USING SIMULATION TO OPTIMIZE PREVENTIVE MAINTENANCE INTERVAL

Zdeněk ALEŠ[1], Jan NOVÁK[2], Marián KUČERA[3], Jindřich PAVLŮ[1]

[1]*Department for Quality and Dependability of Machines, Faculty of Engineering, Czech University of Life Sciences Prague, Czech Republic*
[2]*Kleentek, spol. s r.o., Sazečská 560, 108 00 Prague 10, Czech Republic*
[3]*Technical University in Zvolen, Faculty of Technology, Department of Mechanics, Mechanical Engineering and Design, Slovak Republic*

Abstract
Today's modern agricultural and processing companies use complex machines and equipment that use automated or robotic systems. These machines are usually key objects for the company, and it is therefore necessary to ensure proper maintenance, as the failure of these machines is very costly for companies. The mentioned technologies enable the collection of a large amount of not only data from operation, but also operational data concerning technical condition and faults. This data must be processed using algorithms to obtain feedback for decisions on preventive maintenance. Information technology allows you to create simulations that can be used retrospectively to plan maintenance activities. The paper describes the possibilities of using information technology to optimize preventive maintenance.

Key words: *preventive maintenance, failure, average unit costs, renewal.*

INTRODUCTION

The current maintenance status within industrial companies has improved significantly over previous years in favour of preventive maintenance. At the same time industrial companies began to increasingly implement predictive maintenance tools using a variety of diagnostic methods for determining the operational or structural parameters of a particular manufacturing machinery. The trend of the current development of technical progress in connection with the current challenge Industry 4.0 is characterized, among other things, by an enormous increase in data collection. Industrial companies have a large amount of data; however, they are mostly not able to analyse them and gain valuable information that can be used as feedback for decision making.

Preventive maintenance can be understood as a set of activities aimed at preventing the occurrence of failures and accidents (*Pacaiova & Izarikova, 2019*). Preventive maintenance is performed to maintain and increase the reliability of machines and equipment by restoring worn-out machinery objects before they fail. Preventive maintenance activities include inspections of machinery and equipment, partial or complete changes at predetermined intervals, oil changes, lubrication, and more. In addition, maintenance workers can collect data on the gradual deterioration of the technical condition of machines and equipment. The obtained data help in deciding on the replacement or maintenance of worn-out machinery before the failure. Current technological advances make it possible to monitor many diagnostic signals with relatively high accuracy (*Legat, Mosna, Ales & Jurca, 2017*).

The field of processing and evaluation of reliability data is closely related to the operation of machines and equipment in agriculture. This fact is supported by the application of precision agriculture tools, which are characterized by using navigation systems, sensors, electronics, and information technology in general.

Preventive maintenance in the production industry is one of the most essential measures to eliminate accidental machinery failures by replacing/repairing worn out machines or parts. The decision of when and where to perform preventive maintenance is non-trivial due to the complex and stochastic nature of the industry where preventive maintenance is implemented. Some authors use theoretical and practical implementation of preventive maintenance based on a unique modification of the total productive maintenance methodology. The innovative approach of preventive maintenance management was already implemented in the real production. Within preventive maintenance, the new concept may bring in an innovative method of managing the maintenance process, from abstract methodical conception to practical usage. A challenging task while implementing Industry 4.0 technologies is the issue of how to

fully gather and analyse operational data from various items of equipment and users under various conditions, which would result in innovative services of equipment maintenance to increase production and maintenance efficiency *(Hardt, Kotyrba, Volna & Jarusek, 2021).*
Industry 4.0 has become more popular due to recent developments in cyber-physical systems, big data, cloud computing, and industrial wireless networks. Intelligent manufacturing has produced a revolutionary change, and evolving applications, such as product lifecycle management, are becoming a reality. Other authors proposed and implemented a manufacturing big data solution for active preventive maintenance in manufacturing environments. The manufacturing big data method used for active preventive maintenance has the potential to accelerate implementation of Industry 4.0 (*Wan, Tang, Li, Wang, Liu, Abbas & Vasilakos, 2017*).
Conventional preventive maintenance models often assume that equipment is always available for maintenance activities. However, in many mission-critical industries, equipment may not be available for scheduled maintenance due to busy operational schedules. Forced shutdown of the equipment may incur extra costs that cannot be offset by the benefits from preventively maintaining the equipment. Other paper proposes innovative preventive maintenance policies to address the challenges caused by equipment unavailability. Maintenance models with possible rescheduling are developed for both time-based and condition-based maintenance policies, and the objective is to minimize the long-run cost rate of all maintenance activities (*Zhu, Xiang, Li, Zhu & Schneider, 2019*).
Preventive maintenance is an important component of the Industry 4.0. Modern industry requires intelligent, autonomous, and reliable manufacturing systems. Furthermore, other authors propose methodology for the acquisition of maintenance knowledge, using the computer simulation method to predict possible failures and prepare scenarios for the behaviour of a system *(Klos, 2018).*
The use of system analysis and preventive maintenance in today's industry becomes a necessity as it increases equipment availability. One of the new proposed methods combine three tools: SADT modelling, the FMECA analysis and the Pareto diagram to achieve an optimal maintenance approach that will be a decision support tool to minimize the repair costs and the downtime of the system (*Karoui & Lakhoua, 2021*).
The paper describes how to use computational algorithms to determine the optimal interval for performing preventive maintenance. Knowledge of the characteristics of reliability is a necessity for the application of the theory of renewal, to determine the most appropriate maintenance strategy. Created computational algorithms are validated on model examples. The results can be used as a decision-making tool for maintenance management to determine the optimal interval of preventive maintenance of specific machinery components, and the entire manufacturing machinery. At the same time utilizing the results of the paper may help to simplify the planning of plant downtime, optimizing of maintenance personnel capacity and a quantity of spare parts, which ultimately help to increase the availability of production facilities while reducing costs spent on maintenance.

MATERIALS AND METHODS

According to the standard EN 13306:2010 Maintenance – Maintenance terminology, the maintenance strategy is defined as a management method used to achieve maintenance objectives.
The general objectives of maintenance include:

- carry out the correct renewal, modernization and reconstruction of the property and take care of its optimal use,
- to maintain tangible assets in a serviceable and fit condition and at the required level of availability, efficiency, use and its optimal recovery as a whole,
- prevent the occurrence of faults and the following fault conditions,
- operatively eliminate the failures,
- reduce the environmental impact of the operation and maintenance of production facilities,
- ensure the safety of operation and maintenance of production equipment,
- spend optimal maintenance costs in relation to the availability and efficiency of the production equipment and
- manage asset management and maintenance to excellence using the methods of world best practice – asset management.

Maintenance activities are based on technical and economic decision-making, and it is costs that are essential and need to be paid close attention to. It is always necessary to compare two types of costs, namely the unit cost of corrective maintenance and the unit cost of preventive periodic maintenance. If a diagnostic method can be applied during maintenance, it is necessary to add the unit cost of the diagnostics. The general relations for calculation are described further in the text. Presented calculations were used in algorithms to obtain optimal values.
The calculation model is also based on the calculation of unit costs for operation and maintenance, including induced losses associated with the application of individual maintenance policies (systems). The most suitable is the maintenance system for the given object, which will show the lowest unit costs (3). According to this criterion, the optimal maintenance policy (system) for the given object is selected (*Pavlu, Ales & Jurca 2013*).
The unit costs of corrective maintenance $u_{up}(MOTTF)$ are given by the ratio of the cost of corrective maintenance and the mean operational time to failure and is calculated according to the relation (1)

$$u_{up}(MOTTF) = \frac{N_{up}}{MOTTF} \tag{1}$$

where: N_{up} is the cost of corrective maintenance (costs of primary and secondary (dependent) failures (CZK), spare parts and material inventory holding, production losses, environmental impacts, safety, maintenance personnel availability), *MOTTF* is mean operational time to failure during corrective maintenance (hrs).

If Weibull distribution is considered for the calculation of the mean operational time to failure *MOTTF*, it is calculated according to relation (2)

$$MOTTF = \beta \cdot \Gamma\left(1 + \frac{1}{\alpha}\right) \tag{2}$$

where: *MOTTF* is mean operational time to failure during corrective maintenance (hrs), α is shape parameter of Weibull distribution, β is scale parameter of Weibull distribution, Γ is Gamma function.

The average unit costs of preventive periodic maintenance $u_{pu}(t_{pu})$ are again given by the ratio, where the numerator is the sum of the costs of preventive maintenance N_{pu} multiplied by the reliability $R(t_{pu})$ for the selected interval of periodic maintenance (technical condition without failures) and the costs of corrective maintenance N_{up} multiplied by the probability of failure $F(t_{pu})$ for the selected interval of periodic maintenance (it is a state with the occurrence of failure) and where the denominator is the mean operational time until preventive periodic maintenance is carried out and are calculated according to relation (3)

$$u_{pu}(t_{pu}) = \frac{N_{pu} \cdot R(t_{pu}) + N_{up} \cdot F(t_{pu})}{t_s(t_{pu})} = min \Rightarrow t_{pu} = t_{puo} \tag{3}$$

where: $R(t_{pu})$ is reliability function, $F(t_{pu})$ is the probability of failure, $t_s(t_{pu})$ is the mean time of operation until preventive periodic maintenance is performed with an interval and t_{puo} is the optimal periodical maintenance interval (unit costs reach the minimum value).

If Weibull distribution is considered, it is possible to adjust the calculation relation to the form (4)

$$u_{pu}(t_{pu}) = \frac{N_{pu} \cdot exp\left[-\left(\frac{t_{pu}}{\beta}\right)^{\alpha}\right] + N_{up} \cdot \left\{1 - exp\left[-\left(\frac{t_{pu}}{\beta}\right)^{\alpha}\right]\right\}}{\int_{t_p=0}^{t_{pu}} exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] dt} \tag{4}$$

where: t is operational time (hrs).
In order to model the optimal interval for renewal t_{puo}, different values of Weibull distribution, respectively the shape parameter α, and ratios of the costs of preventive maintenance N_{pu} and corrective

maintenance N_{up} were chosen. The selected values are shown in Tab. 1. More than 7,000 complex calculations were performed using the object-oriented language Visual Basic for Applications.

Tab. 1 Input values for the renewal optimization computational model

Indicator	Minimum value	Maximum value	Increment
Shape parameter α	1.05	10	0.05
Scale parameter β	1000	1000	constant
Ratio of corrective maintenance costs to preventive maintenance costs (N_{up}/N_{pu})	1	10	0.5

Probability density function of failure *f(t)* from table 1 is for better visualization shown for the whole range of shape parameter α are shown in Fig. 1. The result of the model is two 3D graphs for two variable inputs and one calculated output. A description of the axes of the first 3D graph is shown in Fig. 2. The value of the shape parameter α of Weibull distribution is plotted on the x-axis. On the y-axis, the optimal average unit costs of preventive periodic maintenance are calculated. On the z-axis is the ratio of corrective maintenance costs to preventive maintenance costs. At Fig. 3 on the y-axis, the optimal interval of mean operation time for renewal is calculated.

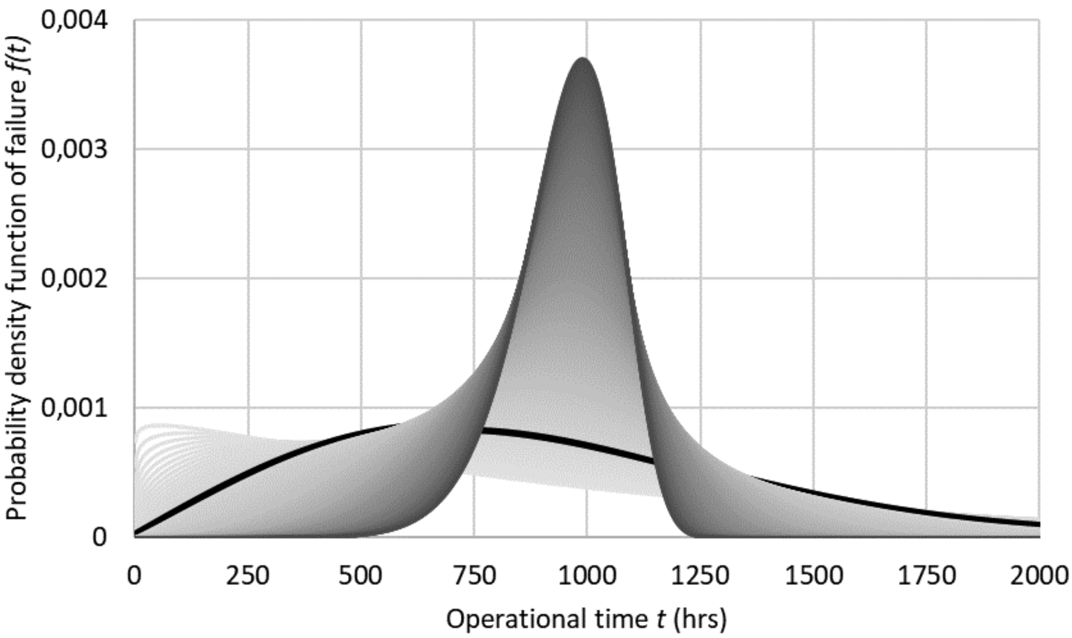

Fig. 1 Probability density function of failure *f(t)* for different shape parameter α of Weibull distribution (α = 1.05 light grey curves, α = 10 dark grey curves, increment 0.05, α = 2 black curve)

RESULTS AND DISCUSSION

The presented Fig.2 and Fig. 3 clearly show the influence of the economic point of view, that when the ratio of N_{up}/N_{pu} increases, then average unit costs for preventive maintenance decrease. The shape parameter α of Weibull distribution can be considered a technical condition of object, and its increase has the greatest effect on the intensity of failures, which has a progressive course if $\alpha > 2$. This fact can be demonstrated by black curve of failure probability density curve *f(t)* in Fig. 1. Simply put, as the shape parameter α of the Weibull distribution increases, the optimal interval for periodic preventive maintenance increases, which contributes to the reduction of maintenance interventions in the long term.

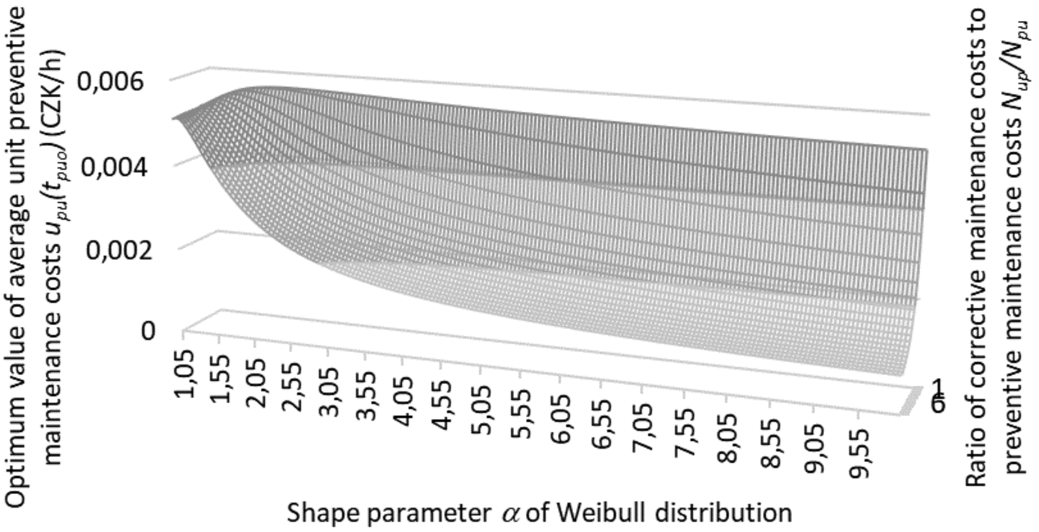

Fig. 2 Dependence of the values of the optimal average unit costs $u_{pu}(t_{puo})$ depending on value of shape parameter α of Weibull distribution and the ratio of corrective maintenance costs N_{up} to preventive maintenance costs N_{pu}

Performed simulation is very important, because it considers both aspects, both economic in the sense of the cost ratio, and technical, how the technical object behaves in terms of reliability characteristics (*Legat, Mosna, Ales & Jurca, 2017*). As mentioned earlier, apart from the solution proposed by the authors, it is advisable to combine with other analysis related to equipment availability (*Karoui & Lakhoua, 2021*) and at the same time implement technologies of Industry 4.0 approach (*Klos, 2018; Hardt, Kotyrba, Volna & Jarusek, 2021*). Results of the paper contribute to preventive maintenance optimization, which is important from the point of view of ensuring machine operability.

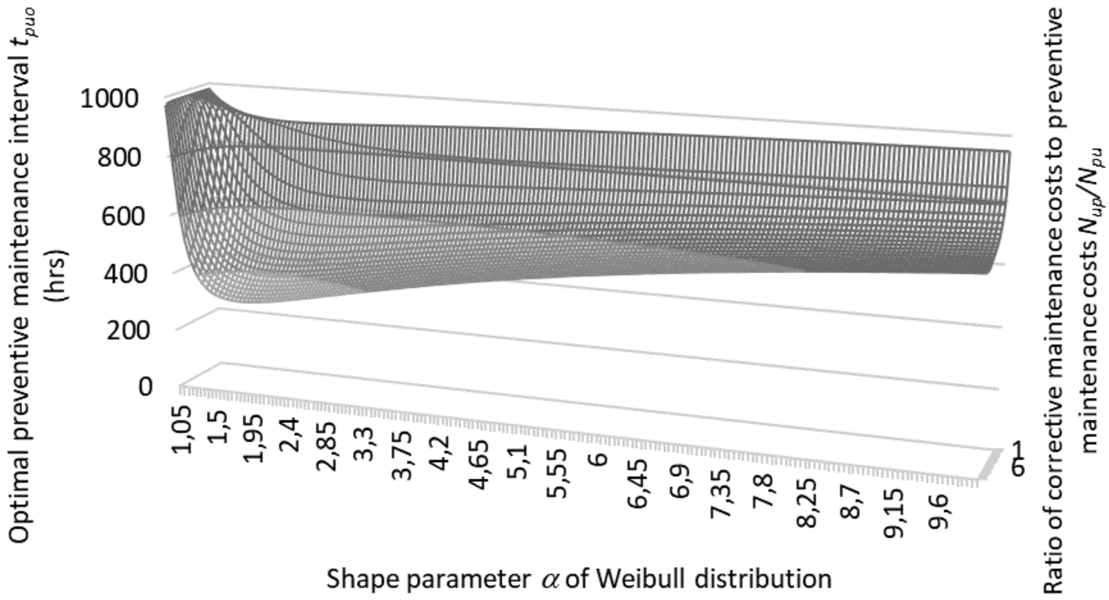

Fig. 3 Dependence of the optimal preventive maintenance operation time interval t_{puo} depending on the size shape parameter α of Weibull distribution and the ratio of corrective maintenance costs N_{up} to preventive maintenance costs N_{pu}

CONCLUSIONS

The use of algorithms in conjunction with computer technology offers several possibilities for specifying the optimal interval for performing preventive maintenance in real time. The proposed algorithms can be used not only as a decision-making tool in maintenance management with the aim of determining the optimal preventive maintenance interval of specific machine elements and thus of the entire production equipment. At the same time, the use of the results of the algorithms will contribute to simpler planning of production equipment shutdowns, the capacity of maintenance personnel and the number of spare parts, which will ultimately help to increase the availability of the production equipment while simultaneously reducing the maintenance costs.

ACKNOWLEDGMENT

This study was supported by Ministry of Industry and Trade – CZU: 31190/1484/314802; MPO: FV20286 - Maintenance management information system with benchmarking module respecting Industry 4.0.

REFERENCES

1. Hardt, F., Kotyrba, M., Volna, E., & Jarusek, R. (2021) Innovative Approach to Preventive Maintenance of Production Equipment Based on a Modified TPM Methodology for Industry 4.0, *APPLIED SCIENCES-BASEL*. Volume: 11. Issue: 15. Article Number: 6953. DOI: 10.3390/app11156953
2. Klos, S. (2018) Knowledge Acquisition Using Computer Simulation of a Manufacturing System for Preventive Maintenance. *INFORMATION AND SOFTWARE TECHNOLOGIES*, ICIST 2018. Book Series: Communications in Computer and Information Science. Volume: 920. Pages: 29-40 DOI: 10.1007/978-3-319-99972-2_3
3. Legat, V., Mosna, F., Ales, Z., & Jurca, V. (2017). Preventive maintenance models – higher operational reliability. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, 19 (1):134141.
4. Pacaiova, H., & Izarikova, G. (2019) Base Principles and Practices for Implementation of Total Productive Maintenance in Automotive Industry. *Quality Innovation Prosperity*, 23(1), 45-59.DOI: 10.12776/qip.v23i1.1203. ISSN 1338-984X.
5. Pavlu, J., Ales, Z & Jurca, V. (2013) Utilization of satellite monitoring for determination of optimal maintenance interval of agricultural machines. *Trends in Agricultural Engineering 2013*, 5th International Conference on Trends in Agricultural Engineering (pp. 512-517). CULS Prague.
6. Wan, JF., Tang, SL., Li, D., Wang, SY., Liu, CL., Abbas, H., & Vasilakos, AV. (2017) A Manufacturing Big Data Solution for Active Preventive Maintenance. IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS. Volume: 13 Issue: 4 Pages: 2039-2047 DOI: 10.1109/TII.2017.2670505
7. Zhu, ZC., Xiang, YS., Li, MY., Zhu, WH., & Schneider, K (2019) Preventive Maintenance Subject to Equipment Unavailability. IEEE *TRANSACTIONS ON RELIABILITY*. Volume: 68. Issue: 3. Pages: 1009-1020. DOI: 10.1109/TR.2019.2913331

Corresponding author:
doc. Ing. Zdeněk Aleš, Ph.D., Department of Quality and Dependability of Machines, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Prague Suchdol, 16521, Czech Republic, e-mail: ales@tf.czu.cz