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A Periodicity Metric for Assessing Maintenance Strategies

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Abstract

The maintenance policy in manufacturing systems is devised to reset the machines functionality in an economical fashion in order to keep the products quality within acceptable levels. Therefore, there is a need for a metric to evaluate and quantify function resetting due to the adopted maintenance policy. A novel metric for measuring the functional periodicity has been developed using the complexity theory. It is based on the rate and extent of function resetting. It can be used as an important criterion for comparing the different maintenance policy alternatives. An industrial example is used to illustrate the application of the new metric.

Keywords

Maintenance, periodicity, complexity, manufacturing systems

1 INTRODUCTION

1.1 Problem description

Manufacturing systems are planned, controlled and maintained with the objective of supplying products with predetermined quality level and maximizing capacity utilization. The system features and capabilities are designed a priori. At the beginning a manufacturing system performs as designed. As time passes, the machines age and un-planned failures occur causing the system performance to drift away from its initial state. Therefore, the function of a manufacturing system must be periodically restored, which is practically achieved by the maintenance operations. This periodic resetting is performed to ensure that the machines are kept in an acceptable condition throughout their useful life. Therefore, it can be said that one of the main outcomes of the maintenance action is introducing periodicity into manufacturing systems and re-initialize their functional state. Nevertheless, there is a lack of reported literature that assesses maintenance from a periodicity perspective. Furthermore, a metric is required to evaluate the effectiveness of maintenance strategies and support decisions regarding designing a new maintenance policy or re-designing an existing one in response to changes in the manufacturing system. Such strategies and metrics should be simple to use to facilitate its application in today's changeable and reconfigurable manufacturing environment [1].

1.2 Literature Review

Maintenance in manufacturing systems has to provide the required machine reliability, availability, efficiency and capability [2]. The current research is focused on the administrative maintenance actions at the policy level rather than its detailed technical aspects at the machines level and proposed general approaches and high level metric, which are not restricted to certain type of machines, systems or industry. The maintenance actions are normally classified as shown in Figure (1) [3] :

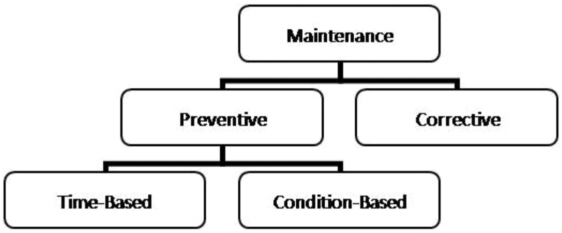

Figure 1 Classification of Maintenance Actions

Corrective maintenance includes all actions performed as a result of failure to restore an item to a specified working condition, while Preventive Maintenance (PM) includes all actions performed on operating equipment to restore it to a better condition [4]. The maintenance strategy is a structured combination of the above mentioned maintenance actions [2], which describes the events (e.g. failure, passing of time, certain machine condition, etc.) and the type of action they trigger (i.e. inspection, repair, maintenance or replacement). The literature contains more than thousand maintenance policies/strategies [5], which can be categorized as follows:

Age dependent PM polices: the PM actions (minimal, imperfect or perfect) are triggered by the age of the component such as (T, n) policy [6].

Periodic PM policies: the PM are pre-planned at fixed time intervals [7] and [8].

Sequential PM policies: PM is carried out at age dependent decreasing time intervals [8, 9].

Repair number counting and reference time policies: the maintenance action depends on the number of previous failures and the item's age at the time of maintenance [5].

Failure limit policies: the PM is carried out when the unit failure rate or reliability indices reach a predetermined level. The intervening failures are corrected by repairs [10].

Reliable evaluation methods are needed to compare the effectiveness of these numerous and diverse maintenance policies/strategies. Different criteria have been used in the literature to assess maintenance strategies such as cost, [11], Availability [12], Reliability [13], and quality [14].

This brief overview of the existing maintenance evaluation methods and criteria highlights the need for a new criterion to evaluate the main role of maintenance strategies in defining the required and sufficient frequency and extent of the maintenance actions.

2 MAINTENANCE STRATEGIES AND PERIODIC SYSTEM COMPLEXITY

The main task of maintenance is to periodically reset the manufacturing system either by repairing failures or by PM. This resetting should be defined in terms of specific parameters that are related to functionality such as production rate or available capacity, and/or physical parameters such as machine tool power efficiency. The notion of periodic resetting in the functional domain has been defined by Suh [15] as a mechanism to reduce complexity and to restore the desired state of operation. Suh [16] explained that introducing functional periodicity transforms the combinatorial complexity into periodic complexity which serves to ensure long term stability for engineered and natural systems. In this context, complexity is defined as a measure of the uncertainty in satisfying the system functional requirements and is measured by the information content. It is defined as follows [16]:

$$I_{sys} = -\sum_{i=1}^{m} \log_2 P_i \tag{1}$$

Where I_{sys} Information content of the system

m Number of functional requirements, FRs

P_i Probability that a function requirement, FR_i, is satisfied.

The complexity is categorized by Suh [17] as shown in Figure (2):

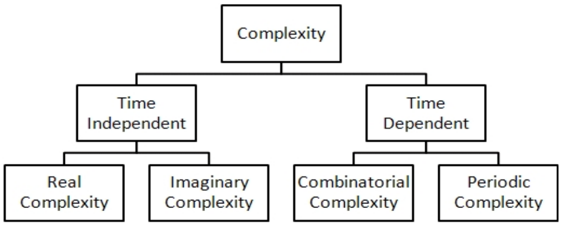

Figure 2 Complexity Categorization

The 'periodicity' causes the deteriorating functions to exhibit a cyclic behavior that restores their desired characteristics periodically. Therefore, periodicity re-initializes the system functionality to a "like new" state, which assures a high degree of functional certainty. Hence, introducing periodicity reduces, if not eliminates, uncertainty and consequently decreases the complexity associated with combinatorial complexity. Lee [18] introduced many examples of periodicity in systems from different fields including manufacturing systems. The deterioration of manufacturing systems performance is characterized by a time varying system range and may be considered as a time dependent complexity. Hence, carrying out maintenance actions would serve to re-set the system performance characteristics.

It is clear from this discussion that periodicity is important for the long-term system functionality. However, how often a system should be reset, to what extent the design parameters should be re-set, what is a desirable level of periodicity and at what cost, remain un-answered questions. Another important question is how much periodicity does exist given a certain maintenance regime and how much periodicity is needed to achieve the desired functionality goals? Therefore, a metric to quantify the amount of required periodicity is needed to help design new and effective maintenance strategies and evaluate existing ones.

3 MAINTENANCE MODELING

In order to develop a periodicity metric for evaluating the maintenance strategies, it is necessary to establish a model to define the maintenance strategies. To date, there is no systematic and mathematically consistent method for modeling the maintenance strategies. The known policies are currently described in a textual non-mathematical form. Therefore, there is a need to develop a mathematical methodology for modeling maintenance strategies.

In this research, the main focus is placed on the time-based maintenance strategies because they are the most commonly used in industry. The developed Maintenance policies, reported in the literature, and the maintenance strategies applied in industry, indicate that there are two sub-strategies for any maintenance policy:

- The failure repair sub-strategy describes when to repair the failure and the level of repair.
- The PM sub-strategy describes the number of PM classes and their levels.

Therefore, the maintenance strategy can be fully determined by defining the five criteria shown in Table 1. The first two criteria determine the failure repair sub-strategy and the last three determine the PM sub-strategy. Since the failure is normally repaired when it happens (assuming that a perfect failure detection system is in place), the first parameter is excluded from the proposed model. The repair / PM level is represented by a continuous real variable in [0 , 1] range where 0 means restoring the machine to its state just before failure and 1 means restoring it to the original new state [19].

Maintenance . Strategies Subcategories	Defining Criterion	Maintenance Policy Parameter
Failure Repair	When to repair a failure?	
	Repair Level	RL
PM	Number of PM classes	N
	Frequency of carrying out each PM class	$PMF_1,\ldots,PMF_N$
	Level of each PM class	$PML_1,.,.,PML_N$

Table 1 Maintenance Strategy Parameters

4 PERIODICITY MODELING

The periodicity is a result of a resetting plan. Each resetting action re-initializes the system functionality, according to a certain pattern (plan). A system may mean a single machine or a whole manufacturing system but the current research considers the case of single machines, therefore, the resetting plan means the machine maintenance policy. The two words machine and system will be used interchangeably in the remainder of this article. First, the case of a single resetting plan is introduced and the formula for the resulting periodicity is developed. Then, the periodicity resulting from multiple resetting plans is investigated.

4.1 Periodicity of Single Resetting Plan

A resetting plan has two essential dimensions that completely define it:

- Frequency of resetting.
- Extent of resetting which expresses the level of re-initialization

These two aspects are illustrated in Figure (4) where different resetting levels are shown with a time between resetting, T.

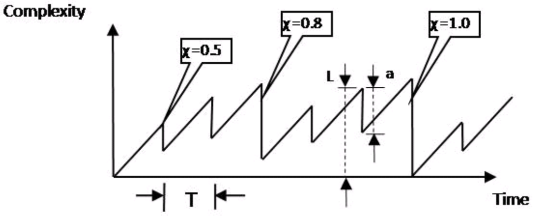

Figure 4 Resetting Frequency and Level

The resetting level is represented in the figure by the ratio $\frac{a}{L}$ where *L* is the total system complexity before the resetting process, and *a* is the amount of complexity actually recovered by the resetting process. The resetting frequency represents the number of resettings per unit time which is expressed as 1/T. It assumes real values in the range [o, ∞] where 0 means no resetting at all and ∞ means system resetting at infinitesimal time intervals. The resetting extent quantifies the amount of resetting and it can be expressed by the following relationship:

$$\text{Resetting Extent}=\frac{\text{amount of resetting}}{\text{amount of full re-initialization}} \tag{2}$$

Where the amount of resetting for any machine functional parameter (such as production rate, availability, etc.) is defined as the difference between the value of the parameter before and after resetting. Furthermore, to make the resetting extent measure more generic and dimensionless, it is expressed in terms of the uncertainty of fulfilling the functional requirement, which represents complexity [16]. Therefore, assuming the complexity related to a defined functional requirement, such as availability [20] of a new system to be zero (i.e. designed system fulfills the specified functional requirement), then the resetting extent is expressed as:

$$\begin{aligned}\text{Resetting Extent}&=\frac{\text{complexity before resetting}-\text{complexity after resetting}}{\text{complexity before resetting}}\\&=1-\frac{\text{complexity after resetting}}{\text{complexity before resetting}}\end{aligned} \tag{3}$$

For simplicity, we will assume that the complexity increases linearly with rate υ, however, other patterns may be used. The complexity change in the presence of a resetting plan with time between resetting *T* and resetting extent χ is shown in Figure (5).

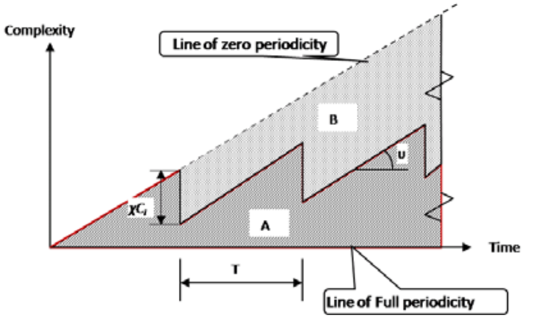

Figure 5 Complexity versus time with resetting policy (T, χ)

When there is no periodicity (*pr* = 0, combinatorial complexity case), the complexity continues to increase without resetting as represented by the dashed line (line of zero periodicity). The other theoretical extreme is when the system is fully reset at infinitesimal time periods such that its complexity is always zero (pr =∞,) and is represented by the line of full periodicity. Therefore, as the periodicity increases, Area B increases and area A decreases. The periodicity is, therefore, expressed as:

$$pr=\lim_{t\to\infty}\frac{Area\ \mathrm{B}}{(Area\ \mathrm{A})\times \mathrm{t}} \tag{4}$$

The area A can be expressed by the following relationship:

$$A=\sum_{i=1}^{\infty}T\chi' C_{i-1}+\frac{\upsilon T^2}{2} \tag{5}$$

Where: C$_i$ complexity at time *iT* where *i* represents the number of resettings

χ' = (1- χ)

Where the complexity at any time *iT* is described by the following relationship:

$$C_i=\chi' C_{i-1}+\upsilon T \tag{6}$$

Where: *T* time between resetting

υ Complication rate

The *complication rate* is a new term introduced in this research to expresses the rate of increase of complexity. It is a property of each machine that depends on the rate of functionality deterioration. It is represented in Figure (5) by the slope of the complexity line. After mathematical manipulation, the following relation can be derived:

$$pr=\frac{1}{2T(\frac{1}{2}+\frac{1}{1-\chi'}-1)}=\frac{1}{T(\frac{2}{1-\chi'}-1)}=\frac{1}{T(\frac{2}{\chi}-1)}=\frac{\beta}{\frac{2}{\chi}-1} \tag{7}$$

Where *β* = *1/T* stands for resetting rate. The periodicity relationship is plotted in Figure (6) where each curve represents the relation between resetting extent and the corresponding time between resetting at a certain periodicity level.

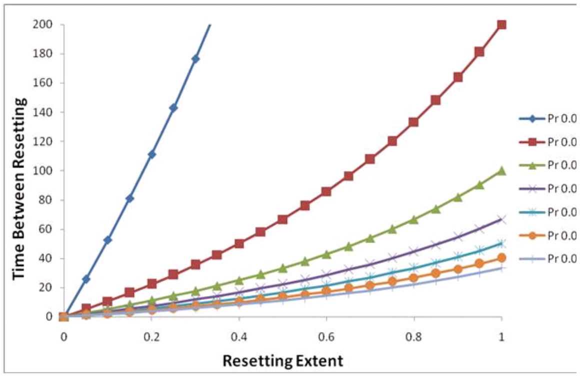

Figure 6 Resetting Extent versus Time between Resetting at Different Periodicity Levels

4.2 Multiple Reseting Plans

Most real systems are reset using multiple resetting plans. These plans can be independent or dependent. In this research independent resetting plans are considered. The independency condition makes it possible to express the total periodicity as a summation of all the periodicity elements. Therefore,

$$pr = \sum_{i=1}^{n} pr_i = \sum_{i=1}^{n} \frac{1}{T_i\left(\frac{2}{\chi_i} - 1\right)} \tag{8}$$

5 PERIODICITY-BASED MAINTENANCE POLICY EVALUATION

The periodicity due to maintenance programs, introduced by two independent sources; the Failure Repair and the Pre-planned PM, will be evaluated.

5.1 Failure Repair Periodicity

The machine periodicity due to failure repair is calculated assuming the machine has a known failure rate λ. It is assumed that the machine is repaired (i.e. functionality reset) as soon as it fails, which is the common practice in industry. Therefore, the resetting rate is the same as the failure rate λ. Using Equation (3), it can be stated that:

$$\begin{aligned}&\text{complexity after resetting} = (\text{1-Resetting Extent})\\ &\qquad\qquad\times\text{complexity before reresetting}\end{aligned} \tag{9}$$

The resetting extent, in the maintenance context, is represented by the repair/maintenance level (more information about the different imperfect maintenance modeling approaches can be found in Pham and Wang [19]). Therefore, the failure repair periodicity can be expressed by the following equation:

$$pr_{rep} = \frac{\lambda}{\frac{2}{RL} - 1} \tag{10}$$

5.2 Preventive Maintenance Periodicity

PM is the main source of periodicity when the maintenance strategy calls for minimal repair of failures. The machine is reset with each PM, therefore, the resetting rate is the same value as PM frequency (PMF) and the periodicity extent is expressed by the level of PM (PML). Therefore, the periodicity resulting from the PM of *n* classes can be described by the following relationship:

$$pr_{PM} = \sum_{i=1}^{n} \frac{PMF_i}{\frac{2}{PML_i} - 1} \tag{11}$$

5.3 Total Maintenance Policy Periodicity

From Equations (10) and (11), the total system periodicity resulting from a given maintenance policy can be expressed as:

$$pr = \frac{\lambda}{\frac{2}{RL} - 1} + \sum_{i=1}^{n} \frac{PMF_i}{\frac{2}{PML_i} - 1} \tag{12}$$

Therefore, given the maintenance policy parameters, *RL*, *PML*$_i$, and *PMF*$_i$ and the machine failure rate λ, the maintenance policy periodicity can be calculated. This calculated periodicity (*pr)* is a measure of the relative ability of the maintenance strategy to reset the machine functionality.

6 ILLUSTRATING EXAMPLE

In the following example, the maintenance policy used at an auto manufacturer assembly plant is used to illustrate the application of the proposed new approach. The plant maintenance policy can be described as follows: When a machine fails, it is instantaneously minimally repaired to quickly restore the production. The PM policy comprises four classes; between shifts: weekly, semi-annual, and annual. Each PM class has associated courses of action for each machine. The exact determination of maintenance level for each maintenance class requires historical data. Nevertheless, based on the courses of action in each maintenance class, the maintenance levels are estimated to be 0.05, 0.3, 0.6, and 0.95 respectively. The plant operates two shifts per day, five days per week. One shift is considered the time unit. Using the proposed maintenance modeling approach, the plant maintenance strategy can by fully described by the following parameters, given in Table (2):

Repair Level	RL	0			
Number of PM Classes	N	4			
PM Frequency	PMF$_i$	1.0 Between shifts	0.1 Weekly	0.004167 Semi-annually	0.002083 Annually
PM Level	PML$_i$	0.05	0.3	0.6	0.95

Table 2 Original maintenance plan parameters

This maintenance strategy applies to every resource/machine in the plant. One of these resources is a frame-welding robot which experiences random failures with an average of one failure/week. The amount of functional periodicity introduced by this maintenance strategy is calculated using Equation (12) to be 0.047. This periodicity measures the relative ability of the maintenance strategy to re-initialize the robot functionality. This measure is relative because it has no physical embodiment, but it is useful when used to compare different maintenance strategy alternatives.

The company is considering a new alternative maintenance strategy described by the following parameters (Table 3):

Repair Level	RL	0			
Number of PM Classes	N	4			
PM Frequency	PMF_i	0.5 Daily	0.025 Monthly	0.0083 Quarterly	0.002083 Annually
PM Level	PML_i	0.1	0.3	0.5	0.95

Table 3 Suggested maintenance plan parameters

Using Equation (12), the periodicity of the new maintenance strategy is calculated to be 0.065.

Since $pr_2 > pr_1$, Therefore, the proposed new maintenance policy provides more periodicity of resetting the machine(s) functionality than the original policy. Hence, it is more capable of reducing the combinatorial complexity which leads to more stable system that is more certain to satisfy its functional requirements. It is important to notice that this conclusion is based only on the periodicity/complexity. But, in real life cases, there may be other criteria to be included in the decision.

7 DISCUSSION AND CONCLUSIONS

Maintenance in manufacturing systems introduces periodicity, which is required to keep the system functional stability throughout its life. A novel general metric for quantifying the periodicity has been presented and developed. A formula for calculating the periodicity introduced by a maintenance policy is derived. A new term called *complication rate* has been introduced to measure functional deterioration. The proposed periodicity metric can be used to quantitatively compare the resetting ability of different maintenance policies, which combined with other performance metrics like cost, availability and quality can vastly enhance decision making in selecting appropriate maintenance strategies.

It has been shown that the calculation of periodicity introduced by a maintenance strategy, using the proposed model and formulation, is quite simple and makes it practically applicable in industry. Although the application of the developed periodicity metric has been discussed in the context of the engineering/manufacturing maintenance field; nevertheless, the method is general enough and can also be applied in any application that involves system resetting such as natural and political systems.

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