three variables' optimum values, n (inspection frequency per month), (mean duration of a single inspection), and (equipment repair rate). The objective function has four components of costs that are subtracted from profit. If n increases, two of these cost components increase, and two of them decrease. It is because the more frequently we conduct inspections, the fewer breakdowns will occur but at the same time, inspection-related costs will increase. Similarly, if we increase the inspection duration, two cost components increase, and two decrease.
Maximize,

Profit = $p - PL_i - PL_r - IC - RC$

$$= p - \frac{pn}{\theta} - \frac{pfe^{-n}}{\mu} - \frac{nC_i}{\theta} - \frac{C_r fe^{-n}}{\mu}$$

Subjected to,

$\mu > 0$

$n \geq 1$

$\frac{1}{\theta} \geq MPMT_{min}$

$\frac{fe^{-n}}{\mu} + \frac{n}{\theta} = TDT_{max}$

f, C_i, C_r, p are constant

$n, 1/\theta$ and μ are variables

$MPMT_{min}$ = Minimum Mean Preventive Maintenance time required for the system; each time PM is carried out; set by the Maintenance Department
TDT_{max} = Maximum total downtime for Preventive and Corrective Maintenance to be maintained, set by the Maintenance Department.

3.4 Preventive maintenance duration per month using fuzzy logic
Three maintenance KPI are used here as inputs to calculate the preventive maintenance duration per month, they are

1. Unscheduled Downtime Percentage
2. Reactive work percentage
3. Maintenance cost percentage

Input 1: Unscheduled Downtime Percentage
Unscheduled Downtime Percentage = $\frac{\text{Unscheduled Downtime}}{\text{Total Operating Time}}$ (Borley 2019)
Unscheduled Downtime Percentage, if less than 5%, then low and greater than 20%, then high

Input 2: Reactive work percentage

Reactive work percentage = $\frac{\text{Total Corrective Maintenance Time}}{\text{Total Maintenance Time}}$ (Borley 2019)

The flour mill maintains a corrective maintenance percentage which doesn't exceed 20% and overall preventive maintenance duration which doesn't exceed 48 hours (about 2 days) a month, that is 48*100/ (24*30) or 6.67%. According to the maintenance department of this factory, preventive maintenance time should not be less than 16 hours a month, that is 16*100/ (24*30) or 2.22%. If less than 42.84%, then RW% is low and if greater than 90%, then RW% is high

Input 3: Maintenance cost percentage

Maintenance cost percentage = $\frac{\text{Total maintenance cost}}{\text{Total Replacement Asset Value (RAV)}}$ (Borley 2019)

Output: Preventive Maintenance Duration
Mean duration of single preventive maintenance. In the flour mill factory from which we collected data for this paper, PM is done for at least 16 hours a month, but not more than a day is suggested. If less than 16 hours, then the mean PM time is low. If greater than 16 hours and less than 24 hours, then PM time is medium and if more than 24 hours, then PM time is high.

4. Data Collection

The maintenance department has several sections, such as mechanical maintenance, electrical maintenance, etc. We gained knowledge of how they perform maintenance currently, why they do it this way and what they are ready to adopt. The experts also gave insights on how maintenance in flour factories differs from other factories. The data was from January 2022 to October 2022 and source type was daily and monthly report. The following tables (Table 1, 2) show the sorted data obtained from raw data, collected from the industry, using Microsoft Excel Sheets.

Table 1. Data table for mill A and B

		Mill A	**Mill B**	
Productivity		500	550	tons per day
Repair costs per month	C_r	1050	1065.821111	BDT per month
Inspection costs per month	C_i	11534.87889	8340.500444	BDT per month
Number of inspections performed per month	n	1	1	PM per month
Mean preventive maintenance time		7.2	7.2	hours per month
Mean of exponentially distributed inspections times	$\frac{1}{\lambda}$	7.2	7.2	hours per month
		0.01	0.01	months
Breakdown hours per month		12.022222	8.233333	hours per month
Number of breakdowns per month		8.111111	8.566666	breakdowns per month
Equipment repair rate	μ	0.674676	1.039136	repairs per hour
Mean time to repair one breakdown	$\frac{1}{\mu}$	1.482191	0.962337	hours
		0.002058	0.001336	months
Number of breakdowns when no inspection done	f	21.768404	22.964360	breakdowns per month
Profit at no downtime losses	p	60000000	66000000	BDT per month
Profit considering downtime losses	profit	58410733.03	64594684.1	BDT per month

5. Results and Discussion

To obtain results from the three methods, MATLAB software was used. The modified model (Method 2) results in higher profit. As it considers all the possible variables in the objective function and optimizes them, it gives a better result. The graphical output from fuzzy inference system gives optimal combinations of three KPIs to be maintained for a better performance.

5.1 Numerical Results

Using the first method, optimal PM frequency per month is one for both mill A and B for a Mean Preventive Maintenance time of 7.2 hours, set by the maintenance department. The modified method results in an optimal PM frequency of one and an optimal Mean Preventive Maintenance time of 4.824 hours for both mills. The following table (Table 3) shows the obtained results from the modified model.

Table 2. Results from two methods

Variables	**Mill A**	**Mill B**
Preventive maintenance frequency per month	1	1
Mean preventive maintenance time (MPMT)	4.824 hours	4.824 hours
Equipment repair rate	16.3 repairs per hour	9.5 repairs per hour
Mean time per breakdown	0.06 hours	0.1 hours
Profit from existing model	5.84×10^7 BDT per month	6.45×10^7 BDT per month
Profit from modified model	5.95×10^7 BDT per month	6.54×10^7 BDT per month

5.2 Graphical Results

We have two inputs with triangular distribution and one with trapezoidal distribution. So, a total of 3X2X3 or 18 rules are to be generated. We only used AND operator in this case. For input 1, 3 and output, triangular distribution is used, and for input 2, trapezoidal function is used. It's because triangular and trapezoidal functions are suitable when the fuzzy sets have crisp boundaries and the shape and data is not complex. The following figures (Figure 1, 2 and 3) represents the surface generated using MATLAB for PM duration per month.

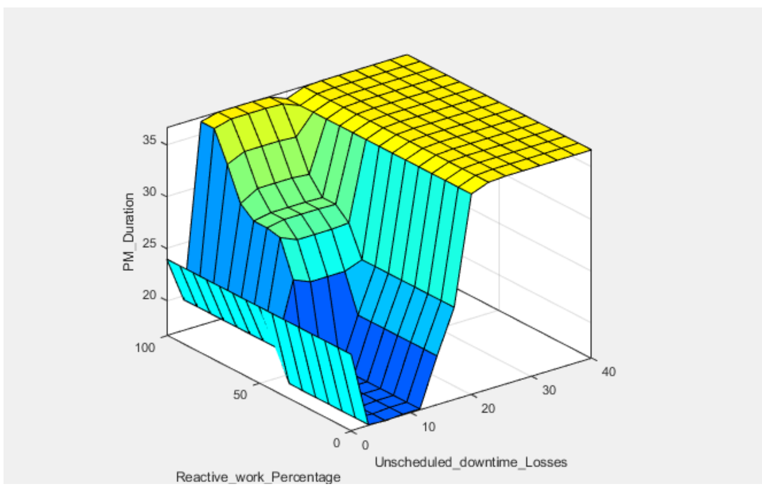

Figure 1. Surface for unscheduled downtime losses and reactive work percentage

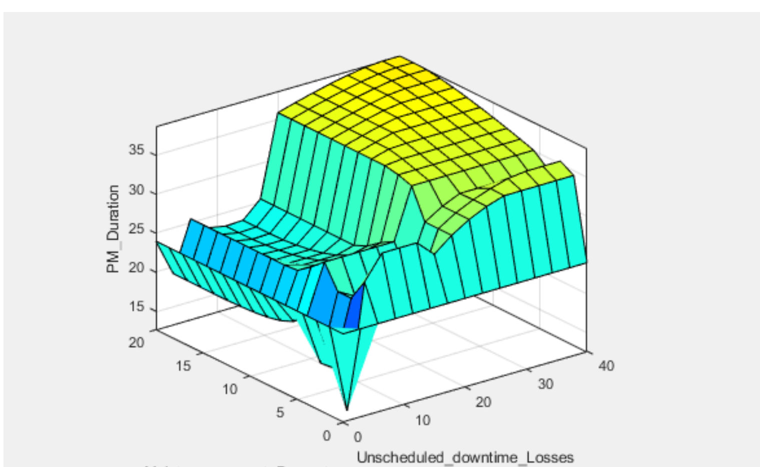

Figure 2. Surface for unscheduled downtime losses and maintenance cost percentage

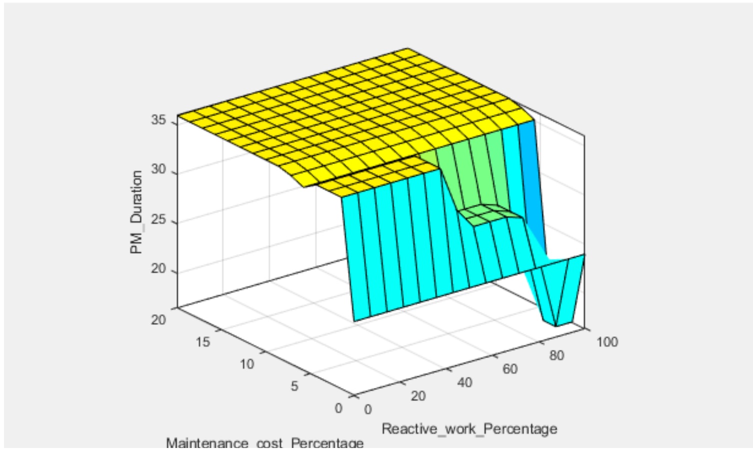

Figure 3. Surface for maintenance cost percentage and reactive work percentage

The following table (Table 3) shows some output values for random values for three inputs.

Table 3. Overall PM duration per month for different KPIs values

Inputs			**Outputs**
Unscheduled Downtime Percentage	Reactive work percentage	Maintenance cost percentage	PM duration
3.68	20.24	4.84	16.2
4.96	36.9	3.57	16.5
12.6	29	10.4	17.2
3.04	13.9	4.05	17.1
3.04	30.6	6.43	16.3
20	50	10	35.9

6. Conclusion

The flour mill factory can save a large amount of profit y reducing the mean preventive maintenance time to an optimal value by implementing the modified model, using two KPIs. They can also determine the overall preventive maintenance duration to be maintained for the following month, for a mill using current KPIs values as inputs in fuzzy model.

As factories tend to implement models which are cost effective, the modified inspection model can be a well suit in industries. By implementing this model, they can maximize the profit considering all the variables necessary for the profit calculation. Besides, they can implement current constraints in their model which will give them an appropriate output aligned with the factory.

Some of the Future works can include, determining optimal KPI values for individual components of a flour mill. The maintenance departments set KPI values. However, techniques for determining their optimum values can be developed. Another scope for future work can be using other KPIs for fuzzy inputs rather than the major three ones.
The flour mill factories can optimize preventive maintenance frequency and duration by using the modified inspection model and the fuzzy logic-based model. Also, factories who maintain a maximum downtime percentage and minimum mean preventive maintenance time, can also implement this model in their factories.

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Biographies

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