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TOTAL PRODUCTION MAINTENANCE AND ROBUST SCHEDULING FOR A PRODUCTION SYSTEM EFFICIENCY INCREASING

In the paper, the proposition of application of two methodologies: the predictive scheduling and Total Productive Maintenance – TPM to increase efficiency of a production system is presented. To assess wastes due to unplanned events in the machine's work the Overall Equipment Effectiveness (OEE) indicator is applied. Any failure of a bottle neck decreases value of the OEE. In this paper, the problem of predicting a time of the bottle neck failure is considered. In the paper, models of a production system and failures are presented. For the bottle neck various reliability characteristics are computed: the probability that, beginning with moment t_0, the first failure occurs after given time *t*, probability that in the interval $[f,g]$, there occurs at least one failure, failure intensity function, Mean Time To Failure (MTTF) and Mean Time of Repair (MTTR). Having the MTTF and MTTR of the bottle neck, a robust schedule is generated. At the time of predicted failure, preventive actions and technical survey of the machine are scheduled. In the second paper a numerical example is given.

1. INTRODUCTION

In production enterprises, the production maintenance department solves problems resulting from manufacturing processes. Improving an efficiency of a production system exploitation depends on: utility of machines, failure and downtimes, schedule and execution of maintenance work. To satisfy a demand of a market, the production enterprise sets the highest priority for a high level of technology, manufacturing efficiency and high level of operational reliability. Changes in a production schedule are due to frequent disruptions. A disruption causes that the cycletime of job increases and pre-elaborated schedule is not feasible. Reorganization cost of production increases and execution time of job extends, that negatively influence on a price of a product. Therefore, in the production schedule a predicted time of failure and time of the machine repair are introduced.

The objective is to obtain a disturbances robust schedule. According to the definition formulated by Al-Fawzan and Haouaria the robustness of the schedule is "the sum of buffers of processes introduced in the schedule to increase the possibility of appearance of a slight increase in the cycle time of processes, as a result of unpredicted disturbance" [3]. Taking into account the disruption: a machine failure, the introduction of temporary buffers

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to the schedule causes that the cost of unused capacity increases, therefore the following definition is presented: the schedule is robust if the machine failure will be predicted with success and introduced in the schedule as a technical survey of the machine, in other case if can be rearranged without decision maker participation with minimum changes to the basic schedule, in other words, to return to a basic state (before the failure of the machine occurrence) as soon as possible.

The obtained schedule is characterized by solution and quality robustness. The solution robustness (instability) of the reactive schedule is measured by computing deviations of operations' starting times between reactive and previous (predictive) schedules. The quality robustness is measured as a deviation between makespan of reactive and previous schedules [11].

The robustness of the schedule can be aided by implementing methodologies relating to: effectiveness of machines, maintenance of machines and continuous improvement of production to a company structure. Systematic survey of machines influences on reduction of a risk of unexpected machine failures. Therefore, the article is a proposal to comprehensive maintain continuity of production by combining the methodology of predictive and reactive scheduling with the methodology of Total Productive Maintenance - TPM. The two methodologies make possible to maintain continuity of production, improve product quality, increase productivity and reduce production costs. The effectiveness of solutions is evaluated using indicator: Overall Equipment Effectiveness (OEE) [9]. Basing on the OEE indicator optimization decision-making process is done. The quality robustness of the schedule can be measured as a deviation between the OEE of reactive schedule and the OEE of predictive schedule.

In the article, the problem of reactive scheduling is omitted, interested may refer to the literature [2].

In this paper, the process of data acquisition is first described, then the method of prediction of *Mean Time To Failure* (MTTF), *Mean Time Between Failure* (MTBF), *Mean Time To Repair* (MTTR) is described. Values of MTTF, MTBF and MTTR are used to describe the model of the production system failure, the predictive scheduling method for the production system is presented. The resulting schedule is analyzed and evaluated using the indicators applied in the TPM methodology.

2. DATA ACQUISITION

Successive failure-free times are followed by times of repairs. Basing on information about a number of failures in a number of periods of the same duration in the past, predictions of reliability characteristics are searched.

Let us consider a classical model of failures in that successive periods of reliable work of a production system are followed by times of repair. Such the system, firstly, is observed on m successive time periods of the same durations, for which the information about

$$[0,T),[T,2T),\ldots,[(m-1)T,mT) \tag{1}$$

numbers of detected failures is known. The prediction of system behavior is being built for the next scheduling period $[mT,(m+1)T)$.

Such the system is observed with application of *Manufacturing Execution Systems* (MES), which allows to download information about the production process directly from machines. The example of such program is the Supervisory Control And Data Acquisition (SCADA) integrated with ERP systems related to production planning. Using SCADA and ERP systems following data are acquised: gross availability time (this is the time of the machine work minus planned downtimes related to maintenance intervals [10]), disability time (the time in that the machine is disable to work because of an unpredicted disturbance) and number of disturbances.

3. MODEL OF A PRODUCTION SYSTEM

A production system with input data: a number of jobs J, $j=1,2,...,J$ have to be executed on a number of machines $W, w=1,2,...,W$. Each job consists of a number of operations V_j, $v_j=1,2,...,V_j$; a_{w,v_j} denotes as an execution time of operation v_j of job j on machine w. Execution times of operations a_{w,v_j} are predefined in a Matrix of Operations' Times $MOT=\lfloor a_{w,v_j} \rfloor$ (3). A production route is described in the Matrix of Processes' Routes $MPR=\lfloor b_{w,v_j} \rfloor$ (2); b_{w,v_j} states as a priority of execution of operation v_j on machine w. Dead line d_j of execution of job j is predefined and described in the Vector of Due Dates $VDD=\lfloor d_j \rfloor$ (4). A butch size of job j is predefined and described in the Vector of Butch Size $VBS=\lfloor s_j \rfloor$ (5).

$$MPR=\begin{bmatrix} b_{v_1,1}, b_{v_1,2},..., b_{v_1,w},..., b_{v_1,W} \\ \vdots \quad \dots \\ b_{v_j,1}, b_{v_j,2},..., b_{v_j,w},..., b_{v_j,W} \\ \vdots \quad \dots \\ b_{v_J,1}, b_{v_J,2},..., b_{v_J,w},..., b_{v_J,W} \end{bmatrix} \quad MOT=\begin{bmatrix} a_{v_1,1}, a_{v_1,2},..., a_{v_1,w},..., a_{v_1,W} \\ \vdots \quad \dots \\ a_{v_j,1}, a_{v_j,2},..., a_{v_j,w},..., a_{v_j,W} \\ \vdots \quad \dots \\ a_{v_J,1}, a_{v_J,2},..., a_{v_J,w},..., a_{v_J,W} \end{bmatrix} \tag{2,3}$$

$$VDD=\lfloor d_1, d_2,..., d_j, \dots, d_J \rfloor \tag{4}$$

$$VBS=\lfloor s_1, s_2,..., s_j, \dots, s_J \rfloor \tag{5}$$

In section 7, measures used to evaluate the production system are described.

4. MODEL OF FAILURES

To predict values of parameters describing failure-free time of a machine and time of the machine's repair the probability theory is used, since it is assumed that the phenomenon - failure of the machine is repeatable.

Failure-free times $X_{i,1},...,X_{i,N_i}$ in the *i*th period $[(i-1)T, iT)$, $i=1,...,m+1$ have distribution with PDF (=probability density function) $f_i(\cdot)$. N_i denotes a random number of failures detected in $[(i-1)T, iT)$. At the end of reliable work period $X_{i,k}$, as the failure occurs, a repair time $Y_{i,k}$ begins immediately and so on. Repair times $Y_{i,1},...,Y_{i,N_i}$ for $i=1,...,m+1$ are supposed to be distributed with PDFs $g_i(\cdot)$

The following simplifying assumption is taken: each new period of the form $[(i-1)T, iT)$, starts with the beginning of reliable work $X_{i,1}$, in other words one "deletes" the residual repair time Y_{i-1,N_i} in the *i*th period $[(i-1)T, iT)$. Thus, one can write

$$\sum_{k=1}^{N_i} Z_{i,k} = \sum_{k=1}^{N_i} \left(X_{i,k} + Y_{i,k} \right) \approx T, \ \ i=1,...,m+1. \tag{6}$$

Random variables $X_{i,k}$, $Y_{i,k}$, for $i=1,...,m+1$ and $k=1,...,N_i$ are supposed to be totally independent. So, the evolution of the production system can be observed on successive cycles $Z_{i,k} = X_{i,k} + Y_{i,k}$, $i=1,...,m+1$, $k=1,...,N_i$ which are independent random variables with PDFs defined as follows:

$$h_i(t) = \int_0^t f_i(t-y) g_i(y) dy = \int_0^t g_i(t-y) f_i(y) dy, t > 0 \tag{7}$$

and DFs (=distribution functions) of the form

$$H_i(t) = \int_0^t h_i(y) dy, \ \ t > 0 . \tag{8}$$

A time of a schedule *t*, takes a positive variable, continuous in the interval [0, + ∞). The failure-free time is characterized by probability density function *f(t)*, the unreliability of the machine (distribution function) *F(t)*, machine's reliability *R(t)* and the failure intensity *r(t)* [8]. Below formulae for the most important reliability characteristics are presented:

1. Function $F(t)$, $t \in [mT, (m+1)T)$, that gives the probability that, beginning with moment $t_0 = mT$, the first failure occurs before time t:

$$F(t) = P\{X_{m+1,1} < t\} = \int_0^t f_i(u) du, \ \ t > 0. \tag{9}$$

2. Reability function R(t), that gives the probability that, beginning with moment $t_0 = 0$, the production system is not disturbed before the time t:

$$R(t) = P\{X_{m+1,1} > t\} = 1 - F(t) \tag{10}$$

3. Probability P that in the interval $[a,b] \in [mT,(m+1)T)$ there occurs at least one failure:

$$P = P\{a \leq X_{m+1,1} \leq b\} = \int_a^b f(u)du. \tag{11}$$

4. Failure intensity function *r(t)* is the quotient of the probability density function of a machine work at time *t* by the probability that the failure-free time the machine is longer than *t* [3]:

$$r(t) = \frac{f(t)}{R(t)}, \quad (t \geq 0, \ \ R(t) > 0) \tag{12}$$

5. The value of failure intensity function $\hat{r}$: is an increase of the number of failures at the period $[mT,(m+1)T)$ in relation to the period $[(m-1)T, mT)$:

$$\hat{r} \cong \frac{\Delta n}{\Delta t} \tag{13}$$

   where: Δn- an increase of the number of failures at the period $[mT,(m+1)T)$ in relation to the period $[(m-1)T, mT)$; Δt- an increase of the time period T, (each time period have the same duration (1))

6. Reliability function can be estimated basing on failure intensity function *r(t)* [3]:

$$H\ (t) = \exp\left(-\int_0^t r\ (u)du\right), \ \ t \geq 0 \tag{14}$$

Basing on the failure intensity curve (the waste intensity curve) (12, Fig.1) one can estimate a time in which the machine will be unable to work:

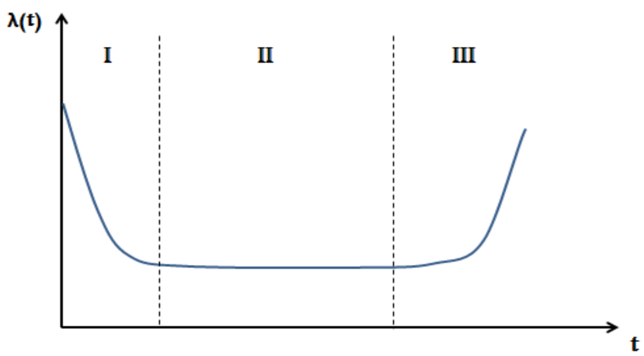

Fig. 1. The failure intensity curve [9]

In the theoretical graph of machine's failure intensity (Fig. 1), three stages describing the technical state of a machine are distinguished [10]. In the first phase, machine's parts incorrectly done are damaged. At this stage of the machine operation, quality control of defective components prevents further accidents and reduces the number of defects. There is no historical data about machine's failure so prediction using probability theory is no reliable but preventing activities of maintenance team should prevent the machine's failure. In [1], to model reliability when failure distributions cannot be determined the exponential distribution is proposed to use. In the second phase, there is a constant number of failures. The failure-free time can be predicted and should be introduced into the schedule. The maintenance team should know the time of predicted machine's failure. In the third phase, there are damages related to natural machine's wear, it is a sign to replace the machine or perform overhaul, scheduled preventive maintenance. The intensity of the machine's failure increases and one can estimate the end time of the last phase of the live cycle of the machine.

5. ESTIMATION AND PREDICTION OF DISTRIBUTION PARAMETERS

Basin on data about the number of failures and failure-free times of the machine in the time periods of equal length T a histogram is built. The histogram represents the dependence of the number of observations and failure-free time of the machine work.

For the variables $X_{i,k}$ and $Y_{i,k}$, a theoretical probability distribution function e.g. normal distribution, gamma distribution, exponential, log normal distribution is fitted. To calculate the degree of goodness of fit of the empirical distribution of $X_{i,k}$ and the theoretical distribution, appropriate tests are applied. For example for the normal distribution the Kolmogorov's test is used. In the test, to check whether the tested sample is described by the given distribution an absolute value of difference between empirical and theoretical distribution functions is computed. Having the biggest difference D the testing statistics ξ [10]:

$$\xi_{obl} = \sqrt{n} D_n \qquad (15)$$

where: n – a sample size,
is computed. If the value of the empirical statistics is less than the critical value of the Kolmogorov's distribution for a given level of significance, the hypothesis: the tested distribution fits the theoretical distribution is accepted [4].

To estimate the reliability characteristics in the ith period $[(i-1)T, iT),\ i = 1,...,m+1$ methods: maximum likelihood approach, empirical moment approach and method based on renewal theory approach are used [4],[7],[8]. Having reliability characteristics for the ith period $[(i-1)T, iT),\ i = 1,...,m$, the classical regression to predict reliability characteristics for period $m+1$ is used.

6. A PREDICTIVE SCHEDULING

For the production system described by MOT, MPR, VDD and VBS a predictive schedule is built. For the most loaded machine, failure-free times $X_{i,1},...,X_{i,N_i}$ of in the ith period $[(i-1)T, iT)$, $i=1,\ldots,m+1$ have distribution with PDF $f_i(\cdot)$ and repair times $Y_{i,1},\ldots,Y_{i,N_i}$ for $i=1,\ldots,m+1$ have distribution with PDFs $g_i(\cdot)$. MTBF, MTTF and MTTR parameters describe the most loaded machine.

MTTR determines an average time of repair or remove failures. MTTR indicates the efficiency of the maintenance department. MTTR can be evaluated using [6]:

$$MTTR = \frac{failure\ time}{number\ of\ repairs}, \tag{16}$$

In this paper, MTTR for scheduling period *m+1* is:

$$MTTR = \varphi_{m+1}, \tag{17}$$

φ_{m+1} - the expected value of $g_i(\cdot)$.

MTTF ratio is defined as an expected value of time of proper working up to the machine's failure. MTTF can be computed [6]:

$$MTTF = \frac{available\ time - failure\ time}{number\ of\ failures}, \tag{18}$$

and [4]:

$$MTTF = \int_0^\infty F(t)dt, \tag{19}$$

where: F(t) - probability that, beginning with moment $t_0 = mT$, the first failure occurs before time t.

The MTBF indicates an average failure-free time of the machine. It is used for serviceable machines. For machines that are irreparable, MTTF is used. In the article the MTBF is used to predict the frequency of technical inspections of the machine. MTBF for irreparable machines can be computed [6]:

$$MTBF = \frac{available\ time}{number\ of\ failures}, \tag{20}$$

For serviceable machines, MTBF is computed as a sum of MTTR and MTTF [4]:

$$MTBF = MTTF + MTTR = E\{X_{m+1,1} + Y_{m+1,1}\} \tag{21}$$

E – the expected value.

The predictive schedule is generated using the Enterprise Dynamics (ED) software. The ED can simulate operation of the production system with work of each machine by two parameters: MTBF and MTTR description. Having MTBF and MTTR the robust schedule is elaborated by increasing a cycle time of the operation predicted to be disturbed, by the time of repair. The job's operation will be disturbed if the start time of the operation $tr_{V_j} \leq MTTF$ and the end time of the operation $tz_{V_j} \geq MTTF$. The start time of the operation will be delayed if $tr_{V_j} = MTTF$ and $tz_{V_j} \geq MTTF$, the ending time of the operation will be delayed if $tr_{V_j} \leq MTTF$ and $tz_{V_j} \geq MTTF$:

$$tr_{V_j^*} = tr_{V_j} + MTTR \tag{22}$$

$$tz_{V_j^*} = tz_{V_j} + MTTR \tag{23}$$

where: $tr_{V_j^*}$ - the start time ($tz_{V_j^*}$ - the end time) of the operation V_j of the job j after the disturbance has occurred.
In the predictive schedule the technical survey of the machine is planed at the time of $MTTF$.

7. THE PRODUCTION SYSTEM EVALUATION

The assumption of the TPM method is to maintain machines in the state of productivity. The responsibility of each maintenance employee is to identify, monitor and remove causes of a waste as a result of disturbances: breakdowns, little downtimes, work below a nominal performance, retooling of a machine and inadequate quality. Breaks for technical service are included in the production schedule. Each unplanned disturbance causes an increase in waste. The objective is to achieve: zero machine's failures, zero defects, zero accidents at work. To assess the waste due to unplanned events in the machine's work, such as unplanned downtimes or too large machine cycle times the Overall Equipment Effectiveness (OEE) indicator is applied.

The OEE indicator compares the real usage of the machine to the ideal usage, according to schedule (16). The available time is the time duration of a shift. The schedule includes predicted downtimes: machine failures, changing of workers' shift, retooling, etc. A time of efficient production is the time of a product production. Components of the OEE have an impact on the waste in the production systems [9].

$$\text{OEE} = \text{Availability x Performance x Quality} \tag{24}$$

The machine's availability represents the percentage of scheduled time that the operation is available to operate. An Available Time is the scheduled time of operation execution minus unplanned disturbances.

$$\text{Availability} = \text{Available Time / Scheduled Time} \tag{25}$$

The performance of the production system represents the speed of the production line run as a percentage of its designed speed. The performance includes each loss of speed: working with reduced speed, incompetence of the employee.

Performance = (Parts Produced * Ideal Cycle Time) / Available Time (26)

Quality is the ratio of Good Units produced to the Total Units Started. The Good Units is a number of products planned to produce minus a number of defective products.

Quality = Good Units / Units Started (27)

Calculation of the OEE indicator allows to specify efficiency of the production system. It is good when the OEE indicator reaches 60%, and should aim to increase efficiency around 80% to make full use of machines and equipments.

8. SUMMARY

In this paper, the proposal to comprehensive maintain continuity of production using both the methodology of TPM and the methodology of predictive and reactive scheduling is presented. Depending on the stage of the live cycle of the machine predictive scheduling or/and TPM is recommended to use. In the first phase, there is no historical data about the machine's failure so the prediction using probability theory is no reliable. The preventing activity of maintenance team should prevent the machine's failure. In the second phase, there is a constant number of failures. The failure-free time can be predicted and should be introduced into the schedule. The maintenance team should know the time of predicted machine's failure. In the third phase, there are damages related to natural machine's wear, it is a sign to replace the machine or perform overhaul, scheduled preventive maintenance. The intensity of the machine's failure increases and one can estimate the end time of the last phase of the live cycle of the machine.

In this paper, the problem of predicting times of machine failure and repair is considered. Reliability characteristics: MTTF, MTTFF, MTTR are estimated using (17,19,21) instead of (16,18,20) because various distributions can describe variables: failure-free time and repair time. Histograms that show the graphical relationship of a number of observations and failure-free/repair times of the machine basing on historical data are created. In Statistica program the histograms to the theoretical distributions: normal, exponential, gamma and Weibull using appropriate tests are fitted. After finding distribution parameters for given past periods one extrapolates values of distributions parameters for the next scheduling horizon using the regression method.

Having information about the MTTF and MTTR of the machine, robust schedule is generated. At the time of the predicted failure, preventive actions and technical survey of the machine is scheduled.

In the article theoretical description of the reliability characteristics are given, in the second article a numerical example is attached.

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