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Numerical Modelling For Predictive Maintenance in Sequentially Configured Manufacturing Systems and Assemblies

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Abstract: *Numerical modelling for predictive maintenance deals with the capturing and recording of process variables during operational phasesof multi-machines configurations intended for maintenance driven decisions. This imply that the design phase of this lean manufacturing strategy draws from the anticipated process conditions and logics of operation of the assembly. In order to investigate the possibility of this proposition, the study conducted twocombinatorial simulationsfor both series and parallel multi-machines configuration. This simulation was done in order to support the proposition of the application of numerical modelling in the area of predictive maintenance. The results of the simulations were tabulated and process sequence graphs were generated to indicate the trend of individual machines performance and the effect of a single machine's poor performance on the entire configuration. The two simulation graphs thus indicate the linearity of the series configuration and the exponentiality of the parallel configuration and further indicated the divergence in their performance assessments, given the same operational parameters and conditions. While the series configuration recorded a plunge to 0.87 units of combined reliability driven availability, the parallel configuration recorded 0.99 units, within the same period of simulated deployment. The difference of 0.12 units of reliability index was argued in favour of the parallel system.*

Keywords*: reliability simulation, process variables, maintenance strategy, lean manufacturing, cumulative reliability, structural configurations, computational predictability*

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I. Introduction

Manufacturing concerns are designed to satisfy the social and economic objectives of their inventors and investors. A fundamental component of this strategic projection is the prevention of operational breakdowns and downtimes of the machines and plants deployed in the manufacturing assembly. In modern manufacturing situation, maintenance conditions constitute significant production related cost, thus making it a technical necessity to factor the type of maintenance strategy into the design phase and process of the plant, equipment and manufacturing layout.

In furtherance of the foregoing, where this is not considered at the design and process planning phase of the manufacturing concern, there is a higher chance that the lack of preliminary (design) maintenance policy may impact significantly on the organization's drive towards profitability and consolidation of its competitiveness. Thus, some schools of thoughts have observed that the demands placed on the reliability factors and considerations of manufacturing utilities, are intended to enable the systems perform as projected[1].

Further, it has also been viewed that although there is an understanding that maintenance cost is a non-value addition component, it is always required to make up for low production condition in the sense that it helps the machine maintain a standard operational health[2].

In the foregoing regard, industrial scale manufacturing operations and studies have indicated that equipment failure commences by some initiators and their consequent indicators which if properly understood and addressed timeously can prevent breakdown. Historically,machines and plants were previously allowed to fail before any maintenance interventions are implemented. This situation was later observed to be ineffective due to the associated costsof production downtimes. Industry practitioners hence evolved time-based preventive maintenance strategies that significantly relied on pre-determined maintenance schedules [3].

It should be noted that under this model of predictable and planned maintenance, the internal health condition of equipment components was not within contemplation. Thus, maintenance under the former condition was predominantly based on servicing of operational assemblies leaving out internal support components. Instructively, planned maintenance is geared towards eradication of unprojected failures[4]. Be that as it may, while this time oriented maintenance held sway, industry operators soon realized that it has a lot of technical pitfalls and proceeded to actualized predictive maintenance strategy; which dealt with the operational condition of the machines or plant in a trendingand predictive manner [5]. It should also be noted that during the work life cycle of a machine, depreciations are recorded and do present their symptoms which marks gradual departure from standard design and operational conditions.

II. Simulation of Combinatorial Assemblies

The aim of this paper therefore, is to propose an operational process simulation of a numerical nature, designed to capture the internal conditions of the machines in their combinatorial network of manufacturing assembly under real-time operational sequence. The stored data are algorithmically computedto indicate the process conditions of the machines, such that the operators or machinist can determine when maintenance is due; given a statistically predictive operational range of behavior which corresponds to a pre-determined chart.
Although this proposition is within the domain of *Computerized Maintenance Management System* (CMMS), its application adopt a more heuristic approach based on the ability of the maintenance engineer or trained operator to interpreted a range of numerically and statistically computed data that is generated from, and based on the operational reliability of the system. In this view, a computational reliability simulation shall be considered for multi-machinesassembly in a standard manufacturing layout.

III. Computational Reliability Interactions in Lean Manufacturing

In the sections that follow below, we propose a reliability interaction that could be algorithmically designed to predict future maintenance programs, using a two-prong approachof series multi-machines reliability and parallel multi-machines reliability.

(a) Series Multi-Machines Reliability Simulation

Mathematically, the structural function of a manufacturing assembly of *n* number of machines or plants has been viewed as a binary random variable which assumes the value of 1 or 0,[6]. Accordingly, its reliability can be found by iterating the following linear equations;

$R = P\{\phi(X_1,X_2 \ldots\ldots X_n) = 1\}$ ……….. 1

It should be noted that in equation (1), the consequences of time are not considered on the basis of limited machine,X_n conditions. Thus, where the iteration is defined for the i^{th} machine, then time $\boldsymbol{t}$, must necessarily be introduced as a function of reliability of the assembly within a specified period of assessment.
However, where machines or plants layout in a manufacturing situation depicts series arrangement, the consequence of equation (1) which is a general equation of reliability becomes,

$R(P_1,P_2 \ldots\ldots P_n) = P\{ \phi\ (X_1,X_2 \ldots\ldots X_n) = 1\}$ ……… 2

This means that, since the structure function, $\phi$is an increasing function of *x*, it is therefore subsumed under the probability of machines interdependencies under series layout.
The mathematical consequences of this understanding is that;

$P\{X_1,X_2 \ldots\ldots X_n) = 1\}$implying that;

$P\{X_1=1,X_2=1 \ldots\ldots X_n= 1\}$ *(as individual reliabilities that are contributory to the cumulative reliability of the system)*

Thus, this can be further represented as,

$P\{X_1=1\}P\{X_2=1\}\ldots\ldots P\{X_n= 1\}$

Therefore, $P = P_1P_2\ldots\ldots P_n$ ……….. 3

In view of the foregoing, granted that in the first year, the probability *P* of the satisfactory performance of machines $X_1X_2X_3X_4X_5$ is equal to reliability *R* of the machines and that the machines would be available for engagement for subsequent year of satisfactory performance. Under this assumption, let the individual reliability of the machines be R_1, R_2, R_3, R_4, R_5 be stated as follows;

$X_{Pi}=R_i=K$ ………..4

where i = machine number in the series array and K is the product of reliability and probability values of individual machines when considered as a multi-machine series configuration, as detailed in this simulation study as follows:

$X_{P1} = R_1 = 0.98$
$X_{P2} = R_2 = 0.97$
$X_{P3} = R_3 = 0.96$
$X_{P4} = R_4 = 0.97$
$X_{P5} = R_5 = 0.98$

(b) Numerical Prediction of Machine Reliability in Series Configuration

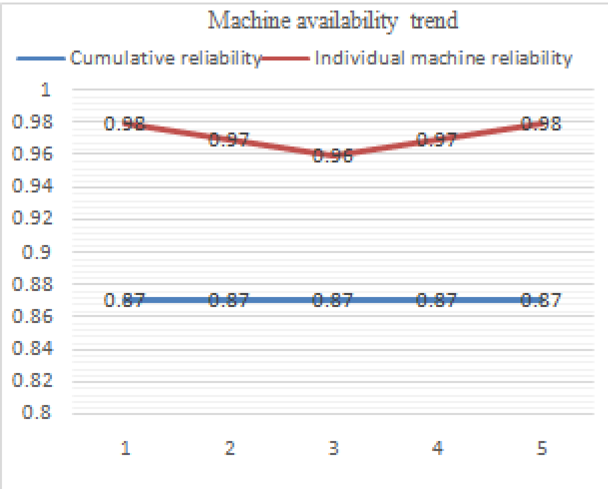
In this section the discussion shall center on the use of numerical computations to predict in tabular and graphic representation, the reliability and availability of a manufacturing concern that is arranged as an integrated series configured system which can be computed and presented in a graphical form to depict the individual availability of the machines. Further, it should be noted that availability is the total time in percentage, that an equipment is in an operable state and capable of deployment. Its reliability is a characteristic and quantifiable measure of how long the machine can optimally produce satisfactory performance as intended by its design and operational constraints.

In view of the foregoing, this study can safely opine that the reliability of a machine is the same for its probability, however, where multi-machines condition applies, reliability is the product of all the probabilities of the machines in that configuration.

The given values for X_{Pi} as $X_{P1} =1$, $X_{P2} =2$, $X_{P3} =3$, $X_{P4} =4$, $X_{P5}=5$, corresponds to all the machines, in the $X_i$range and are arranged in the logical sequence of operation. The following table and graph is generated for analysis and interpretation. This table is further simulated to indicate the characteristic behavior of the configuration in terms of the performance of the assembly.

Table 1: Table of Machine Availability under Series System

Machine No.in Layout	Probability Factor(X_i)	Cumulative Reliability, R_C	Individual Reliability R_i
X_1– 1	0.98	0.87	0.98
X_2– 2	0.97	0.87	0.97
X_3– 3	0.96	0.87	0.96
X_4– 4	0.97	0.87	0.97
X_5– 5	0.98	0.87	0.98



IV. Analysis of Table 1 and Machine Availability Trend

It should be noted that the computational predictability in terms of maintenance schedules as the table and graph above show, indicate that the individual reliability of the machines in the system can be graphically determined by plottingthe R_C, P,X_i graph as shown above and taking corresponding reading. Note that cumulative reliability,R_C and individual reliability,$R_i$are both represented on the same y-axis. Note also machines X_i, i.e 1,2,3,4,5is represented on the x-axis.

Thus, since cumulative reliability contributed by the various reliabilities of the machines in the system is a common denominator to all, it is treated as a reference value and seen running through machines, X_1 to X_5while maintaining the same value of $R_c= 0.87$, within the configuration constraint of $R\leq 1$. Hence, the projected performance of this configuration, is determined by the simulation of the reliability of the system assembly.

Accordingly, the value of individual machine reliability, R_i is read off and traced in the graph to the particular machine. This tracing is to enhance the analysis of the downward behavioral tendencies of each machine during operations and apply that tendency to determine the direction for maintenance decisions. Thus, from the graph it could be seen that, machine X_3 has the lowest probability of performance and can be said to possess the lowest reliability. This practically imply that a computationally based predictable failure of machine availability has been established. This means that should the trend in the graph be ignored, this series machine configuration could fail on account of the non-satisfactory performance of machine X_3. Further, the deterioration pattern of machine X_3 can further increase until it goes below the running line of cumulative reliability of $R_C = 0.087$of the configuration.

V. Parallel Multi-Machines Reliability Simulation

In multi-machines manufacturing situations, parallel machines interconnection is largely achieved under the design and installation strategy, such that where one machine fails, the entire *n* machines also fail. Accordingly, it has been noted that a system of this nature of interconnection, performs satisfactorily if at least one of the *n* components performs satisfactorily, with all the *n* components performing simultaneously [7].

It should further be noted that under multi-component analysis this crucial property of a parallel system of configuration,is referred to as redundancy, where alternative backup component within the system serve as bias buffers to support the smooth operation of the system when some direct components fail.

Consequently, and for purposes of system performance iteration that can be deployed for predictive machine simulation, the structural function for a parallel machine system is expressed as;

$\phi\ (X_1,X_2 \ldots X_n) = 1 - (1-X_1)\ (1-X_2)\ \ldots.(1-X_n) = \max\ \{X_1,X_2\ldots\ldots X_n\}$ ..……..5

the foregoing means that performance indicator sequel to equation (5) is only possible on the condition that each machine X_i is either 1 or 0. The implication of this binary en-codement is that the structure function takes on a value of 1 if at least one of the machines equals 1. Consider a manufacturing assembly of two machines linked parallel to each other.In this regard, if one of the machines work satisfactorily it also guarantees that the second machine would work satisfactorily, although in actual sense, its performance may not be too efficient. This system is akin to front and rear brakes in an automobile. If one brake works well, then the other also works well, since the performance of the brake system lies in the vehicle stopping its motion on the application of brakes.

For multi-machines assembly that are designed to function under parallel system as this, then the integrated structure function of the system can be stated as;

$\phi\ (X_1,X_2) = 1-(1-X_1)\ (1-X_2)\ (1-X_3)(1-X_4)(1-X_5)$ …………6

Since equation 6 depicts an exponential expansion function, suffice to state that under binary computation the objective function represented by equation 6 reduces to:

$\phi(1,1) = \phi(1,0) = \phi(0,1)=1,\ \phi(0,0) = 0$ ……… 7

which is limitedly exhaustive of the various possible combinations available within the binary scheme. Additionally, a parallel system of *n* array of machines as described above would be a continuous binary function up to n^{th} term of the machines condition.Consequently, equation 5 can be reviewed for its exponential reliability component, resulting the expanded equation (8) as;

$R\ (P_1, P_2, P_3, P_4, P_5) = P\ \{\max\ (X_{1,}\ X_{2,}\ X_{3,}\ X_{4,}\ X_{5)} = 1\}$

$= 1-P\ \{\max\ (X_{1,}\ X_{2,}\ X_{3,}\ X_{4,}\ X_{5)} = 1\}$, under binary condition, this implies that:

$R\ (P_1, P_2, P_3, P_4, P_5) = 1-\ P\ \{X_1=0,\ X_2=0,\ X_3=0,\ X_4=0,\ X_5=0\}$

Therefore, by parallel interconnected systems iteration,

$R = 1-(1-P_1)\ (1-P_2)\ (1-P_3)\ (1-P_4)\ (1-P_5)$ ………… 8

It is imperative to note that the simulation equation (8) can be further used to analyze a parallel system of manufacturing machinery array, by deploying the values of probability of the five stated machines in the determination of its cumulative reliability R_C as follows;

R_C = 1-(-0.98) (1-0.97) (1-0.96) (1-0.97) (1-0.98)

= 1- (0.02) (0.03) (0.04) (0.03) (0.02)

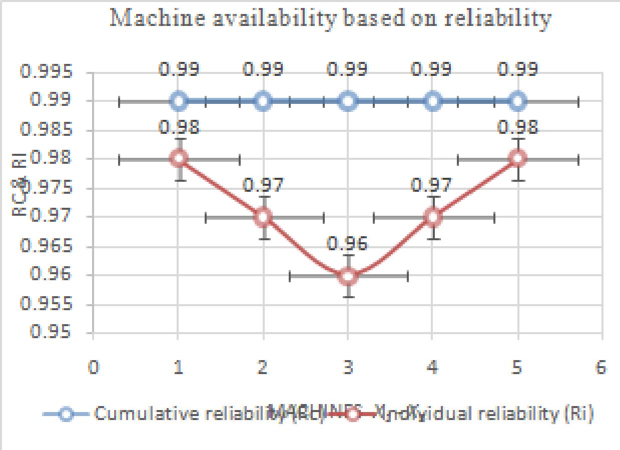
1-0.0000000144= 0.99

Therefore, R_C = 0.99

In view of the reliability of the parallel machines, suffice to state that table of machines availability on account of the various reliability conditions of the parallel system can be stated as follows;

Table 2- Machine availability based on reliability

Machine No. in Layout	Probability Factor P_f	Cumulative Reliability, R_C	Availability/ Individual Reliability,R_i
X_1– 1	0.98	0.99	0.98
X_2– 2	0.97	0.99	0.97
X_3– 3	0.96	0.99	0.96
X_4– 4	0.97	0.99	0.97
X_5– 5	0.98	0.99	0.98



VI. Discussions

Consequently, the reliability concerns of the configuration in table 2 above and the probability factor, $P_f(X_i) = R_i$, where (X_i); is indicative of the process and analytical value of one machine at a time. This means that the stated expression confirms the predictability ofindividual machine reliability as a function of the probability that the machine would be available for satisfactory performance upon deployment within the specified time.

A careful observation of the two tables indicate that although the parameters of the machine characteristics are the same, the graph resulting from the two tables maintain the same shape in structural context but in terms of reliability factor, the parallel systems portends better reliability on the ground that its reliability is higher at 0.99 as compared to the series machine arrangement of 0.87. Thus, a choice of lean manufacturing cell to deploy between the two indicates that parallel layout of machines is more efficient in terms of availability and deployability.

Further, since no attempt was made with respect to energy consumption of the two types of configurationin determination of general performance, suffice to say that manufacturing system availability is not a function of power consumption if all other parameters are considered integral to the performance of the system. Consequently, series configuration as compared to parallel configuration possesses different beneficial purposes which depends on the individual synergetic effects of the particular configuration.

The foregoing is further depicted by the linearity of the error bars in the graph which established the parallel sense of the configuration and consequently locks X_i,$R_i$and $R_c$into their shared operational compartments. It should thus be stated that the dumbbell shape of the graph shows that, although the performance of the system is satisfactory, urgent attention was required to address the reliability issues of machine code X_3, which is indicating lower performance characteristics. If this predictive model is applied in the case of machine X_3, then the stability of the system can be guaranteed.

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