# Analysis of the impact of time and maintenance strategy on availability of complex technical system

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**Abstract**

The paper considers reliability and availability of technical systems and highlights the fact that maintenance strategy based on "constant durability" is more favorable than maintenance strategy based on "constant date". Time analysis was carried out and basic expressions for operative and total availability are given. Reliability diagrams, failure intensity, and maintenance costs are presented.

**Key words:** preventive maintenance, reliability, availability, costs.

## 1. Introduction

The results of the research on availability of complex technical systems are not sufficiently known yet. Bearing that in mind, and taking into account that availability can be presented in the percentage of the time of correct functioning of the system, or as a probability that at a point of time the system is operative, a study of a number of technical systems in iron and steel industry was carried out. [1] As a motive of research it can be mentioned that availability also depends on strategy of preventive maintenance. The results of the research are obtained in conditions of real exploitation of technical systems (results for Agio-machine are presented here), whose reliability have impact on the production which is worth around 107,000 EUR a day.

## 2. Explanation of terms malfunction and probability of occurrence of malfunction

The aim of maintenance is to provide functionality of technical systems. We should try to keep the systems and their functionality and not only operational aspect used by operators. Redundancy improves functional reliability but also increases the costs of life cycle in the sense of preparations and keeping the level of work of technical systems.

Types of malfunctions are specific malfunctions of equipment which result in functional malfunction of a system and/or a subsystem. Dominant types of system malfunction are those which are responsible for importance of proportion of all malfunctions within them. Not all the types or causes of malfunctions justify preventive maintenance or maintenance according to the condition due to low probability rate in their appearance and their inconsistent effect. For addressing technical content, analysts and planners have to establish if the existing maintenance activities cover all identified potential types of malfunctions and result in desired/expected levels of reliability. Type of malfunction must be envisaged or the existing maintenance activities will not be effective in identifying type of malfunction. Later, it can result in incorrect identification in distribution of fundamental probability in malfunction of function. A lot of information can be proved or upgraded through reliability checks.

Reliability can be presented as probability of a unit to function successfully in a defined operational period under specific operational conditions, without malfunctions, which is usually expressed as a life cycle, period until malfunction, or period between two malfunctions. Conditional probability in appearance of malfunction measures probability of a unit with defined operational period of work without occurrence of "state of malfunction" which will eventually lead to malfunction within the interval. If the conditional probability of occurrence of malfunction increases with time elapsed, technical system will show characteristics of wearing out. Level or frequency of malfunction is relatively insignificant for maintenance program, being too simple to be measured. Frequency of malfunctions is useful for the process of decision making regarding expenses, as well as for establishing maintenance intervals, but gives us no information on what maintenance activities are suitable or which, on the other hand, will be a consequence, i.e. result of malfunction. Solutions regarding malfunctions should be estimated within sphere of safety and economic consequences which we want to prevent. Maintenance activities must be applicable, with the aim of their efficiency.

In the table 1 a possible method of quantifying probability of malfunction is presented. In case historical data is available, "powerful" tool for establishing rank can be provided. In case historical data is not available, ranking can be estimated based on experience with similar systems within a company.

Contemporary maintenance methods are focused on a whole technical system. They are meant more for maintenance of functionality of whole system than functionality of its components. Reliability is the base for making decision. Characteristics of malfunction of technical systems must be understood in order to establish efficiency of preventive maintenance. For successful realization it is necessary to constantly search for knowledge of conditional probability in occurrence of malfunction in specific time period (possibility that malfunction will occur in every supposed operational period).

We should always consider safety first, and then economic reasons. Safety must always be preserved. When safety is out of question, preventive maintenance must be based on economic reasons.

## 3. Dependence of operative and total availability on time

Availability of technical system in a general case can be presented by time relationship:

$$A = \frac{T_{or}}{T_{or} + T_z} \quad \text{..............................} (1)$$

where:

$T_{or}$ - average time at work,

$T_z$ - average time in failure.

It can be said that availability is in direct correlation with the exploitation capacity of a technical system, excluding the causes of failure (breakdown). In a general case, availability includes:

– proper availability $A_v$,
– operative availability $A_{op}$, and
– total availability $A_u$.

The same can be calculated by applying the following patterns:

*Table 1. Categories of probability in occurrence of malfunction*

| Rank | Effect | Description |
|---|---|---|
| 1. | 1/10000 | Small probability of occurrence of malfunction, i.e. it would be unreasonable to expect it |
| 2. | 1/5000 | Low probability of occurrence of malfunction, similar to previous plans in the past which had low level of occurrence of malfunction for given volume / load |
| 3. | 1/2000 | Low probability of occurrence of malfunction, similar to previous plans in the past which had low level of occurrence of malfunction for given volume / load |
| 4. | 1/1000 | Accidental occurrence of malfunction, similar to previous plans in the past which had low level of occurrence of malfunction for given volume / load |
| 5. | 1/500 | Medium probability of occurrence of malfunction, similar to previous plans in the past which had low level of occurrence of malfunction for given volume / load |
| 6. | 1/200 | Medium - high probability of occurrence of malfunction, similar to previous plans in the past which had low level of occurrence of malfunction for given volume / load |
| 7. | 1/100 | High probability of occurrence of malfunction, similar to previous plans in the past which had high level of occurrence of problems |
| 8. | 1/50 | High probability of occurrence of malfunction, similar to previous plans in the past which had high level of occurrence of problems |
| 9. | 1/20 | Very high probability of occurrence of malfunction, almost certain to cause a problem |
| 10. | 1/10 | Very high probability of occurrence of malfunction, almost certain to cause a problem |

$$A_v = \frac{T_{oz}}{T_{oz} + T_{pog}} \quad \text{.........................} (2)$$

$$A_{op} = \frac{T_{op}}{T_{op} + T_{po}} \quad \text{.........................} (3)$$

$$A_u = \frac{T_{op}}{T_{op} + T_{pov}} \quad \text{.........................} (4)$$

where:

$T_{oz}$ - average time between the failures,

$T_{po}$ - average technical time of duration of repair after a failure,

$T_{op}$ - average time between two consecutive maintenance interventions,

$T_{pog}$ - average technical time of duration of repairs after failures, and

$T_{pov}$ - average time of duration of repairs including the stand-by time.

In this paper, the time when preventive maintenance intervention should be performed, is the time when the total maintenance costs (EUR/hour) are minimal. Account was also taken of reliability magnitudes R(T) and failure intensity λ(T) in the process. The highest operative and total availability for the minimal maintenance costs (EUR/hour) can be calculated:

for preventive maintenance based "on constant date" (D) (the elements are replaced at pre-set moments of time, regardless of the 'age' of elements):

$$A_{OP_D} = \frac{T\ C_{D_{min}}}{T\ C_{D_{min}} + T_{pog} + H_m + T_{pop}} \quad \text{.............} (5)$$

$$A_{U_D} = \frac{T\ C_{D_{min}}}{T\ C_{D_{min}} + T_{pov}\ g \cdot H_m + T_{pov}\ p} \quad \text{.............} (6)$$

where:

$T(C_{dmin})$ - the period of work when total maintenance costs are minimal,

$T_{pop}$ - average technical time of duration of repairs for operations of preventive maintenance,

$T_{pov}(g)$ - average time of repairs, including the stand-by time (repair after a failure),

$T_{pov}(p)$ - average time of stand-by (repair in a preventive intervention),

$H_m$ - restoring function (average number of restoring).

for preventive maintenance based on "constant durability" (T) (elements are replaced when they reach a certain life):

$$A_{OP_T} = \frac{T_{op}\ C_{T_{min}}}{T_{op}\ C_{T_{min}} + T_{pog}\ F\ T + T_{pop} \cdot R\ T} \quad \text{..........} (7)$$

$$A_{U_T} = \frac{T_{op}\ C_{T_{min}}}{T_{op}\ C_{T_{min}} + T_{pov}\ g \cdot F\ T + T_{pov}\ p \cdot R\ T} \quad \text{........} (8)$$

where:

$T_{op}$ $(C_{Tmin})$ - average time between two consecutive maintenance interventions for the period of work when total maintenance costs are minimal,

F(T) - distribution function,

R(T) - reliability function [R(T) = 1-F(T)].

The quoted patterns (5),(6), and (8) can be used for calculating the availability for any time period of work, and also for some current system availabilities $A^{\bullet}_{opD}$,, and $A^{\bullet}_{opT}$ average time of duration of repair (system restoring time $T_{pop}$) can also be calculated. If the expressions are minimized:

$$\frac{T_{pog}}{T\ C_D} \cdot H_m + \frac{T_{pop}}{T\ C_D} = m_1 \quad \text{....................} (9)$$

$$\frac{T_{pog}}{T_{op}\ C_T} \cdot F\ T + \frac{T_{pop}}{T_{op}\ C_T} = m_2 \quad \text{................} (10)$$

then the maximum availability can be obtained, which is, in fact, the basic aim. By applying the relations (9), and (10), the following is obtained:

$$T_{pop}\ O = \left(\frac{1}{A^{\bullet}_{opD}} - 1\right) \cdot T\ C_D - T_{pog}\ O\ , \quad \text{.....} (11)$$

$$T_{pop}\ T = \frac{T_{op}\ C_T \cdot \left(\frac{1}{A^{\bullet}_{opT}} - 1\right) - T_{pog}\ T \cdot F\ T}{R\ T} \quad \text{.......} (12)$$

## 4. Result and data processing

The data on performance of the technical system are obtained from the "Report on system performance" and refer to the time period of system work between two average repairs. In order to enable defining of appropriate conclusions on possibilities of increasing the availability by organizing maintenance actions in real conditions of exploitation on the basis of all the recorded data, the obtained data are arranged in a new way, as shown in Table 1 and Table 2.

Time period *(T)* of occurrence of a failure has been chosen in the time interval of 100 hours, considering the periodicity of maintenance teams' work in shifts. In other words, it turned out that the occurrence of failures in particular time intervals also depends on the makeup of the workgroups - maintenance teams.

By x-square test, the hypothesis of normal (Gauss) distribution of probability of failure was verified. It was also determined that average time between failure (failure-free operation) has a normal distribution which facilitated calculating the restoration function $(H_m)$. Maintenance cost estimate was performed for one preventive intervention, for both preventive maintenance based on "Constant durability", and "constant date", taking into account total costs for failure elimination $(C_g)$ and for preventive intervention $(C_p)$ as follows:

*Table 1 and 2 The data on performance of the technical system*

| TABLE 1 | | | | | | | | | TABLE2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Maintenance costs with "constant date" | | Maintenance costs with "constant durability" | | | |
| Ordinal No. | Period T(h) | Number of failures (Ni) | Probability of failure occurrence (f=Ni/∑Ni) | Unreliability (F-∑f) | Reliability (R=l-F) | Failure intensity λ=f/R | Average number of restoring (Hm=∑F) | Average duration time of repair (Tpo/h/) | Expenses caused by the occurrence of a failure Cq-Hm /EUR/ | Toial maintena-nce costs CD /EUR/h/ | Average time between two maintenance interventions Top /h/ | Costs caused by the occurre-nce of a failure CgF/R/ | Costs caused by reventive interve-ntions Cp-R(T) | Total maintenance costs CT /EUR/h/ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 100 | 6 | 0.046 | 0.046 | 0.954 | 0.048 | 0.046 | 5.580 | 2131.20 | 40.44 | 288.50 | 1027.20 | 8930.00 | 34.51 |
| 2 | 200 | 3 | 0.023 | 0.069 | 0.931 | 0.024 | 0.115 | 11.110 | 32.82 | 36.82 | 377.80 | 1.14 | 8860.00 | 23.48 |
| 3 | 300 | 5 | 0.038 | 0.069 | 0.893 | 0.042 | 0.222 | 27.275 | 1207.20 | 22.41 | 466.40 | 400.80 | 8330.00 | 18.72 |
| 4 | 400 | 1 | 0.007 | 0.114 | 0.886 | 0.007 | 0.336 | 27.395 | 272.22 | 17.12 | 549.70 | 76.61 | 8030.00 | 14.75 |
| 5 | 500 | 7 | 0.053 | 0.167 | 0.883 | 0.063 | 0.503 | 32.015 | 231.96 | 14.62 | 630.00 | 59.77 | 7570.00 | 12.11 |
| 6 | 600 | 4 | 0.030 | 0.197 | 0.803 | 0.037 | 0.700 | 32655 | 3640.70 | 17.06 | 705.70 | 817.36 | 7270.00 | 11.46 |
| 7 | 700 | 6 | 0.046 | 0.243 | 0.757 | 0.060 | 0.943 | 35.845 | 11659.55 | 24.07 | 778.40 | 2559.43 | 6580.00 | 11.74 |
| 8 | 800 | 4 | 0.030 | 0.273 | 0.727 | 0.041 | 1.216 | 40.835 | 1741.11 | 11.74 | 844.20 | 347.64 | 6120.00 | 7.66 |
| 9 | 500 | 9 | 0.069 | 0.342 | 0.658 | 0.104 | 1.558 | 53.705 | 1842.89 | 10.77 | 905.40 | 331.02 | 5740.00 | 6.71 |
| 10 | 1000 | 6 | 0.046 | 0.388 | 0.612 | 0.075 | 1.946 | 55.165 | 7223.66 | 14.35 | 962.80 | 1181.90 | 5360.00 | 6.44 |
| 11 | 1100 | 5 | 0.038 | 0.426 | 0.574 | 0.066 | 2.372 | 56.875 | 6253.46 | 12.50 | I0I6.4 | 981.74 | 4670.00 | 5.66 |
| 12 | 1200 | 5 | 0.038 | 0.464 | 0.536 | 0.070 | 2.836 | 61.095 | 7853.83 | 12.75 | 1061.10 | 1138.24 | 4290.00 | 5.11 |
| 13 | 1300 | 9 | 0.069 | 0.533 | 0.467 | 0.147 | 3.369 | M.I 35 | 1315.71 | 7.54 | 1106.00 | 172.39 | 4060.00 | 3.83 |
| 14 | 1400 | 5 | 0.038 | 0.571 | 0.429 | 0.088 | 3.940 | 67.435 | 31065.35 | 25.67 | 1146.60 | 3879.43 | 3530.00 | 6.46 |
| 15 | 1500 | 3 | 0.023 | 0.594 | 0.406 | 0.056 | 4.534 | 67.915 | 3151.60 | 7.74 | II8I.9 | 364.69 | 3230.00 | 3.04 |
| 16 | 1600 | 7 | 0.053 | 0.647 | 0.535 | 0.150 | 5.181 | 77.715 | 1902.74 | 6.61 | 1214.20 | 203.15 | 3000.00 | 2.64 |
| 17 | 1700 | 4 | 0.030 | 0.677 | 0.323 | 0.092 | 5.858 | 78.605 | 31155.04 | 21.66 | 1244.00 | 3387.36 | 2000.00 | 4.33 |
| 18 | 1800 | 3 | 0.023 | 0.700 | 0.300. | 0.076 | 6.558 | 79.085 | 8720.39 | 9.36 | 1264.20 | 905.92 | 1470.00 | 1.88 |
| 19 | 1900 | 13 | 0.100 | 0.800 | 0.200 | 0.500 | 7.358 | 84:2 05 | 174497.97 | 13.07 | 1278.13 | 1773.61 | 7100.00 | 1.94 |
| 20 | 2000 | 7 | 0.053 | 0.853 | 0.147 | 0.036 | 8.211 | 85.965 | 34313.09 | 20.14 | 1285.00 | 338.94 | 0.00 | 2.63 |
| 21 | 2100 | 10 | 0.076 | 0.929 | 0.071 | 1.070 | 9.140 | 89.295 | 2131.20 | 40.44 | 288.50 | 1027.20 | 8930.00 | 34.51 |
| 22 | 2200 | 8 | 0.061 | 1.000 | 0.000 | 2.070 | 10.140 | 95.255 | 32.82 | 36.82 | 377.80 | 1.14 | 8860.00 | 23.48 |

$$C_D = \frac{C_g \cdot H_m + C_p}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$C_T = \frac{C_g \cdot F\,T + C_p \cdot R\,T}{T_{op}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Maintenance costs were calculated by applying the relations (13) and (14), and are shown in Table 2. From Table 2 and Figure 2, it can be seen that the minimal maintenance costs (1.88 EUR/hour) are for the operation time of 2,000 hours, and it is for maintenance strategy based on "constant durability". For this period of time, the highest operative and total availabilities can also be calculated by applying the patterns (5), (6), (7), and (8):

$$A_{op_D} = \frac{2000}{2000 + 1{,}72 \cdot 8{,}211 + 68} = 0{,}96066$$

$$A_{U_D} = \frac{2000}{2000 + 1{,}76 \cdot 8{,}211 + 72} = 0{,}95856$$

$$A_{op_T} = \frac{1264{,}2}{1264{,}2 + 1{,}72 \cdot 0{,}853 + 68 \cdot 0{,}147} = 0{,}9910$$

$$A_{U_T} = \frac{1264{,}2}{1264{,}2 + 1{,}76 \cdot 0{,}853 + 72 \cdot 0{,}147} = 0{,}9505$$

It is obvious that higher availability values are obtained for the maintenance strategy based on "constant durability" than for the maintenance strategy based on "constant date", which confirms again the fact that for the observed technical system, the most acceptable maintenance strategy is the one based on "constant durability". The results arouse special interest, because the exclusive maintenance strategy based on "constant date" has been applied to the technical system (Agio-machine) until now. By applying Table 1 and Figure 1, it can be noticed that the failure intensity *λ(T)* begins to rise sharply-after 1,800 hours of work, and thus the system should be covered and maintenance preventive action should be carried out. However, as maintenance costs for this period of time are higher than the costs for the period of time of 2,000 hours, the preventive activity is therefore delayed until the 2,000$^{th}$ work hour.

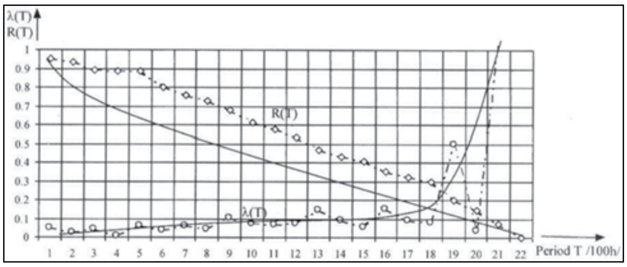


*Figure 1 Diagram of Failure Intensity A and Reliability R in the period of six months*

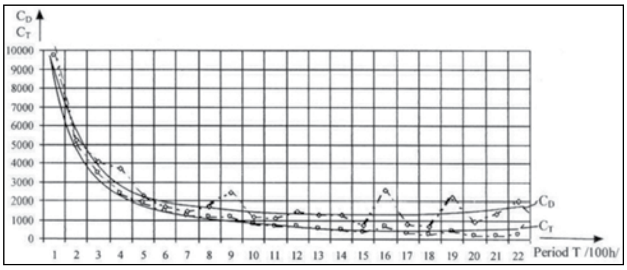


*Figure 2. Diagram of costs of preventive maintenance based on constant date ($C_D$) and constant durability ($C_T$) for six months*

## 5. Conclusions

It is common to estimate the state of a technical system each time when preventive maintenance is carried out. After realization of certain number of actions in preventive maintenance and recording them for each technical system, sufficient quantity of information will be available for establishing whether a technical system should be exposed to more or less frequent maintenance actions, and how frequently preventive maintenance should be carried out.

The research results provide the following conclusions:

1. The better preventive maintenance is, the better availability. The difference between operative and total availability gives the impact of preparation time for failure elimination.
2. However, total availability is lower than the operative one if maintenance organization is improved, and it is possible for total availability to come closer to the operative one in value. The ultimate goal should be operative availability
3. The applied method of obtaining availability and total maintenance costs is suitable for maintenance planning. Detailed comments

of all the results have not been given in the analysis of the given example, since the stress has been laid on defining availability, and the objective was to indicate to a possible way of calculating the availability of a complex technical system.

Optimizing available technical resources of a company with minimal expenses is a fundamental principle of contemporary business management. It is explained as a way of obtaining maximum time of flawless work and achieving value of every technical system. By applying the right form of maintenance, and at the right time, significant financial savings can be made, thus increasing time of flawless work of a technical system.

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