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# A NUMERICAL EXAMPLE OF TOTAL PRODUCTION MAINTENANCE AND ROBUST SCHEDULING APPLICATION 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. In this paper, an example of problem of predicting a time of a bottle neck failure is presented. Using the *Statistica* program, histograms that show the graphical relationship of a number of observations and failure-free times of the bottle neck for historical periods are created. The fitting of the histograms to the theoretical distributions: normal, exponential, gamma and Weibull using appropriate tests (for example the Kolmogorov-Smirnov test for normal distribution) is researched. After finding distribution and setting parameters for historical periods, for the next scheduling horizon values of parameters are extrapolated using the regression method in the *Statistica* program. For the bottle neck various reliability characteristics are computed. Having the Mean Time To Failure (MTTF) and Mean Time of Repair (MTTR) of the bottle neck, robust schedule is generated. At the time of the predicted failure, preventive actions and technical survey of the machine are scheduled. The production system is modeled in the simulation program - *Enterprise Dynamics 8.1*.

## 1. INTRODUCTION

In this paper, the proposition of applying two methodologies: the predictive scheduling and Total Productive Maintenance – TPM to increase efficiency of a production system is presented. The efficiency of solutions (quality robustness of a schedule) is evaluated using indicator: Overall Equipment Effectiveness (OEE) [3].

This paper is continuation of the first part, where the process of data acquisition, models of a production system and machine failures, method of *Mean Time To Failure* (MTTF), *Mean Time Between Failure* (MTBF), *Mean Time To Repair* (MTTR) prediction, method of predictive scheduling and method of the production system efficiency evaluation are presented.

In this paper, a numerical example is given. First, the production system that produces pulleys is described. Based on historical data of failure-free times and repair times of the most loaded machine and numbers of observations, histograms are built; next, for

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successive periods, empirical distributions to theoretical distributions are fitted and parameters of distributions are evaluated using *the Statistica* program; reliability characteristics: MTTR and MTTF for the next scheduling period are calculated; in *the Enterprise Dynamics 8.1 (ED)* the production system is modeled; simulations are done, and effectiveness of the production system is evaluated.

The objective is to obtain value of efficiency of the production system around 80% to make full use of machines. The efficiency of the production system is measured using the OEE indicator.

## 2. A MODEL OF A PRODUCTION SYSTEM

The enterprise has received an order for production of pulleys for two car brands. The monthly demand for each pulley equals 2084 pieces.

For the purpose of this article, the pulley manufacturing process is simplified to the operations executed on machines. The production system consists of machines:1,2,7,8 - Production Lathes (TP), 3 and 4 - Drilling-Milling Machines (WF), 5 and 6 – Slotting Machines (D), 9 – Grinding Machine (Sz). In the $MPR$ (2) the processes routes are described. In the $MOT$ (1) the operations' times $a_{v_j,w}$ $(v_j = 1,2,3, w = 1,2,...,5)$ [in minutes] are described. In the matrices $MOT$ and $MPR$, a number of row represents a number of job *j*, a number of column states as a number of machine *w*. Let us consider the first operation of the first job $v_1 = 1_1$, the operation is produced on machine $w = 1$ (TP1) and the duration time equals $a_{1,1} = 8$ minutes. Butch sizes of jobs are described in the VBS. In the VBS, a number of column states as a number of job *j*. For example the butch size of job *j*=1 equals 2084 (3).

$$MOT = \begin{bmatrix} 8,0,1.5,0,2,0,5,0,3 \\ 0,8,0,1.5,0,2,0,5,3 \end{bmatrix}, MPR = \begin{bmatrix} 1,0,2,0,3,0,4,0,5 \\ 0,1,0,2,0,3,0,4,5 \end{bmatrix}, \tag{1,2}$$

$$VBS = \lfloor 2084, \ 2084 \rfloor \tag{3}$$

In the *ED*, the production system described by: MOT, MPR, VBS (1,2,3) is modeled. In order to identify the most loaded machine one simulation of the production process is done. The TP1 and the TP2 are bottle necks. MTTF needs to be predicted for each bottle neck and the objective to obtain the OEE of the bottle neck around 80% needs to be set. Every unpredicted failure of the bottle neck may disturb the production process.

First, the objective to obtain the OEE of the TP2 around 80% is given. It is possible by reduction of a number of the TP2 failures. Historical data of the number of failures, failure free times and repair times of the TP2 were collected. Data are essential to predict the failure-free time and repair time for the next scheduling period and to evaluate the OEE. Past and future efficiencies of the TP2 evaluated using the OEE are compared and issues affecting reduction of the OEE are emphasized.

It is assumed that there are 7 successive time periods of the same durations, for which the information about numbers of detected failures and failure-free times $X_{i,2,1},...,X_{i,2,N_{i,3}}$ of the TP2 ($w=2$) in the $i$th period $[(i-1)T,iT)$, $i=1,...,7$ is presented in Table 1. Each scheduling period - "time window" takes $T=1020$ hours.

After the failure of the TP2 occurs, a repair time $Y_{i,w,k}$ begins immediately in $k$th sub-period of $i$th period. In Table 2 repair times $Y_{i,2,1},...,Y_{i,2,N_{i,w}}$ of the TP2 in $i=1,...,m+1$ scheduling period $[(i-1)T,iT)$, $i=1,...,5$, are presented.

Table 1. The failure-free times of *2nd* machine (the TP2) in the *i*th period

| ***i*** | $N_{i,w}$ | $x_{i,2,1}$ | $x_{i,2,2}$ | $x_{i,2,3}$ | $x_{i,2,4}$ | $x_{i,2,5}$ | $x_{i,2,6}$ | $x_{i,2,7}$ | $x_{i,2,8}$ | $x_{i,2,9}$ | $x_{i,2,10}$ | $x_{i,2,11}$ | $x_{i,2,12}$ | $x_{i,2,13}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 13 | 72 | 70 | 72 | 75 | 77 | 70 | 75 | 70 | 77 | 70 | 71 | 70 | 75 |
| **2** | 13 | 67 | 71 | 76 | 71 | 67 | 71 | 74 | 76 | 71 | 73 | 67 | 71 | 76 |
| **3** | 12 | 74 | 77 | 74 | 77 | 80 | 74 | 83 | 77 | 83 | 78 | 78 | 80 | |
| **4** | 13 | 67 | 70 | 76 | 82 | 67 | 64 | 78 | 70 | 78 | 82 | 78 | 67 | 64 |
| **5** | 12 | 72 | 80 | 72 | 87 | 76 | 87 | 74 | 80 | 76 | 72 | 80 | 74 | |
| **6** | 13 | 66 | 66 | 68 | 72 | 83 | 68 | 72 | 78 | 66 | 70 | 83 | 78 | 70 |
| **7** | 12 | 86 | 65 | 84 | 73 | 85 | 65 | 84 | 73 | 76 | 84 | 76 | 87 | |

Table 2. The repair times of *2nd* machine (the TP2) in *i*th scheduling period

| ***i*** | $N_{i,w}$ | $y_{i,2,1}$ | $y_{i,2,2}$ | $y_{i,2,3}$ | $y_{i,2,4}$ | $y_{i,2,5}$ | $y_{i,2,6}$ | $y_{i,2,7}$ | $y_{i,2,8}$ | $y_{i,2,9}$ | $y_{i,2,10}$ | $y_{i,2,11}$ | $y_{i,2,12}$ | $y_{i,2,13}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 13 | 6 | 4 | 7 | 6 | 3 | 7 | 2 | 6 | 7 | 5 | 5 | 8 | 10 |
| **2** | 13 | 6 | 14 | 8 | 2 | 5 | 3 | 12 | 4 | 5 | 7 | 2 | 13 | 8 |
| **3** | 12 | 4 | 7 | 8 | 6 | 14 | 6 | 8 | 10 | 3 | 12 | 3 | 4 | |
| **4** | 13 | 5 | 10 | 8 | 3 | 13 | 5 | 4 | 7 | 3 | 7 | 7 | 2 | 3 |
| **5** | 12 | 8 | 14 | 4 | 10 | 4 | 8 | 14 | 8 | 2 | 5 | 8 | 5 | |
| **6** | 13 | 14 | 7 | 2 | 5 | 6 | 9 | 4 | 5 | 12 | 4 | 2 | 6 | 4 |
| **7** | 12 | 12 | 4 | 6 | 3 | 14 | 5 | 6 | 10 | 2 | 8 | 5 | 7 | |

In order to predict the production system behavior in the next scheduling period $[7T,8T)$ one has to model the behavior of the production system in the $i$th period $[(i-1)T,iT)$, $i=1,...,7$. We search for a distribution function for failure-free times $X_{i,2,1},...,X_{i,2,N_{i,3}}$ and repair times $Y_{i,2,1},...,Y_{i,2,N_{i,3}}$ of the TP2 in the $i$th period $[(i-1)T,iT)$, $i=1,...,7$.

## 3. DISTRIBUTION FUNCTION SELECTION

In the Statistica program, for the data of Table 1 histograms that show the graphical relationship of the number of observations and the failure-free times for seven periods are created. For the data (histograms) following distributions: normal, exponential, gamma and Weibull using appropriate tests are fitted. The histograms are presented in Fig.1,2,3,4.

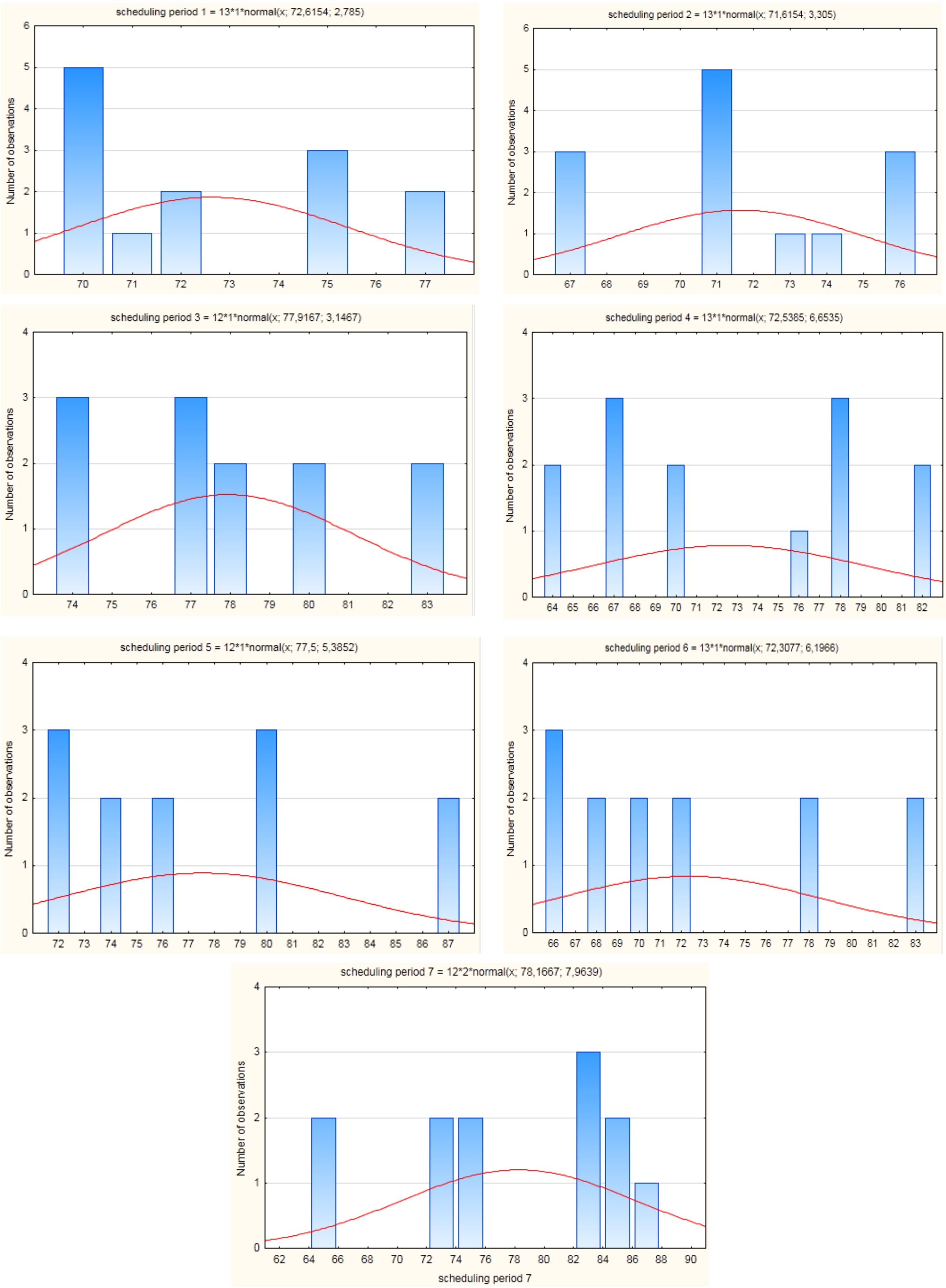



Fig. 1. Histograms with the normal distribution fit in historical periods $i = 1,\dots,7$

If the p-value is bigger than the accepted level, the hypothesis: the tested distribution fits the theoretical distribution is accepted. The level of significance is a measure of the reliability of a representative sample for the entire study population [5]. It is assumed that the level of significance equals 0.05. For seven scheduling periods, histograms with the normal distribution fit are presented in Fig. 1.

Visual assessment of exponential and Weibull probability density functions indicates that the data do not fit to the theoretical distributions, and therefore examples of functions only for 2$^{nd}$ and 6$^{st}$ scheduling periods are presented. In Fig. 2 histograms with the exponential distribution fit are presented. In Fig. 3 histograms with the Weibull distribution fit are presented. In Fig. 4 histograms with the Gamma distribution fit are presented.

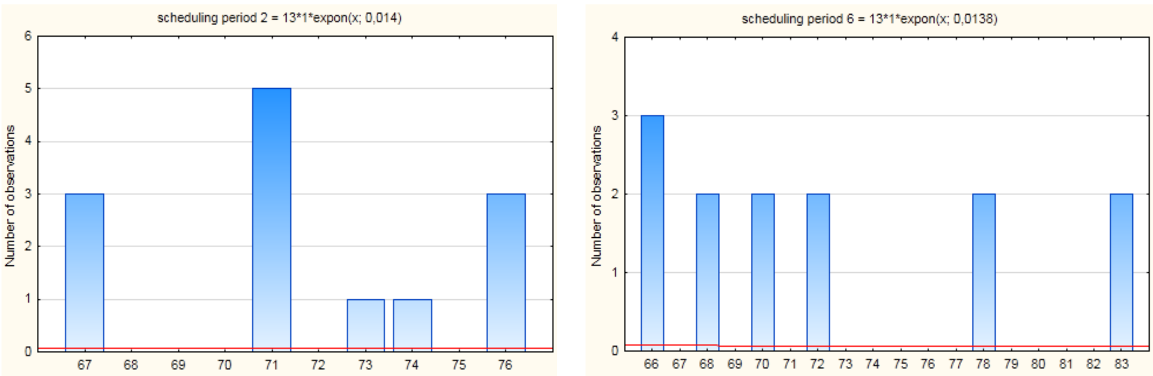



Fig. 2. Histograms with the exponential distribution fit

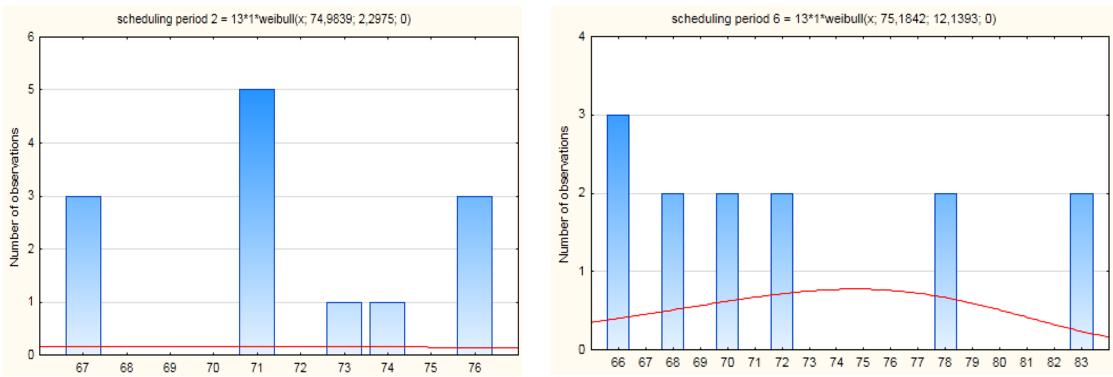



Fig. 3. Histograms with the Weibull distribution fit

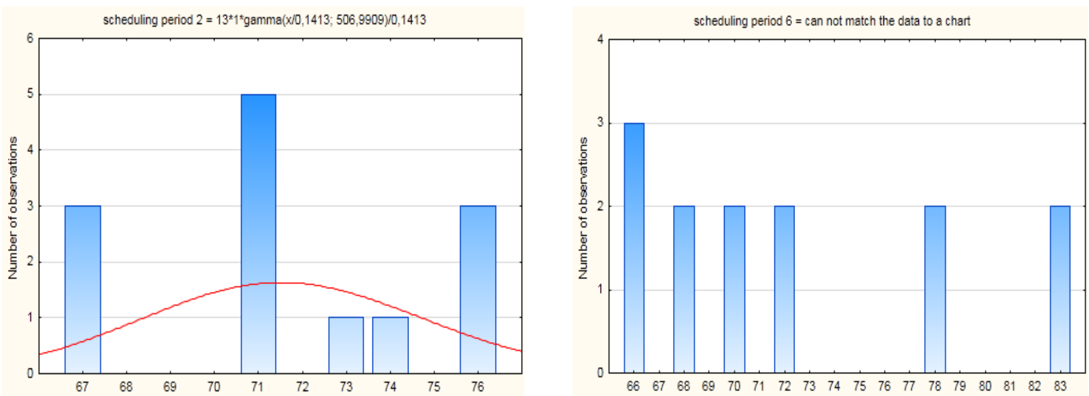



Fig. 4. Histograms with the Gamma distribution fit

Analyzing shape of the distribution functions and the values of the significance level, the most fitted distribution is the normal distribution. Quite a good fit has the gamma distribution, however, for the sixth scheduling period the distribution function is not build (Fig. 4), moreover *p*–values for the gamma distribution are greater than for the normal distribution (Table 3).

In Table 3, the p-values for the best fitted distributions: normal and gamma are presented. The *p*–values for the normal distribution deviate from the accepted value of significance level - 0.05 in the two scheduling periods, but only one of them is a significant difference (for first period). For the gamma distributions results are not reliable. In Table 4, values of parameters of normal distribution N ($\mu_{i,2}$ ,$\sigma_{i,2}$**)** for failure-free times are presented.

Table. 3. *p*–value for *i*th scheduling period

| scheduling period *i* | *1* | *2* | *3* | *4* | *5* | *6* | *7I* |
|---|---|---|---|---|---|---|---|
| *p* for normal distribution | 0,0123 | 0,0633 | 0,1825 | 0,0864 | 0,0521 | 0,0390 | 0,0572 |
| *p* for gamma distribution | 0,0975 | 0,1413 | 0,1157 | 0,5616 | 0,3335 | ------- | 0,7752 |

Table. 4. Values of parameters of normal distributions: N($\varphi_{i,2}$, $\gamma_{i,2}$ ) and N ($\mu_{i,2}$ ,$\sigma_{i,2}$)

| *I* | $\varphi_{i,2}$ | $\gamma_{i,2}$ | $\mu_{i,2}$ | $\sigma_{i,2}$ |
|---|---|---|---|---|
| 1 | 5,85 | 1,57 | 72,61 | 2,78 |
| 2 | 6,86 | 4,04 | 71,61 | 3,30 |
| 3 | 7,08 | 3,53 | 77,92 | 3,15 |
| 4 | 5,92 | 3,17 | 72,54 | 6,65 |
| 5 | 7,5 | 3,80 | 77,50 | 5,38 |
| 6 | 6,15 | 3,60 | 72,30 | 6,19 |
| 7 | 6,83 | 3,61 | 78,17 | 7,96 |

Analogous steps should be repeated for the variable: repair time of the TP2. It is assumed that the variable Y is normally distributed with parameters N($\varphi_{i,2}$, $\gamma_{i,2}$). In Table 4, the values of parameters of the normal distribution N($\varphi_{i,2}$, $\gamma_{i,2}$) describing repair times are presented.

## 4. PARAMETERS OF A NORMAL DISTRIBUTION PREDICTION

After finding estimators $\varphi_{1,2},...,\varphi_{m,2}$, $\gamma_{1,2},...,\gamma_{m,2}$, $\mu_{1,2},...,\mu_{m,2}$ and $\sigma_{1,2},...,\sigma_{m,2}$ we extrapolate values $\varphi_{m+1,2}$, $\gamma_{m+1,2}$ , $\mu_{m+1,2}$ and $\sigma_{m+1,2}$ for the next scheduling horizon using the regression method in the *Statistica* program.

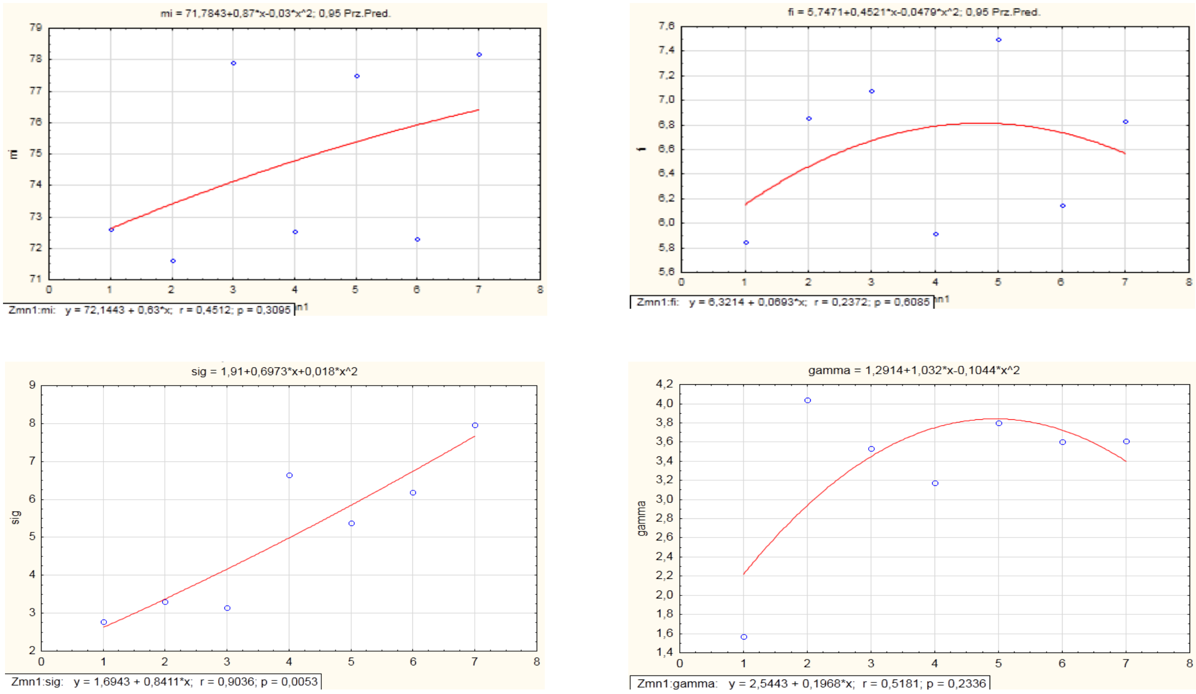



Fig. 5. Polynomial trends

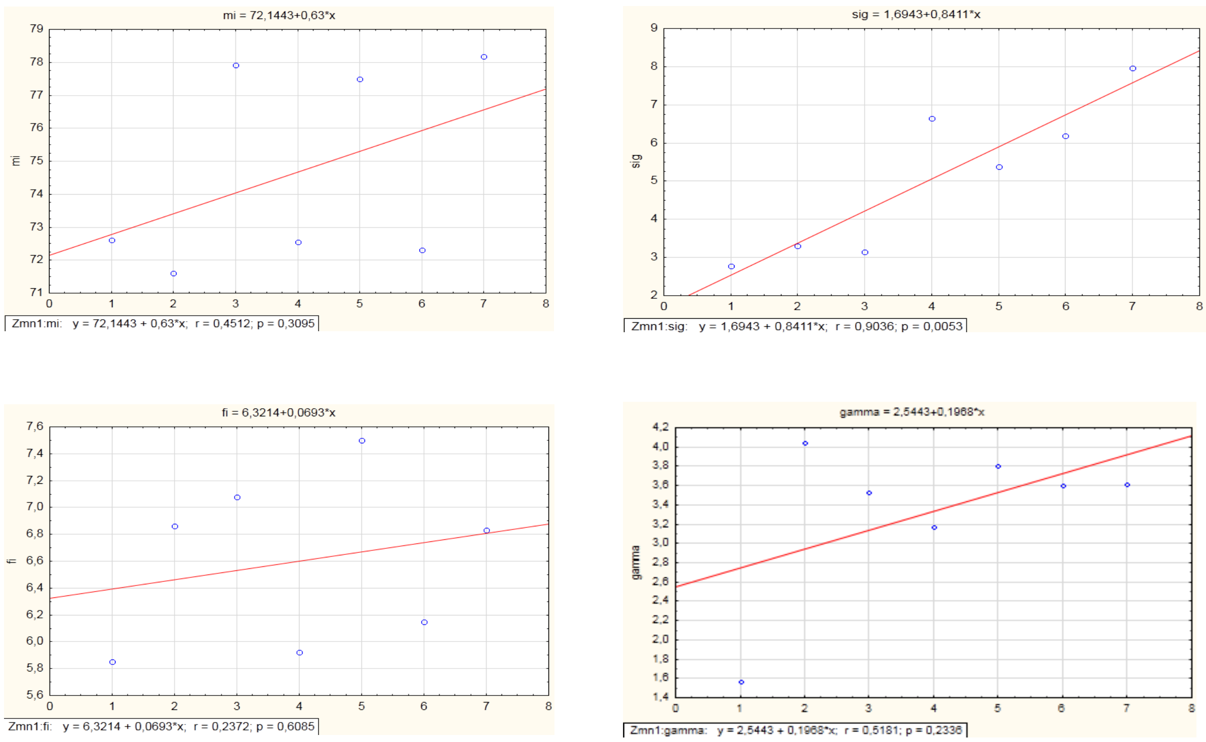



Fig. 6. Linear trends

To obtain the analytical form of a trend function a graphical analysis is performed. It is based on: observation of empirical points, describing variables: $\varphi_{i,2}$, $\gamma_{i,2}$, $\mu_{i,2}$, $\sigma_{i,2}$ for scheduling periods in the coordinate system, and research if the points “group” along the curve describing the trend sufficiently well. For smoothing time series into a linear (Fig. 6) and square (Fig. 5) functions, the least squares method is used.

To confirm the hypothesis: that the square function has the best fit, the coefficient of determination ($R^2$) and residual sum of squares (RSS) are calculated. $R^2$ is a measure of the ability of the model to predict future values of parameter. RSS indicates a fit of the model to the data (the smaller the better) [5]. For this purpose, the option "advanced models" in "Nonlinear Estimation" in *Statistica* program is used. Results are presented in Table 5. We noted that the $R^2$, is larger, and the RSS is smaller for the square function. Therefore the hypothesis is confirmed.

Table 5. $R^2$ and RSS for the regression functions

| Parameter | *Linear function* | | *Square function* | |
|---|---|---|---|---|
| | $R^2$ | RSS | $R^2$ | RSS |
| $\mu$ | 0,2036 | 43,468971429 | 0,2050 | 43,393371429 |
| $\sigma$ | 0,8164 | 4,454253571 | 0,8175 | 4,427109524 |
| $\varphi$ | 0,0563 | 2,253871429 | 0,1368 | 2,061485714 |
| $\gamma$ | 0,2684 | 2,955196429 | 0,4951 | 2,039566667 |

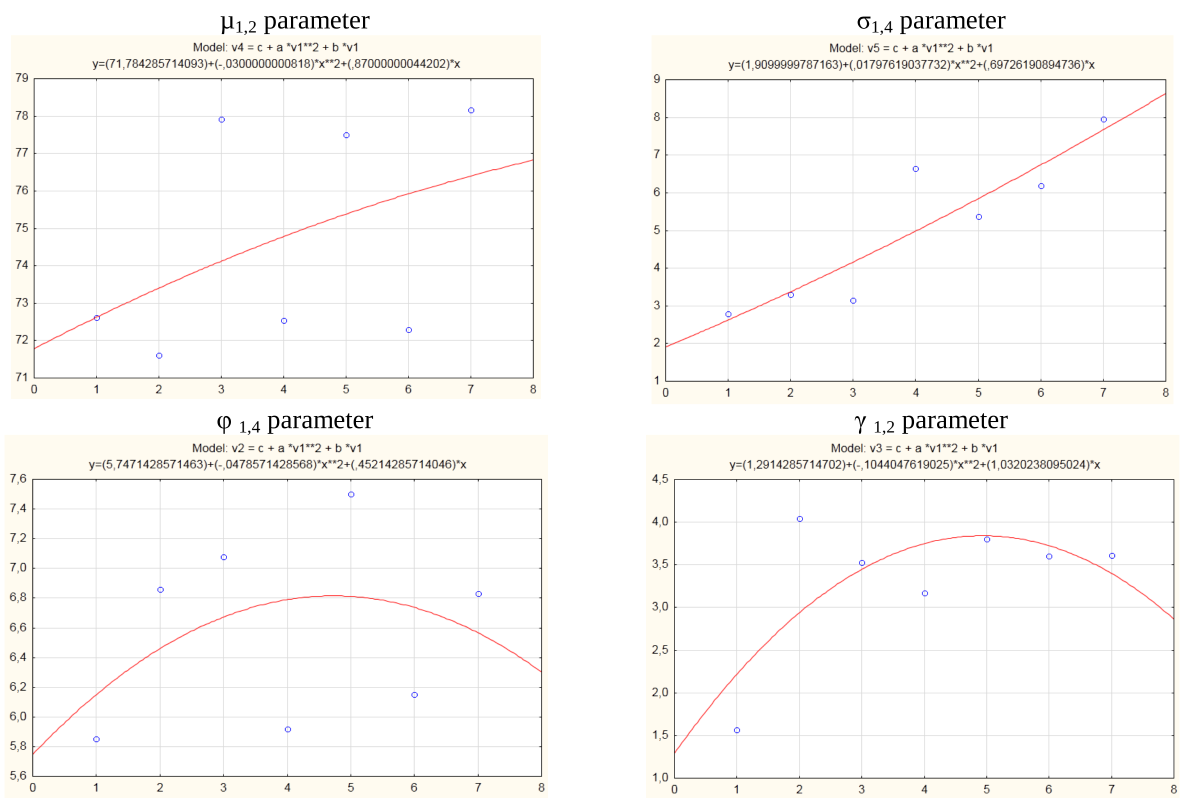



Fig. 7. Smoothed trends of squared functions describing parameters $\varphi_{i,2}, \gamma_{i,2}, \mu_{i,2}, \sigma_{i,2}$

Each square function (Fig. 5) is filtered from the noise, and the data are transformed into a smooth curve, unbiased by deviations using the least squares method. In Fig. 7, smoothed trends of squared functions describing parameters $\varphi_{i,2}, \gamma_{i,2}, \mu_{i,2}, \sigma_{i,2}$, are presented.

Having the smoothed square functions (Table 6), prediction of $X_{8,2,k}$ and $Y_{8,2,k}$ for the next scheduling period (7T, 8T) is done. In scheduling period $i$=8, variable $X_{8,2,k}$ is described by normal distribution N($\mu_{8,2}$ ,$\sigma_{8,2}$), where $\mu_{8,2}$ = 76,824 and $\sigma_{8,2}$= 8,639, and variable $Y_{8,2,k}$ is described by the normal distribution N($\varphi_{8,2}$, $\gamma_{8,2}$ ), where $\varphi_{8,2}$= 6,301 and $\gamma_{8,2}$= 2,866.

Since the variables: failure-free time and repair time have only positive values, normal distributions describing these variables must be limited at the point 0.

Table 6. The prediction of the values of parameters of the normal distribution describing variable $X_{8,2,k}$ and $Y_{8,2,k}$ for $i$=8

| The equation of square functions | Result |
|---|---|
| $\mu = -0.03x^2 + 0.87x + 71.7843$ | 76.824 |
| $\sigma = 0.018x^2 + 0.6973x + 1.90999$ | 8.639 |
| $\varphi = -0.0479x^2 + 0.4521x + 5.7471$ | 6.301 |
| $\gamma = -0.1044x^2 + 1.032x + 1.2914$ | 2.866 |

The probability density function (PDF) of the cut normal distribution N($\mu_{i,w}$ ,$\sigma_{i,w}$) is [1]:

$$s(t) = \frac{f(t)}{1 - F(0)}, \tag{4}$$

where: $f(t)$- the PDF of the normal distribution N($\mu_{i,w}$ ,$\sigma_{i,w}$):

$$f(t) = \left[\frac{1}{\sigma\sqrt{2\pi}}\right] e^{-\left[\frac{(t-\mu)^2}{2\sigma^2}\right]} \tag{5}$$

$F(t)$ - the DF of the function $f(t)$:

$$F(t) = \int_0^t \left[\frac{1}{\sigma\sqrt{2\pi}}\right] e^{-\left[\frac{(t-\mu)^2}{2\sigma^2}\right]} dt \tag{6}$$

and the distribution function (DF) of the cut normal distribution N($\mu_{i,w}$ ,$\sigma_{i,w}$) (limited to the case of positive values of a random variable):

$$S(t)=\int_t^{110}\left[\frac{1}{(1-H(0))\sigma\sqrt{2\pi}}\right]e^{-\left[\frac{(t-\mu)^2}{2\sigma^2}\right]}dt \tag{7}$$

Analogous step we do for the cut normal distribution N($\varphi_{8,2}$, $\gamma_{8,2}$ ). In Fig. 8, following graphical functions: $q(u)$ - the PDF of the limited normal distribution N($\varphi_{8,2}$, $\gamma_{8,2}$ ), $g(u)$- the PDF of the normal distribution N($\mu_{i,w}$ ,$\sigma_{i,w}$), $G(u)$ - the DF of the function $g(u)$ and $Q(u)$ - the DF of the limited normal distribution N($\varphi_{8,2}$, $\gamma_{8,2}$ ) are presented (instead of equations).

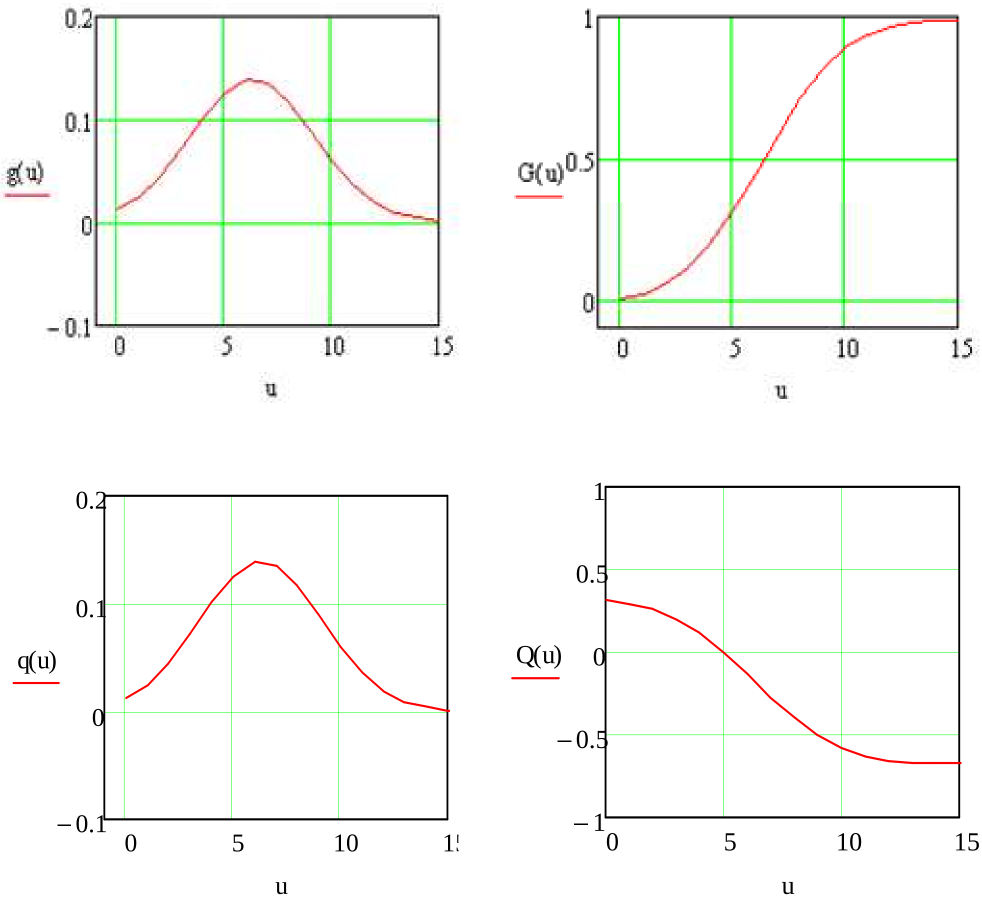



Fig. 8. The PDF and DF of the normal distribution (g(u) and G(u)) and cut normal distribution (q(u) and Q(u)) describing the variable $Y_{8,2,k}$

Corrected variable $X_{8,2,k}$ is described by the cut normal distribution N($\mu_{8,2}$ ,$\sigma_{8,2}$), where $\mu_{8,2}$ = 76,824 and $\sigma_{8,2}$= 8,639, and $Y_{8,2,k}$ is described by the cut normal distribution N($\varphi_{8,2}$, $\gamma_{8,2}$ ), where $\varphi_{8,2}$= 6,301 and $\gamma_{8,2}$= 2,866. Values of the parameters $\varphi_{8,2}$, $\gamma_{8,2}$, $\mu_{8,2}$, $\sigma_{8,2}$ are the same as before limitation at the point 0. Since $\varphi_{8,2} >> 1$, $\gamma_{8,2} >> 1$, the cut normal distributions and normal distributions almost coincide.

## 5. PREDICTION OF RELIABILITY CHARACTERISTICS

Below, the formulae for the most important reliability characteristics are presented, with the assumption that $f_i(u) = s_i(u)$:

(1) the probability that, beginning with moment $t_0 = mT$, the first failure occurs before time $t$ (9,first article) (Fig. 9a).

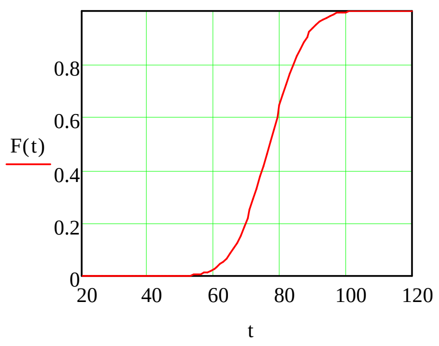
(2) Reability function R(t), that gives the probability that, beginning with moment $t_0 = 0$, the production system is not disturbed before the time *t* (10, first article ) (Fig. 9b).

(3) Probability $P$ that in the interval $[60{,}90] \in [7T{,}8T)$, there occurs at least one failure (11, first article) (Fig. 9c).

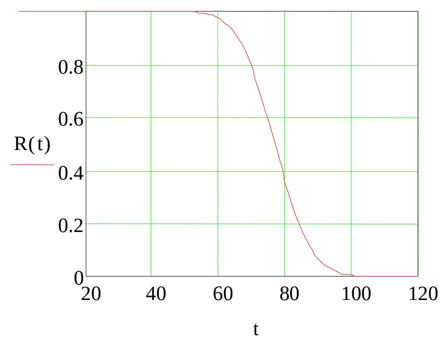
(4) Failure intensity function *r(t)* (12, first paper) (Fig. 9d).

(5) The value of failure intensity function $\hat{r}$ (13, first paper) (Fig.10). The TP2 is in the second stage of the live cycle.

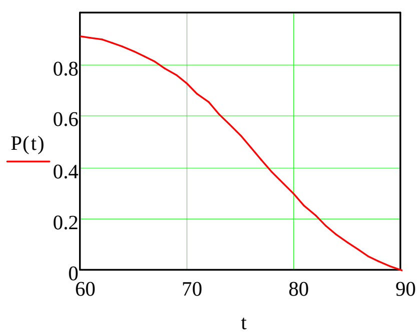
(6) Reliability function estimated basing on failure intensity function *r(t)* (14, first paper), (Fig. 9b).



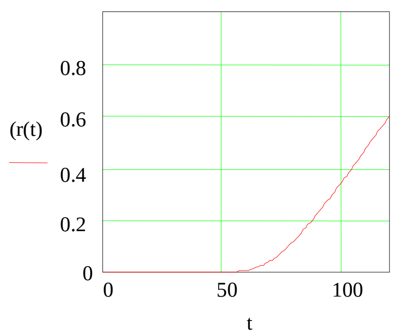

a) The probability that, beginning with moment $t_0 = mT$, the first failure occurs before time $t$




b) The probability that, beginning with moment $t_0 = 0$, the production system is not disturbed before the time *t*




c) Probability $P$ that in the interval $[60{,}90] \in [7T{,}8T)$, there occurs at least one failure




d) Failure intensity function

Fig. 9. The reliability characteristics

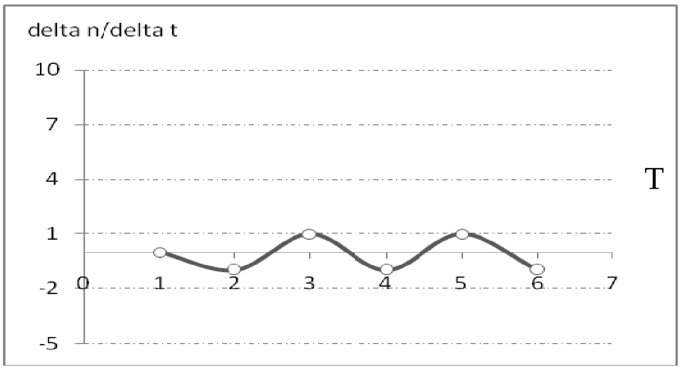



Fig. 10. The failure intensity function

MTTR determines the average time of repair or remove failures (17, first paper).

$$MTTR = 6.3. \tag{8}$$

MTTF ratio is defined as the expected value of working time of the machine up to the machine's failure time.

$$MTTF = E\{X_{m+1,1}\} = \mu_{8,2} = 76.824 \tag{9}$$

The MTBF indicates an average failure-free time of the machine (21, first paper).

$$MTBF = 83.124 \tag{10}$$

In the eighth scheduling period, the average failure free time equals 76 hours 49 minutes and the average repair time equals 6 hours 18 min. Having the values of reliability variables, the availability (25, first paper) of the TP2 for the future scheduling period can be computed:

$$\frac{MTTF}{MTTF + MTTR} = \frac{76.824}{76.824 + 6.3} = 0.924. \tag{11}$$

In the eighth scheduling period the TP2 will be available by 92,4% of time.

## 6. PRODUCTION SYSTEM MODELING

In the ED, the production system described by: MOT, MPR, VBS (1,2,3) is modeled. Fig. 12 represents the layout of machines. Operations times [in seconds] are introduced in the object: *Table of Cza* (Fig. 11).

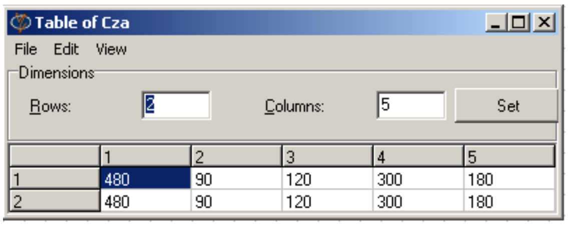


Table of Cza

File Edit View

Dimensions

Rows: 2 Columns: 5 Set

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 480 | 90 | 120 | 300 | 180 |
| 2 | 480 | 90 | 120 | 300 | 180 |

Fig. 11. Operation times

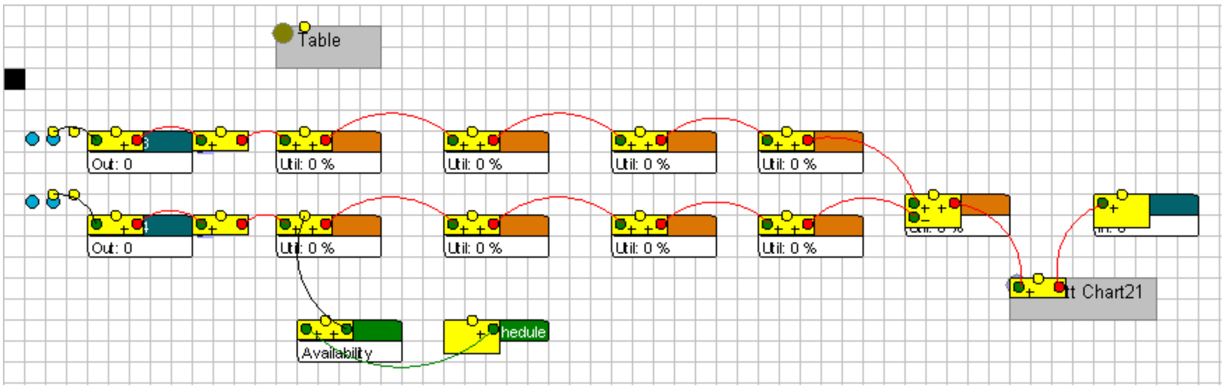



Fig. 12. Layout of machines of the production system

Objects of *Availability Control* type: *Availability Control*, *Time Schedule Availability* are introduced to the model of the production system to control availability of the TP2. Objects are green or red, the green color indicates that the object switches his controlled unit on, the red color indicates that the union is switched off. During the TP2 failure the objects are red.

| **M** | ***1*** | ***2*** | ***3*** | ***4*** |
|---|---|---|---|---|
| ***i*** | 8 | 8,075 | 8,15 | 8,225 |
| ***MTTF*** | 76,82 | 76,85 | 76,88 | 76,91 |
| ***MTTR*** | 6,30 | 6,27 | 6,25 | 6,23 |

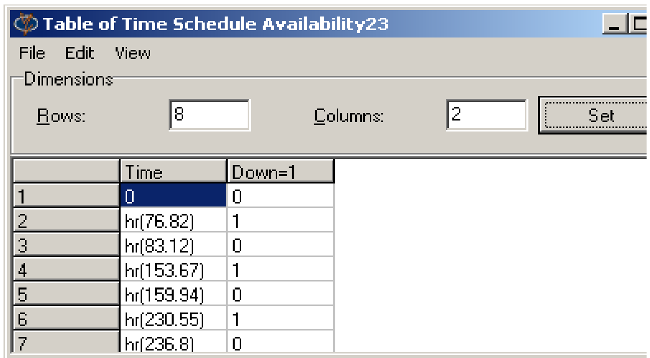


Table of Time Schedule Availability23

File Edit View

Dimensions

Rows: 8 Columns: 2 Set

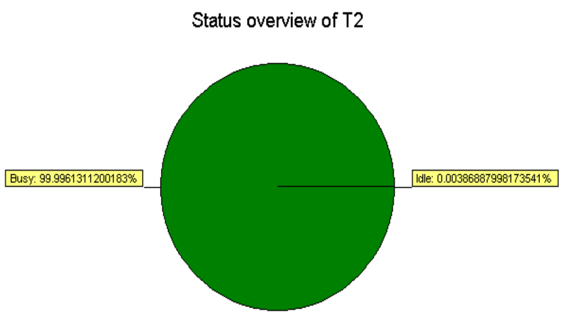
| | Time | Down=1 |
|---|---|---|
| 1 | 0 | 0 |
| 2 | hr(76.82) | 1 |
| 3 | hr(83.12) | 0 |
| 4 | hr(153.67) | 1 |
| 5 | hr(159.94) | 0 |
| 6 | hr(230.55) | 1 |
| 7 | hr(236.8) | 0 |

Table 7. MTTF and MTTR Prediction and introducing to the ED program

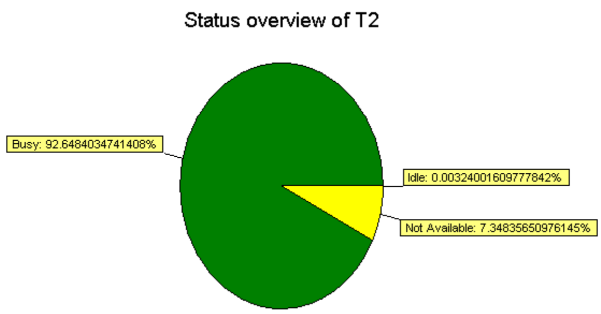
Basing on the equations (Table 6) we predict MTTF and MTTR for 4 scheduling sub-periods ($i$=1,2..4) of $m$=8 scheduling period, results are presented in Table 7. MTTF and MTTR [in hours] are introduced to the object *Time Schedule Availability*. "0" determines failure-free time of the TP2, and "1" determines unavailability time the TP2 because of repairing work after the failure has occurred. During the time from 0 to 76.81 hours, the TP2 is working properly, at 76.82 o'clock there is a failure and repair time equaled 6.30 hours, next the machine operates properly through 76.85 hours to 158.67 hours of simulation. The horizon of the schedule availability takes 255 hours because of software constrain.

## 7. SIMULATION AND PREDICTIVE SCHEDULE GENERATION

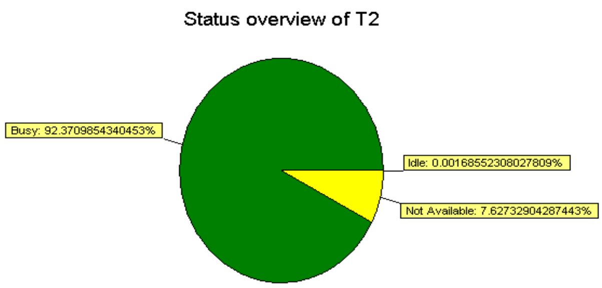
Terminal condition of the simulation is production of butch size equaled 2084. After introducing MTTR and MTTR, the availability of TP2 is measured and presented in Fig. 13. After the production of 539 products the availability of TP2 equals 99.99%, after the first



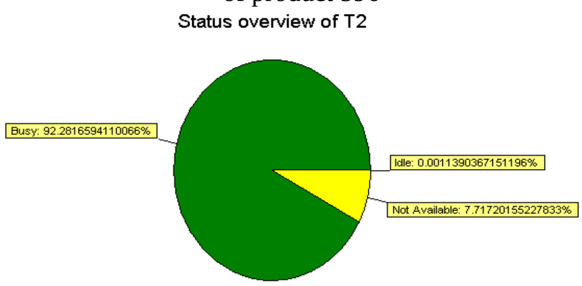

Availability of the TP2 after production of product 539



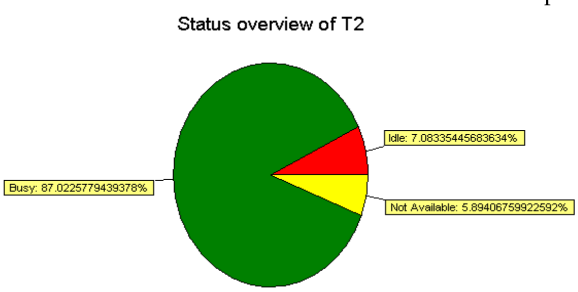

Availability of the TP2 after first failure and production of product 596




Availability of the TP2 after second failure and production of product 1142




Availability of the TP2 after third failure and production of product 1688




Availability of the TP2 after production of product 2084

Fig. 13. Availability of the TP2 during simulations

failure and production of 596 products the availability of TP2 equals 92.64%, after the second failure and production of 1142 products the availability of TP2 equals 92.37%, after the third failure and production of 1688 products the availability of the TP2 equals 92.28%. After the production of 2084 products the TP2 is available by 87.02 and idle by 7.03%.

In order to increase the availability of the TP2 the maintenance team should make technical inspection of the TP2 before the failure is predicted to appear. The predictive schedule represents times of the TP2 failure and repair and how much the start times of successive operations will be deleted if the first failure occurs (compare Fig. 14 and Fig. 15).

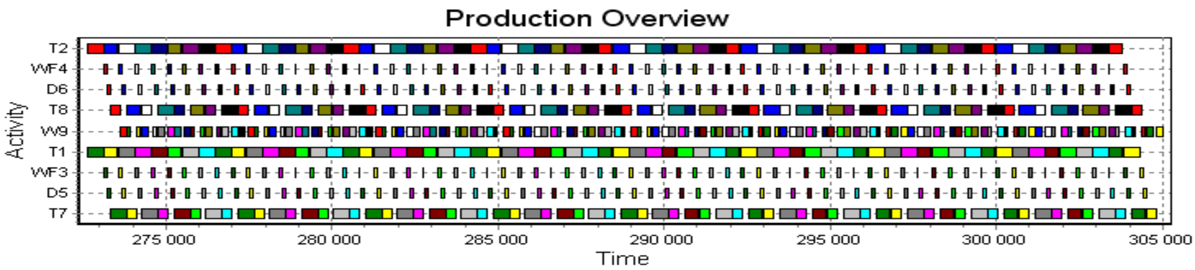



Fig. 14. The Gantt's chart without failure of the TP2

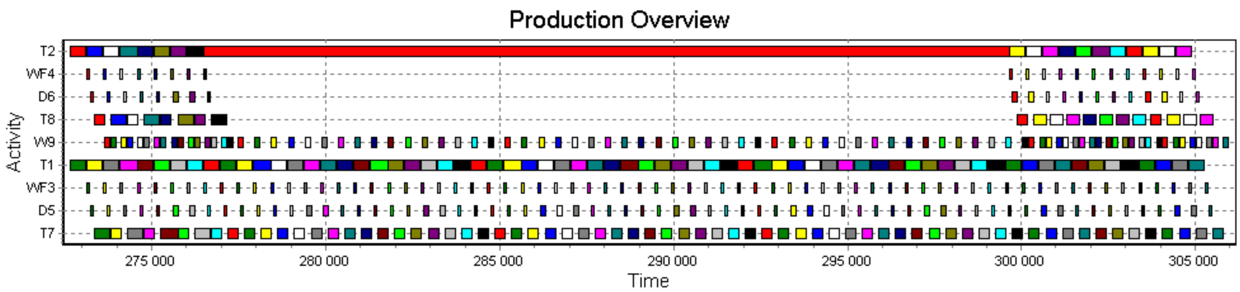



Fig. 15. Gantt's chart after the first failure of the TP2

## 8. EVALUATION OF THE PRODUCTION SYSTEM

To assess a waste due to unplanned events in the TP2's work, such as unplanned downtime or too large machine cycle times the Overall Equipment Effectiveness (OEE) indicator is computed. Calculation of reliability indicators allows the verification of the production system and production schedule, technical maintenance of machines, and can reduce the occurrence of disturbances in the production process.

Let we assume that the time of the TP2 operation is 85 hours (after the first failure), the time is reduced by a time of break of machine's operator, break between two shifts, setup times, maintenance. In 76$^{th}$ hour of simulation, the failure of the TP2 is predicted, thus a technical review of the machine is planned to carry out. The avialiability of the production system equals:

$$Availability = \frac{85[h] - 6.3[h]}{85[h]} \cdot 100\% = 92.58. \tag{12}$$

In order to calculate the performance index, it is necessary to determine the Ideal Cycle Time of the production line No. 2. The cycle time of the operation on the machine, which is a bottleneck determines the rhythm of the production line. The Ideal Cycle Time of the production line equals 8 minutes. Number of products executed during the 85 hours of simulation equals 589 (Fig. 16), therefore:

$$Performance = \frac{589 \cdot 0.133[h]}{85[h] - 6.3[h]} \cdot 100\% = 99.53 \tag{13}$$

| name | content current | content average | throughput input | throughput output | staytime average |
|---|---|---|---|---|---|
| Cza | 0 | 0.000 | 0 | 0 | 0.000 |
| P1 | 0 | 0.000 | 0 | 0 | 0.000 |
| P2 | 0 | 0.000 | 0 | 0 | 0.000 |
| Source3 | 1 | 0.979 | 639 | 638 | 469.263 |
| Source4 | 1 | 0.981 | 592 | 591 | 507.580 |
| T1 | 1 | 1.000 | 638 | 637 | 480.000 |
| T2 | 0 | 0.000 | 0 | 0 | 0.000 |
| T2 | 1 | 1.000 | 591 | 590 | 518.441 |
| WF3 | 0 | 0.187 | 637 | 637 | 90.000 |
| WF4 | 0 | 0.174 | 590 | 590 | 90.000 |
| D5 | 0 | 0.250 | 637 | 637 | 120.000 |
| D6 | 1 | 0.231 | 590 | 589 | 120.000 |
| Product | 0 | 0.000 | 0 | 0 | 0.000 |
| Product | 0 | 0.000 | 0 | 0 | 0.000 |
| T7 | 1 | 0.793 | 637 | 636 | 381.509 |
| T8 | 0 | 0.749 | 589 | 589 | 389.338 |
| W9 | 1 | 0.720 | 1225 | 1224 | 180.000 |
| Sink18 | 0 | 0.000 | 1224 | 0 | 0.000 |

Fig. 16. Summary report after 85 hours of simulation

A number of defects is estimated at 1% of production butch, in this case it will be $5.89 \approx 6$ pieces. Therefore:

$$Quality = \frac{589 - 6}{589} \cdot 100\% = 98.98. \tag{14}$$

The OEE indicator equals:

$$OEE = Availability \cdot Performance \cdot Quality \cdot 100\% = 91.52. \tag{15}$$

The high value of OEE indicator results from the fact that the time available was reduced by the time of the technical review / repair of the TP2. Assuming, that there has been unplanned TP2 failure, the following formula is proposed to use:

$$Performance = \frac{589 \cdot 0.133[h]}{85[h]} \cdot 100\% = 92.16. \tag{16}$$

Then the OEE would be:

$$OEE = 84.39 \tag{17}$$

At the predicted time of failure, maintenance service, actions to prevent the failure should be planned, to increase the value of the OEE. In the researched problem the value of the OEE increases from 84.39% to 92.16%.

An enterprise objective is to minimize any type of waste. At the time of unplanned machine failure, the production is broken, which reduces the OEE. To increase the number of executed products, schedule robust to disturbances is proposed to apply. The robust scheduling bases on rescheduling heuristics - jobs predicted to be disturbed are rescheduled on parallel machines available. After repair and rescheduling times, the schedule returns to the steady state - before the machine failure. In the period predicted to disturb, operations are scheduled according to rule Minimal Impact of Disturbed Operation on the Schedule (MIDOS) [2]. Quality robustness is measured as a deviation between makespan of reactive and predictive schedules [4]. The deviation is minimized which helps to obtain the steady state of the schedule.

## 9. SUMMARY

The objective to achieve: zero machine's failures, zero defects, zero accidents at work is possible to obtain if the MTTF is known. To assess wastes due to unplanned events in the machine's work, such as unplanned downtime or too large machine cycle times the Overall Equipment Effectiveness (OEE) indicator is applied. The OEE indicator describes the efficiency of machines and devices in the production system. The key objective of the calculation of this indicator is to develop guidelines how to improve the production processes. In this paper the method of the MTTF and MTTR prediction based on theory of statistical inference is presented. The presented method consists in knowledge acquisition from historical data about failure-free times and repair times.

In the production system two products are executed, the efficiency of the production system decreases from 91.52 to 84.39 if the failure of the bottle neck is not predicted.

In the presented production system there are two bottle necks: TP1 and TP2. Activities done for the TP2 described in the paper should also be done for the TP1.

In this paper, the problem of predicting a time of machine failure is considered.

Using the *Statistica* program, histograms that show graphical relationship of the number of observations and the failure-free times of the bottle neck for seven periods are created. The fitting of the histograms to the theoretical distributions: normal, exponential, gamma and Weibull using appropriate tests in the *Statistica* program is tested. After finding distribution parameters for seven periods we extrapolate values of parameters for the next scheduling horizon using the regression method in the *Statistica* program. Having distributions describing the failure-free and repair times of the bottle neck various reliability estimators are computed: the probability that, beginning with moment $t_0$, the first failure occurs after given time, reliability function, probability that in the interval $[f,g]$, there occurs at least one failure, failure intensity function.

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

The production system is modeled in the simulation program - *Enterprise Dynamics 8.1*. In the production model, elements of the group *Availability* are introduced to control unavailability of the bottle neck. The bottle neck is unavailable at time when the failure is predicted.

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