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Research Article

Increasing the Probability of Fault Detection in Non Perfect Inspection Model of Delay Time Analysis with Compromise on Inspection Time

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Abstract: This study separates the real inspection content (soft portion) within the total maintenance inspection activity and attempts to repeat the same some additional number of times during actual inspection. Effect of repetition of soft portion on inspection related time, fault detection probability and the consequence variable of down time per unit time is analyzed. Statistical test proves that both the inspection time and probability of fault detection has nearly same rate of influence on the consequence variable though in opposite direction. A factor ω is introduced to account for the proportion of soft portion over the maintenance inspection time. As the number of repetitions of soft portion is increased for a given value of ω, it is found from analysis that the new set of inspection time and probability of fault detection improves downtime per unit time until an optimum number of repetitions is reached. Improvement is better as the value of ω is on the lower side. The practitioner is to take this possibility of soft repeatable portion of maintenance inspection time into account while estimating these two input parameters when employing delay time methodology as a preventive maintenance strategy.

Keywords: Delay time analysis, down time, maintenance inspection, non perfect inspection, optimizing down time, preventive maintenance

INTRODUCTION

While a preventive maintenance inspection of a part or a systemthat is done periodically by adopting the Delay Time Methodology (DTM), the intention is to see if there is any fault. If a fault is detected, it is immediately rectified by corrective maintenance action. If the fault occurs after the maintenance inspection is over, brews to a failure before next inspection, then it will call for a breakdown maintenance leading to more losses either by way of time or money or both.In Delay Time Analysis (DTA), the basic concept is when a fault arises in a part or a system, it gives certain indication before it mature to reach the stage of a breakdown. DTA recognises this and the models have parameters like maintenance inspection time (t_i), corrective maintenance time (t_c), breakdown maintenance time (t_b)to optimize the downtime per unit time by introducing periodic mainteanance at interval, T that consumes an inspection time of t_i. During such maintenance inspection, it is also recognised that the inspection need not be perfect. There exists a probability of detecting the fault, if a fault is present, called as the β factor (0<β<1). As β increases, better is the chance of detecting a fault that is present and hence expect to achieve a better value of downtime per unit time, which is considered as the popular consequence variable for optimization in DTA.

This study is based on the observation that the total content of the estimatedinspection time (t_i) is not spent for the pure act of inspection alone. Most inspection activities generally have a set up activity (hard portion) and the actual inspection activity (soft portion); in most cases the soft portion is responsible for the detection of fault. Having made an inspection set up, repetition of soft portion will increasesmaintenance inspection time (t_i) and along with it the the probability of fault detection (β) too; Effect of repeating the number of soft portions on $\{t_i, \beta\}$ is anlaysed with the intention of getting a better downtime per unit time.

Concept of Delay Time Analysis (DTA): The delay time in its simpler form is the duration of time from when a defect is first observable to a point of time when a repair would be essential if a corrective action is not performed within this period. As per Christer and Waller (1984a) the delay time concept defines a two stage stochastic process where the first stage is the initiating phase of a defect (or fault) and the second is the stage where the defect leads to a failure. Before a component breaks down, assuming that it is not going to be a sudden breakdown, there will be tell-tale signs of reduced performance or abnormalities. The time gap

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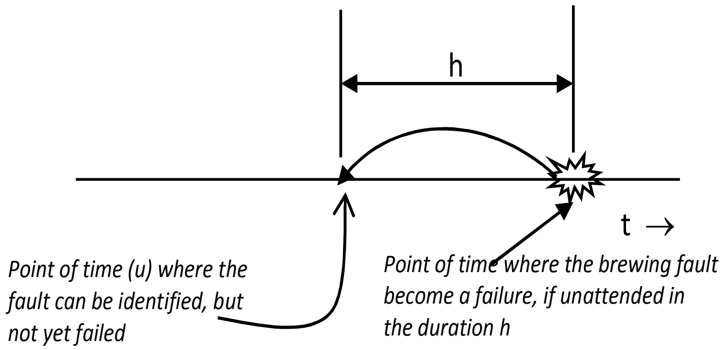

Fig. 1: Concept of delay time

between the first indications of abnormality (initial point u in Fig. 1 and the actual failure time (failure point) will vary depending on the rate of deterioration; this time gap is the delay time or the opportunity window to carry out the corrective maintenance and avoid a failure situation.

The concept is illustrated in Fig. 1. If an inspection is carried out during the delay time h, then the defect is likely to be identified and corrective maintenance action can be taken thereby saving the situation of entering in to a failure and facing the associated consequences.

The time lapse from when a defect can be first identified at an inspection to the time that the defect causes a failure (breakdown) is called the delay time. If at all the failure distribution and the delay time distribution could be arrived at for a part or a system then it is possible to model the relationship between the PMI interval T and the expected down time per unit time. By analyzing sufficient number of faults or failures, a distribution for f(h) may be obtained.

Review of literature: Models for determining the maintenance interval frequency has been developed and applied on many case studies for the past 2 decades, for example (Christer and Waller, 1984b, c; Jones *et al*., 2009), with the objective in most cases to get reduced down times and or to reduce total maintenance costs spent on that equipment per unit time.

Delay-time based modeling has been developed and applied in many industrial maintenance inspection problems over the past decade (Christer and Waller, 1984a, b, c). In most cases objective has been to reduce equipment downtime with preventive maintenance inspection (PMI) interval as the decision variable. Methodologies started being published on the application of DTA (Christer and Waller, 1984c; Jones *et al*., 2009). In Christer and Waller (1984a) research papers dating back to 1980s have been referred to. Almost in all the early papers researchers had been mentioning about the lack of objective data from the industry, since the factories never realized that some data like the possible delay time or its estimate had to be noted down as and when a fault or failure was encountered.

Christer and Waller (1984a) assumed that the time of origin of a fault is uniformly distributed over time since the last inspection and is independent of the delay time h. The length of delay time is assumed to follow the exponential distribution.

A modified delay time model allows non-perfect inspection and arbitrary distribution of the initial fault time and delay time distributions, which make delay time models more practical which is explored by Christer and Waller (1984c) and later referred by Cunningham *et al*. (2011). Methodology of obtaining the subjective estimate on the delay time is in Christer and Waller (1984a) which are also mentioned in Francis and Mak (1996).

In the case study of Christer and Waller (1984b) DTA is applied at Pedigree Petfoods Limited to derive an optimum-cost maintenance policy for the canning line. It was observed that the distribution of h was observed to be approximately exponential, with a longer tail. Another case study is available in Christer and Waller (1984c) where the DTM and failure analysis was applied to model the preventive maintenance of a vehicle fleet of tractor units operated by Hiram Walker Limited.

Wang (1997) investigated the series of problems faced by researchers in the methods of obtaining subjective estimate on the delay time distribution and also has proposed a revised method of obtaining the same, by explaining how to combine the opinions of more than one experts on delay time. A method of using objective data collected from records kept by engineers maintaining several items of medical equipment was proposed in Baker and Wang (1991, 1993). Considering the difficulties in obtaining the estimates on parameters, Wang and Jia (2007) has suggested proceeding initially with subjective data and then improving the same when objective data starts pouring in due course of time.

The Delay time, the basic mathematical model: As per Christer *et al*. (1998) the down time per unit time, D(T), is:

$$D(T) = \frac{t_i + \lambda T.b(T)t_b}{T + t_i} \tag{1}$$

where, λ is the parameter for the exponential distribution for the failure process indicating the rate of occurrence of defects built from past data t_i is the average down time due to maintenance inspection and the t_b being the mean downtime due to breakdown repairs and $b(T)$ is the proportion of faults that will end up as failures during the period T, given that faults will occur in T, where:

$$b(T) = \int_0^T \frac{(T-h)}{T} f(h)dh \quad (2)$$

And $f(h)$ representing the distribution of delay time, a data gathered from the past history or by subjective estimate. Here after this down time symbol, D(T), shall be represented in this study as DT_u but with same meaning of down time per unit time. Definition for t_i can been seen in Jones *et al*. (2009).

In case of imperfect inspection Christer *et al*. (1998) uses same equation (1) with a change in the expression for b(T) as:

$$b(T) = 1 - \left\{\int_{y=0}^{T} \sum_{n=1}^{\infty} \frac{\beta}{T}(1-\beta)^{n-1} R(nT - ydy, t_b << T \quad (3)$$

where, β is the probability of detecting a fault during inspection, if the fault is present at the time of inspection and:

$$R(x) = \int_x^{\infty} f(h)dh \quad (4)$$

and n being the number of attempts the same fault has lived up before being caught up at an inspection point. Practical values for β, in case studies of a company manufacturing brake linings have been found to be as low as 0.13 for a complex equipment, Christer *et al*. (1998).

Same final expression for D(T) in Eq. (1) can be arrived at by following the model of Wenbin (2012) which calls for the replacing expected number of faults in (0-T), λT.b (T) with:

$$\int_0^T \lambda F(h)dh$$

In Eq. (1), which shall again lead to the same result for the homogenous Poisson arrival of defects model. In all further analysis the HPP arrival of defects is considered.

THE PROPOSED MODEL TO REPEAT THE SOFT PORTION OF INSPECTION ACTIVITY

Problem background-case study: Semi automatic sand filler conveyer is used for preparing molds in batches in a medium sized steel foundry in South India that is in the business of manufacturing valves ranging from ¼ kg. to 20 kg. The rocking rod in the sand filler station develops cracks frequently and the influencing factors are innumerous that engineering solution has not been feasible at this medium scale factory environment. At the same time if the part breaks down while the line is operational amidst a batch of mold preparation, the downtime created shall throw the plan out of schedule considering the time consumed in mending the damage on partially filled up sand molds, breakdown repair time and returning back to mold preparation cycle for the batch. On the other hand it is not possible to implement an inspection of this part every time a batch is launched, considering the physical work involved in dismantling, cleaning and inspecting which is laborious and time consuming. Therefore this part has been subjected to periodic maintenance inspection. Current practice is to check by dye penetrant test, ring test etc; the ring test however, is something which can be done any number of times without any implication on t_i. However the penetrant test needed severe cleaning action on the part and drying up which requires almost an hour before the inspector starts the dye-penetrant procedure. This penetrant test consumes only about 15 minutes of time. Subjective data from the inspector has it that 25% of the times the rod had failed immediately after the an inspection that reported no presence of crack and that they did not expect such breakdowns (due to crack) within such a short time after an inspection. The 'short time' was later clarified to be the estimated delay time. That means that this test revealed the defect on this part, with a β 0.75 when the fault is present. Maintenance inspector also opined that a second time penetrant test reveals the presence sometimes. Such repetitions are done on their own when they realize that no processing load awaits the sand filler line.

As per the current definition of maintenance inspection time t_i, it is the time the part or the system that shall be held up to complete the maintenance inspection activity on various parts or system before returning the part or system or equipment back to the production line (Christer and Waller, 1984a; Jones *et al*., 2009). The inspection time t_i is mentioned as d_s (mean downtime per inspection) in Wenbin (2012) in his comprehensive review paper. Maintenance inspection activity, at component level, in most cases may not be a single activity. It could be that the part may have to be sent for thorough water cleaning, degreasing, etching, drying up (the hard portion of the total activity) and then subjected to the real inspection act (the soft portion of the activity). This is prominent in the condition inspection that is performed while doing major repairs in military installations. In some other cases even a small clean machining cut too is

Table 1: Input data for factorial experiment

Ti	β	*T*	*Dtu*
0.3	0.50	7.25	0.0945520
0.3	0.75	8.47	0.0757610
0.3	1.00	9.85	0.0622180
0.6	0.50	12.8	0.1209600
0.6	0.75	13.5	0.1000110
0.6	1.00	14.9	0.0840740
0.9	0.50	19.4	0.1368570
0.9	0.75	18.5	0.1160780
0.9	1.00	19.4	0.0993630

proposed before resorting to the actual application of the die and developer procedure. In this case the preparation could be a solid constant activity and the application of the dye and testing can be taken as the soft portion of the total activity.

The proposed model: Let there exist a part, belonging to a system, that is subjected to maintenance inspection activity along with its counter parts in the system and that this part dominates the parameters inspection time t_i and the probability of fault detection β. It is assumed that contributions to the aggregation of t_i and β from other parts is negligible for analysis purpose. This is true in reality for the fact that, by the time the longest time consuming inspection is going on in a part, inspection activities of other eligible parts within the system would be completed in parallel.

Let there be a repeatable soft portion of the inspection activity which is responsible for the detection of fault on the part with the probability, β hitherto.

Assuming that ω be that proportion of t_i which can be repeated without any need for additional set up time, if the repeatable portion of inspection is done for r number of times, then the total revised inspection time, mentioned as t_{ir}, if given by:

$$t_{ir} = t_i\{1 + (r-1)\omega\},\ 0<\omega<1$$
$$r = 1, 2, 3.$$

where, r is the number of times the soft portion of total inspection time is repeated; r = 1 representing the very first time the inspection is carried out and r = 2 means that the soft portion of the total activity alone is repeated for the second time. And the corresponding revised probability of detecting the fault if it exists, denoted as β_r becomes:

$$\beta_r = \left(1 - \beta'^{r}\right)$$
$$\beta' = (1 - \beta)$$
$$0<\beta<1$$

Investigating the influence of t_i and β over down time per unit time, (DT_u), by Factorial design of experiments: In order to find out the factor that influences the DT_u the most, among t_i and β, a factorial experiment (2 factor/3 level) is conducted. Keeping the levels as practical as possible for each of the factors, the output value of the consequence variable, the DT_u* is computed as per equation (1) by EXCEL Solver for the 9 sets of input data, given in Table 1 and the same is fed into MINITAB and the result is presented in Fig. 2 and Table 2. Other standard values for the input data shown in Table 1 are λ0.2, t_i0.3, t_b0.8 and the delay time parameter of 0.05, as taken in the benchmark example

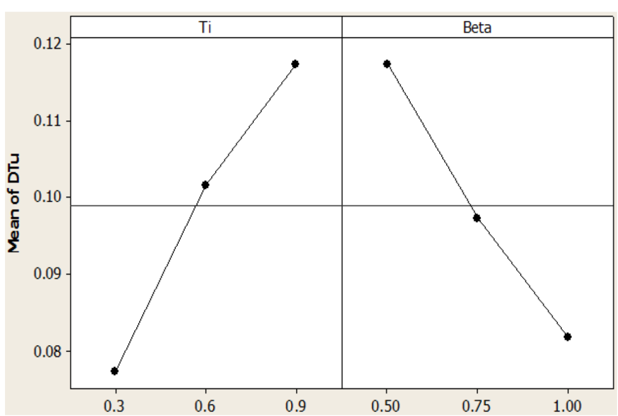

Fig. 2: Main effect plot showing the influence of t_i, β on DT_u

Table 2: ANOVA test output to determine the extent of influence of t_i and β

Analysis of variance for DTu, using adjusted SS for tests

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Ti	2	0.0024261	0.00242661	0.0012131	600.26	0.000
β	2	0.0019094	0.00190940	0.0009547	472.41	0.000
Error	4	0.0000081	0.00000810	0.0000020		
Total	8	0.0043436				

S: 0.00142158, R-sq: 99.81%; R-sq (adj) 99.63%

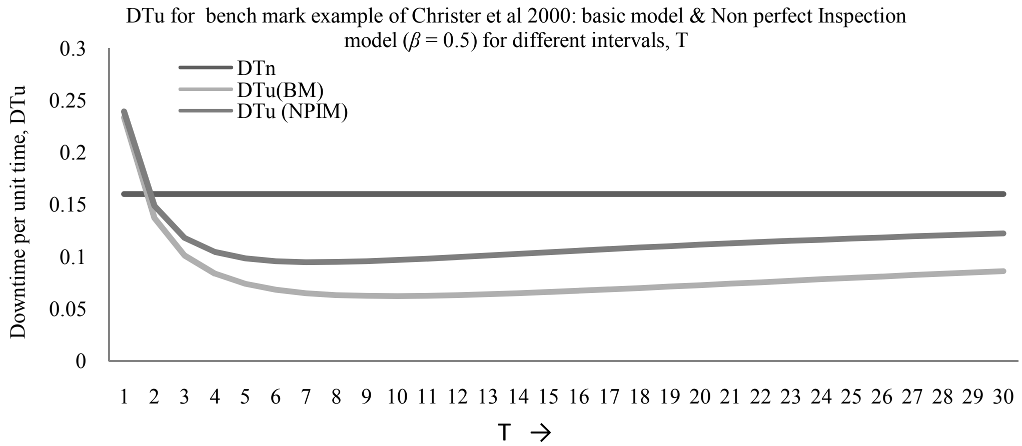

Fig. 3: Variation of downtime per unit time as per Christer and Lee (2000) for non perfect inspection model

Table 3: Input values for revised set of t_i and β to compute DT_u*

r	t_i	ω	β	t_{ir}	β_r	T	DT_u
1	0.3	0.1000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.1000	0.5	0.3300	0.75000	9.010	0.07882
3	0.3	0.1000	0.5	0.3600	0.87500	10.20	0.07411
4	0.3	0.1000	0.5	0.3900	0.93750	11.10	0.07317*
5	0.3	0.1000	0.5	0.4200	0.96875	11.80	0.07382
1	0.3	0.2000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.2000	0.5	0.3600	0.75000	9.530	0.08169
3	0.3	0.2000	0.5	0.4200	0.87500	11.30	0.07909*
4	0.3	0.2000	0.5	0.4800	0.93750	12.60	0.07993
5	0.3	0.2000	0.5	0.5400	0.96875	13.80	0.08217
1	0.3	0.3000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.3000	0.5	0.3900	0.75000	10.00	0.08440
3	0.3	0.3000	0.5	0.4800	0.87500	12.30	0.08361*
4	0.3	0.3000	0.5	0.5700	0.93750	14.10	0.08589
5	0.3	0.3000	0.5	0.6600	0.96875	15.70	0.08934
1	0.3	0.4000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.4000	0.5	0.4200	0.75000	10.60	0.08696*
3	0.3	0.4000	0.5	0.5400	0.87500	13.20	0.08775
4	0.3	0.4000	0.5	0.6600	0.93750	15.50	0.09122
5	0.3	0.4000	0.5	0.7800	0.96875	17.50	0.09565
1	0.3	0.5000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.5000	0.5	0.4500	0.75000	11.10	0.08939*
3	0.3	0.5000	0.5	0.6000	0.87500	14.20	0.09158
4	0.3	0.5000	0.5	0.7500	0.93750	16.90	0.09606
5	0.3	0.5000	0.5	0.9000	0.96875	19.30	0.10128
1	0.3	0.6000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.6000	0.5	0.4800	0.75000	11.60	0.09171*
3	0.3	0.6000	0.5	0.6600	0.87500	15.10	0.09514
4	0.3	0.6000	0.5	0.8400	0.93750	18.20	0.10049
5	0.3	0.6000	0.5	1.0200	0.96875	21.00	0.10638
1	0.3	0.7000	0.5	0.3000	0.50000	7.250	0.09455
2	0.3	0.7000	0.5	0.5100	0.75000	12.10	0.09392*
3	0.3	0.7000	0.5	0.7200	0.87500	16.10	0.09847
4	0.3	0.7000	0.5	0.9300	0.93750	19.60	0.10458
5	0.3	0.7000	0.5	1.1400	0.96875	22.80	0.11103

in the literature for the basic downtime model for non-perfect inspection case in Christer and Lee (2000).

Figure 2 indicates the logical relationship that an increase in t_i values increases DT_u and any increase in β values decreases the DT_u calling the need for an optimization between the values of this combination {t_i, β}, if there are scope for changes. From Fig. 2, it is noticed that the t_i has more influence on DT_u in attempting to reduce the downtime per unit time, than does β; however the difference is small as observed in the Fishers's ratio values of 600.26 and 472.41 in Table 2. R-Sq value of 99.81% indicates that the statistical model is valid for the experimental data.

Numerical example to demonstrate the role of *ω* factor in refining the downtime per unit time: For this purpose the numerical example in Christer and Lee (2000) is taken as the bench mark problem whose solution is given in Fig. 3, where DT_n represents the downtime per unit time in the event of a no-DTA based inspection policy and DT_u(BM) representing the result for Christer's basic model (where T10 units of time and DT_u 0.0622). DT_u(NPIM) represents the non perfect inspection model (where T 7.25 units of time and DT_u 0.09455).

Retaining the same input data as per same numerical example of Christer *et al*. (1998), assuming a series of values for proportion of soft portion of inspection activity, ω (from 0.1 to 0.7 in steps of 0.1), a number of repetitions r is considered for each value of ω. Change in number of repetitions in conjunction with particular value of ω lead to different revised sets of {ti, β} which are called as $\{t_{ir}, \beta_r\}$. The revised combination of values of $\{t_{ir,} \beta_r\}$ are treated in equation (1) and (3) for the non-perfect inspection model and the corresponding optimized values of the consequence variable DT_u are shown in Table 3; all other input data of numerical data of Christer *et al*. (1998) being retained same. In all values of ω from 0.1 to 0.7, the very first set of value in Table 3 represents Christer's input data of t_i0.3 and β0.5, since r = 1 means first time doing of the soft portion of inspection activity.

Table 3 is read as follows: when the repeatable portion of the t_i is considered as ω0.1 (10% of t_i) and when the inspection is done for the first time (r = 1) the t_i0.3 is consumed with detection probability of β0.5; when the same repeatable part of inspection is done for the second time, (r = 2), then the revised inspection time t_{ir} is 0.33 which increases the detection probability to β0.75. The consequence of these changes is treated in the optimization computation produced the result of T*9.01 and DTu*0.07882.

RESULTS AND DISCUSSION

Figure 4, graphical representation of Table 3, shows DT_u values for different sets of $\{t_{ir}, \beta_r\}$ as repetition is increased for a given assumed value of ω. Since r = 1 happens to be the first time inspection, the starting point of graph in Fig. 4 (for different ω) corresponds to the input values of numerical example of Christer *et al*. (1998), i.e., {t_i0.3, β0.5}, irrespective of value of ω. In case of all other repetitions (r>1), the curves branch off from the Christer's point (r = 1) showing a change in the DT_u for the set $\{\omega, r, t_{ir}, \beta_r\}$.

In Table 3, for any particular value of ω, for an increase in *r*, the t_{ir} increases at constant pace of ω but the probability of detection β_r increases rapidly at first and then reduces as we further increase *r*. This is the reason why largest saving in DT_u is achieved at the initial repetitions and the effect tapers off on further attempt to increase t_i as can be clearly seen in Fig. 4. This warns us that there is a limit to which we can attempt to increase soft repetitions to get an increased βwith the final target of a better DT_u. For example taking the case of ω0.2 in Table 3, the DT_u shows a decreasing trend to our favor at the beginning as we start repeating the repeatable portion of t_i. But, after {t_{ir}0.42, β_r0.875} where DT_u reaches 0.07909, the DT_u value again starts increasing for next set of values of $\{t_{ir}, \beta_r\}$. However it is also noticed that, inspite of this increasing trend, DT_u value is still better than the original value we started with at {t_i0.3, β0.5}.This tells us that while deciding the estimate for the inspection time, t_i, care should be taken by the inspector to look for the presence of any repeatable component in the inspection activity and proceed with soft repetitions only till the set $\{t_{ir}, \beta_r)$ influences to the least downtime per unit time, DT_u.

The value of ω is the characteristic of the total inspection activity needed for the particular part or fault mode and its value can estimated accurately by a time study. As ω increases and approaches1, the effect on

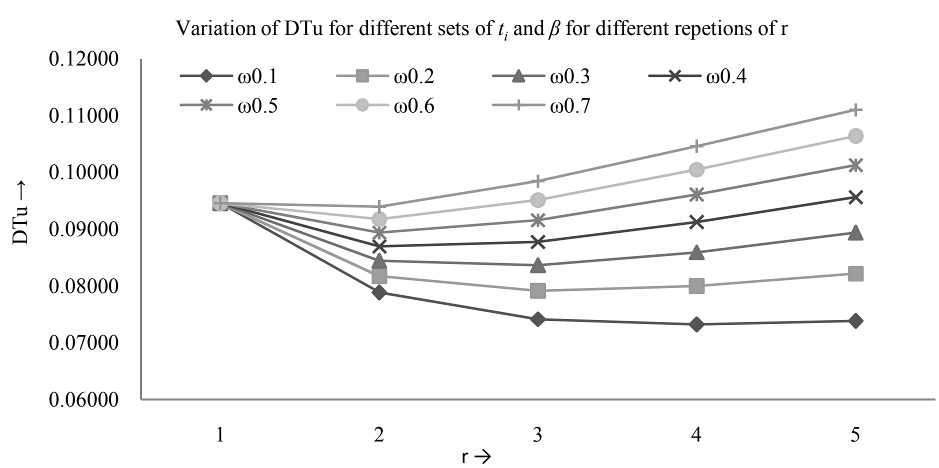

Fig. 4: Variation pattern of DT_u for revised set of $\{t_i, \beta_r\}$ for 5 repetitions each for different proportion of soft portion over the inspection activity

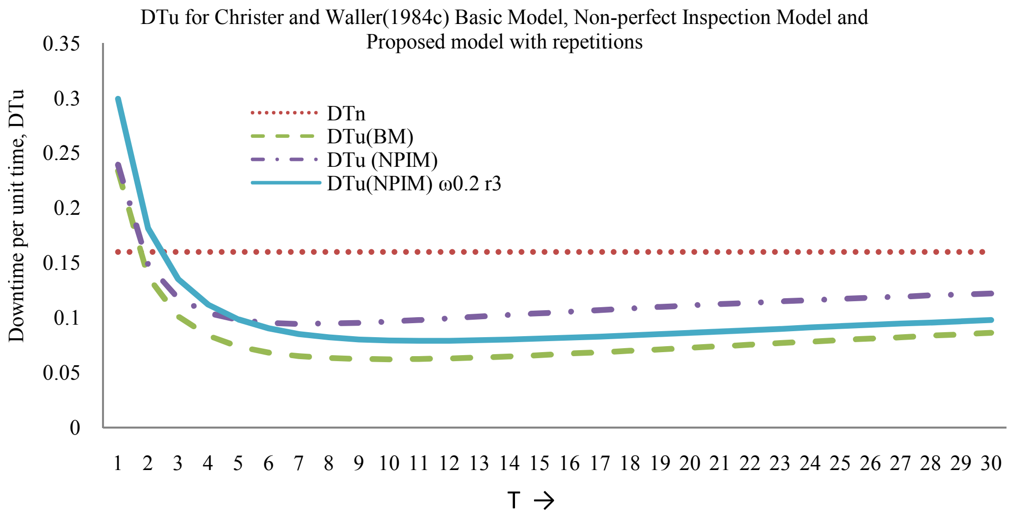

Fig. 5: Improvement of optimal DT_u for soft repetitions with ω0.2, r = 3 in comparison to Basic delay time model, Non perfect inspection models; DTn (T∞, 0.16), DTuBM (T10, 0.06222), DTuNPIM (T7, 0.094598), DTuNPMIw0.2r3 (T11, 0.07911)

downtime per unit time is not much encouraging which is expected since t_i nearly gets doubled only to get a smaller gain on the value of probability of fault detection, β even on the second repetition. Figure 5 shows the comparison between the basic model, non perfect inspection model of Christer *et al*. (1998) and the improved optimal value of DT_u for a ω0.2 with 3 repetitions of soft inspection portions.

Selection of candidate for revising {ti, β}:

- List out the components which have distinct hard and soft portions within the group of participating parts for input data aggregation. This is purely technical and the list must be obtained from the maintenance inspectors.
- Arrange the parts in the descending order of (β/t_i).
- Choose the part having least (β/t_i) for DTA treatment to obtain a new set of $\{t_i, \beta\}$.

CONCLUSION

Maintenance inspection activity of a part or a system will not be a single activity in case of all participants. Some part within a system may have a set up time like a hard portion and a soft portion which is repeatable and that this soft portion alone could be responsible for the probability of fault detection. If such a part is found to dominate the values of parameters of inspection time and the fault detection probability during final parameter aggregation, with the participating partners, then there exists the potential for improving the downtime per unit time by soft repetitions. Soft portion can be identified by work study within the part's total maintenance inspection activity. The proportion of soft portion to the total maintenance inspection activity by way of time consumption is unique for the part depending on the fault mode and inspection technique. Statistical test prove that maintenance inspection time and fault detection probability influences the downtime per unit time at same rate, though, in opposite directions.

Depending on the proportion of the soft repeatable portion (ω) compared to the original t_i, the new set of $\{t_i,\beta\}$ lead to better expected downtime per unit time, though, an upper limit for soft repetitions to achieve optimal downtime per unit time exists.

As the soft portion amounts to a smaller proportion of original inspection time, the encouragement to get a better downtime per unit value is higher.

It can be argued that the original t_i value has already been increased to that extent to get the maximum probability of detection β by adopting maximum number of repetitions (*r*) of repeatable portions. But such increase could not have been done with a DTA point of view which enforces an upper limit for repetition; Repetitions could have been over-done. It is possible that the previously established combination values of $\{t_i, \beta_r\}$ may not lead to DT_u* and a subsequent DTA analysis with the parameters t_i, β and ω could even lead to a intentional reduction in *r*.

Hence the practitioner can look for the presence of a soft repeatable portion of maintenance inspection activity, in case a single part dominating the decision on the parameters inspection time, fault detection probability and plan a number of repetitions to get optimal DT_u while preparing estimates for parameters $\{t_i, \beta\}$ at the first instance of implementation. In case of already established parameters for the combination of $\{t_i,\beta\}$, the practitioner can consider treating them with the DTA point of view and revise the same.

The advantage of bifurcating maintenance inspection activity and planning repetition of soft portion on eligible parts can best be recognized when DTM is applied on a system having fewer components as its subset for input data aggregation.

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