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New method to optimize the production functions in the system of safety in operation management

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Abstract

The Safety in Operation system represents the framework within which every technological process operates. Any technological parameter - production, quality, must be analyzed in terms of this system. Mathematical and/or empirical modeling, as the first stage in the determination of the technological processes optimum operation regimes, represents a “must” both in the phase of conception, but mainly in the operation analysis phase. From this standpoint, the introduction of the active optimization method based on scheduled experiment represents an efficient tool to relieve the extreme conditions and to get information for technological processes optimum management.

The work is focused on the mathematical modeling of the production function for an assembly of 13 drawing frames from two Romanian units, in terms of maintainability and reliability parameters. After determining the polynomial that characterizes the model, the work investigates the optimization of non-linear multi-variable polynomial function, and explains the context of getting the extreme values within the multi-factorial space.

The work defines in its structure the notions of the safety in operation system used in research, applies quantitative study on a system from textile spinning mill field (one notices reliable operation times, break-down times, number of failures and the production of the technical systems on a pre-established time horizon); it statistically validates and mathematically optimizes the results.

The theoretical approach consists in an algorithm in a unitary software application that can be used as a tool in the decision problems appeared during the technological process.

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*Keywords:*textile technological process, statistic modeling, reliability, production, industrial processes optimization

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1. Introduction

Determination of wanted production values in terms of an established system of Safety in Function (SF) represents still a desiderate for all the technological processes (Pedro Moreu De Leon et al., 2012), (Damjan Maletic et al., 2014). The SF system is characterized by 4 parameters: Maintainability (M), Reliability (R), Security (S) and Disponibility (D) (Stapelberg, 2009). Because the disponibility is a linear function of maintainability and reliability, and security is a qualitative parameter, the problem reduces to optimizing the *production* parameter as function of M and R (Rachid et al., 2010). (Hincheeranan & Rivepiboon, 2012), (Stoica, 2010) and (Huang & Lai, 2003) propose new tools for measuring maintainability of system in the design phase that is a “must” to improves the maintainability of the system before to produce it, methods to whose results I have reported. In this paper I have referred to some of the metrics proposed in (Barabadi A, et. al. 2011) and (Babu & Bharathi (2013) and the proposed methods was based on the techniques described in (Reussner, 2003), and (Crowe & Feinberg, 2001).

The studied problem can be seen as a first order feed-back system (Fig.1.), where the input is given by the production P strategies, the output is given by the real values of production Pr, the maintenance parameters being computed (approximated) through the function *f*. The transfer function *f* can be modeled mathematically or with evolutional techniques (Vilcu, Verzea & Rachid Chaib, 2016), (Verzea & Luca, 2003). One compares the computed values with real values of the system (Mr, Rr) and computes the error e_r. The objective is to make this error tends to zero. In the second part of the system, one determines the computed values of P that are influenced by the two SF parameters, Mr, and Rr. One applies the reliability and maintenance values calculated in the technical process, and obtains the real values of production and quality. Based on the error $e_r = \|(Ps) - (Pr)\|$, one can adjust the parameters of the transfer function *f* such that the error is zero.

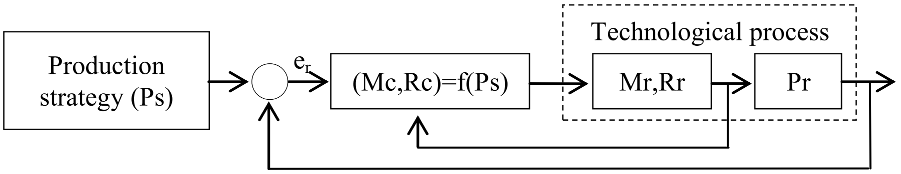

Fig.1. Production functions in the system of Safety in Operation Management.

The system to optimize is presented in the next figure (Fig.2).

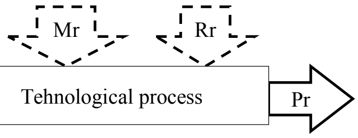

Fig.2. The system to optimize the objective function Pr.

2. Materials and method

The methods for technological processes optimization are meant to determine the extreme values of dependent parameters as function of independent parameter. If the relations between system parameters are linear or non-linear function, the optimization process reduces to finding the optimum coordinate in multi-factorial space and its value. (Catana, Safta & Panduru, 2004), (Rachid Chaib, et. al., 2010).

We shall realize in this work an unrestricted optimization through active experiment, which means that we shall determine the maximum level of production and quality for any values combination of the independent factors, combination resulted from processing the information supplied by the mathematical model.

The first stage of optimization through active experiment consists in **experiment programming** (Taloi, 1983) - establish the necessary number of experiments and the conditions to realize them. The technique of “passive optimization”, also called empirico-statistical modeling, is characterized by assigning intuitive values for independent parameters, computing on their base the values of output experimental data for which the precision increases with the increase of the number of performed determinations. On the other side, the active experiment technique of optimization reduces the complexity of the equation system and increases the efficacy of the modeling algorithm by extending the independent variable limits such that the regression conclusions have a general character. Thus, the model based on active observations can "drive" a technological process.

The second stage is characterized by the determination of the relation between process parameters, outlined by a mathematical expression (mathematical function or statistic regression function) or through an empirically determined qualitative relation.

The third stage consists in the determination of optimum values of the production parameters within the SF space.

2.1. Theoretical organization of the experimen

In this way, the active experiment method simplifies the determination of objective function values by reducing the experiments number to 13. The algorithm is as follows:

- initialize the initial value of the objective function (let this be the solution S1)
- generate 4 experimental points around the solution S1 to determine the gradient direction - direction of y parameter modification as function of x_1, x_2; thus one determines a linear equation $y = a_0 + a_1x_1 + a_2x_2$
- generate some experiments in the direction of gradient and retain an extreme value;
- generate around this extreme value other 4 experimental points and determine a new linear equation $y = b_0 + b_1x_1 + b_2x_2$ in the direction of optimization gradient of the objective function reported to the 2 parameters x_1 and x_2.
- generate five experiments on the direction of the last equation until one obtains the optimum value of the objective function.

Even if the active experiment method does not guaranty optimality, it is especially useful due to the quality of the solution obtained through a small experiments number, which implies reduced calculation and time resources.

2.2. Defining the optimization problem

Optimization problem must describe a technological process in a simple, concise and clear manner. Thus, one needs to identify the technological process parameters (which will represent the dependent and independent variables of the system function) and their mathematical codification.

Thus, the function of the technological process optimization is Pr= f(Mr,Rr), where Mr and Rr are independent variables, and Pr the variable to optimize.

Identify 4 levels for each variable:

- basis, denoted with "0", which represents the coordinates in factorial space of the start point;
- superior, denoted with "+1", which represents a value= level 0 + variation interval of the variable;
- inferior, denoted with "-1", which represents a value = level 0 - variation interval of the variable;
- any, denoted with "+1,4", which represents some value differing from the values of levels 0, +1, -1.

One desires that the intervals of variables variation are as small as possible, because the determination of linear approximation function is the more precise, the smaller is the interval size. On the other side, one cannot reduce very much the variation interval, due to physical limitations of technological parameters measurements.

2.3. Modeling the non-linear functions

Utilization of non-linear models is useful because, in most of cases, the linear models are not able to determine the optimum solution, as the gradient directions cannot refine enough the solution zone. These ones introduce additional searches in the area surrounding the local extreme points. At the same time, the non-linear modeling is used when the linear modeling does not verify the concordance hypothesis from a statistical standpoint.

Most of the times, the non-linear equation is a second order polynomial, of the form:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{\substack{i=1 \\ j=1 \\ i \neq j}}^{k} b_{ij} x_i x_{ji} + \sum_{i=1}^{k} b_i x_i^2 \qquad (1)$$

where k is the number of factors. The number of unknown coefficients in this relation is $\frac{(k+1)(k+2)}{2}$.

After determining the coefficients (through the least- squares method) and their significance (statistical tests), in order to determine the optimum it is necessary to convert the equation to a canonic form. This form is determined by choosing a new coordinate system generated by a translation of the old system along axes (the terms $\sum_{i=1}^{k} b_i x_i$ disappear) and a rotation of the old system (the terms $\sum_{\substack{i=1\\j=1\\i\neq j}}^{k} b_{ij} x_i x_{ji}$ disappear).

3. Application of modeling techniques for case study

The applicative methodology for carrying out the observations was based on the technique of the determination of reliability indices and the textile machines mechanisms. We subjected to observation 13 drawing frames from two textile units of Romania. The machines were chosen randomly and subjected to observation for 4 weeks, in 3 shifts regime, after the working program of the corresponding units. Given the differences related to raw material, manufacturing technologies, the changes occurred due to processed yarns assortment, as well as to some dead- times and to the possibility to remove the flaws, the registered data show variations in terms of their weight and size (Verzea, 2015), (Verzea, Luca & Manea, 2009).

3.1. Determination of equipment operating regime

If one admit that both the device quality and the operation conditions remain unchanged during the observation interval, then one admits also the conclusion that the down-times flux under established conditions of device utilization is also stable and can be determined (Vilcu, Verzea & Cojan, 2017).

Probabilistic appreciations of the reliability in operation result from the hypothesis that the interruption series is considered as random events with a uniform distribution, and the hypothesis H_0, according to which the machines entered in stable exploitation regime can be verified using the Pearson' criterion χ^2,where:

- k= selection volume $m = (m_1, \dots, m_k), m_i$= volume of mechanical breakdowns in the day i of observation;
- m_{t_i} = theoretical number of mechanical breakdowns in the day i of observation, calculated according to the formula: $m_{t_i} = \frac{\sum_{r=1}^{k} m_r}{\sum_{r=1}^{k} B_r} * B_i, i = \overline{1,k}$. Here $B_i$represents the value of production in day i.

The H_0 hypothesis is validated if the relation $\chi_0^2(m,k) < \chi_{n,\alpha}$ is satisfied, where $\chi_{n,\alpha}$ is the tabular value for the significance level α and with the number of degrees of freedom n= k-1; if this relation is not verified, the H_0 is denied.

The observation time interval for production and the determination of the number of mechanical breakdowns is represented by 7 complete days with 3 work shifts.

We have supervised 6 drawing frames from Unit 1 and 7 drawing frames from Unit 2. Data were summarized in table 1 and 2 (we have noted with *B* the drawing frame production in m/24 h):

Table 1. The drawing frame production for unit 1.

Unit1	1		2		3		4		5		6		7	
K	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]
1	3	173320	4	179549		174449	4	155886	5	217031	3	168047	2	188881
2	9	155412	4	158611	4	220637	4	225159	4	241717	5	171096	3	203050
3	1	81589	2	95965	11	122169	2	109413	6	162512	3	121650	12	191602
4		156552	3	148052	1	168834		149842		171865	3	180329	1	145311
8	3	190017	2	144029	1	204746	2	136564	1	103505	1	149092		97066
9	2	190737		142544		179581	3	134745	1	121354		147925		128204
Total	18	947627	15	868750	17	1070416	15	911609	17	1017984	15	938139	18	954114

Table 2. The drawing frame production for unit 2.

Unit2	1		2		3		4		5		6		7	
K	m	B[m/24h]	m	B[m/24h]	M	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]	m	B[m/24h]
L2A	0	168524	0	170000	0	183000	0	175000	0	180000	4	195100	1	141400
L2B	2	172000	0	175400	1	193000	0	182400	0	181000	0	207000		143700
L3A	2	198000	1	194000	1	187000	1	201000	1	179000	2	132000		181000
L3B	0	204958	1	189200	0	193532	0	194532	0	179931	0	133389		188107
L4A	1	196000	2	190000	1	137000	1	180000	3	171000	1	155000	1	148000
L4B	2	190000	2	188000	1	144000	5	190000	5	170000	0	156000		242000
L5A	0	184000	0	179000	0	202000	0	224000	0	179000	0	159000		180000
Total	7	1313482	6	1285600	4	1239532	7	1346932	9	1239931	7	1137489	2	1224207

Checking-up the hypothesis *H₀* for unit 1 is computed in table 3:

Table 3. Checking-up the hypothesis *H0* for unit 1.

Unit1	m_k	m_{t_k}	$m_k - m_{t_k}$	$(m_k - m_{t_k})^2$	$\frac{(m_k - m_{t_k})^2}{m_{t_k}}$
1	18	16.24429	1.75571	3.082503	0.1898
2	15	14.89218	0.10782	0.011625	0.0008
3	17	18.34915	-1.34915	1.820212	0.0992
4	15	15.62687	-0.62687	0.392967	0.0251
5	17	17.45036	-0.45036	0.202823	0.0116
6	15	16.08165	-1.08165	1.169967	0.0728
7	18	16.35549	1.64451	2.704397	0.1654
Total					0.5645

The value $\chi_0^2 = 0.5645 < \chi_{5,0.05}^2 = 11.07$, where $\chi_{5,0.05}^2$ is the tabular value of the distribution χ^2 for 6 degrees of freedom and a significance level $\alpha = 0.05$. Therefore, the hypothesis *H₀* is validated, which means that the drawing frames from Unit 1 entered the stable exploitation regime.

Checking-up the hypothesis *H₀* for unit 2 is computed in table 4:

Table 4. Checking-up the hypothesis *H0* for unit 2.

Unit2	m_k	m_{t_k}	$m_k - m_{t_k}$	$(m_k - m_{t_k})^2$	$\frac{(m_k - m_{t_k})^2}{m_{t_k}}$
1	1	3.009136	-2.009	4.036626	1.3415
2	7	3.05389	3.9461	15.57178	5.099
3	2	2.524456	-0.524	0.275055	0.109
4	6	3.410046	2.59	6.707863	1.9671
5	1	3.554905	-2.555	6.52754	1.8362
6	2	3.233979	-1.234	1.522705	0.4708
7	3	3.213588	-0.214	0.04562	0.0142
Total					10.838

The value $\chi_0^2 = 10.838 < \chi_{5,0.05}^2 = 11.07$ .Therefore, the hypothesis *H₀* is validated, which means that the drawing frames from Unit 1 entered the stable exploitation regime.

3.2. Mathematical modeling

The mechanical failures (N), times of break-down (sec), operational (sec), observation (sec), as well as the machine production (kg/month) were summarized in the next table (table 5), and MTBF (mean time between failures) and MTTR (mean time to repair) were computed.

The transformation relationship between [m/24h] in [kg/month] is $\frac{4*\sum_{i=1}^{number\ of\ days\ of\ the\ month} production_i(m/24h)}{1000}$ (kg/month).

Table 5. Centralized information in quantitative research.

Nr.	Drawing frame	N	Break-down times (s)	Operational times(s)	Observation Times(s)	MTBF (s)	MTTR (s)	Production (kg/month)
1	2A	19	703073	1370527	2073600	72133	37004	8400
2	2B	18	727194	1346406	2073600	74800	40400	9792
3	3A	6	448081	1625519	2073600	270920	74680	13908
4	3B	5	435009	1638591	2073600	327718	87002	15675
5	4A	13	515338	1558262	2073600	119866	39641	8514
6	4B	15	477211	1596389	2073600	106426	31814	8820
7	5A	15	1916524	157076	2073600	10472	127768	1080
8	1	15	756565	856235	1612800	57082	50438	5431
9	2	20	797371	815429	1612800	40771	39869	4671
10	3	11	1176391	551609	1728000	50146	106945	3987
11	4	15	1055302	672698	1728000	44847	70353	5144
12	8	17	977286	721914	1699200	42466	57487	5872
13	9	18	972279	726921	1699200	40385	54016	5784

One has defined the parameters of experimental matrix. Independent parameters of the considered technical process are: x_1 - MTBF (s) and x_2 – MTTR (s).

The experimental matrix, based of the variation levels of the two independent parameters, with 13 experimental variants (Vilcu, Verzea & Vilcu C.,2017), is presented in table 6.

Table 6. The experimental matrix.

Experimental variants	Independent parameters				Production (kg/month) measured values
	x_1 – MTBF(s)		x_2 – MTTR(s)		
	Coded value	Real value	Coded value	Real value	
1.	-1	40771	-1	37004	1080
2.	1	74800	-1	39869	15675
3.	-1	40385	1	106945	3987
4.	1	270920	1	87002	9792
5.	-1,414	10472	0	74680	5784
6.	1,414	327718	0	39641	13908
7.	0	72133	-1,414	31814	5872
8.	0	119866	1,414	127768	5144
9.	0	106426	0	40400	8400
10.	0	50146	0	50438	4671
11.	0	44847	0	70353	5431
12.	0	42466	0	57487	8820
13.	0	57082	0	54016	8514

The first modeling operation is to determine the coefficients by the least squares method followed by determining the significance of these by using the statistical test t.

The results are centralized in Table 7.

Table 7. The value of the coefficients and their significance

Coefficient	Value	Statistic t_c	Statistic $t_{tab}(\alpha,\nu)$	Significance
bo	7169.1	8.1937	$t_{tab}(0.05,4)=2.132$	yes
b1	3985.9	5.7624		yes
b2	-500.6	0.7238		no
b11	1326.7	1.7882		no
b22	-841.6	1.1344		no
b12	-2197.5	2.2464		yes

The final form of the polynomial equation is:

$$y = 7169.1 + 3985.9x_1 - 2197.5 * x_1x_2 \qquad (2)$$

The fact that the terms x2, in simple and square forms, are missing from the equation, confirms the hypothesis that production is directly proportional to the MTBF factor that defines reliability.

The poor correlation between production and maintenance is evidenced by the presence in the equation of factor x_1x_2. The presence of the minus sign in front of the term $x_1x_2$weighs the effect of the direct proportionality of the relationship between production and reliability with the influence of the maintenance factor.

The next stage of modeling is to determine the statistical relevance of the model. This is checked by two statistical methods: the Fischer-Snedecor test (Fc and Fc' statistics) and by estimating the approximate error amplitude A.

The third stage of modeling is the determination of the new center and the establishment of the extreme type and its value. Of the calculations shows that the new center (x_1_new=0, x_2_new=1.8138) is neither a minimum nor a maximum, but is an inflection point (a saddle point) with a production value of 7169.1.

The rotation angle is -450, and the canonical form of the regression equation is

$$y - 7169.1 = +1098.8 * Z_1^2 - 1098.8 * Z_2^2 \qquad (3)$$

The new coordinate axes are:

X_1=0.7071*(x_1-0)-0.7071*(x_2-1.8138) (4)
X_2=0.7071*(x_1-0)+0.7071*(x_2-1.8138)

Because the coefficients of the canonical equation have different signs the surface is of the "minimax" type and the lines of equal value of *y* being hyperbolic functions.

To observe that the center of the figure is near the center of the experiment.

The y values increase by moving from the center S on the X_1 (reliability) axis and decrease by moving on the X_2 (maintainability) axis (Fig.3.).

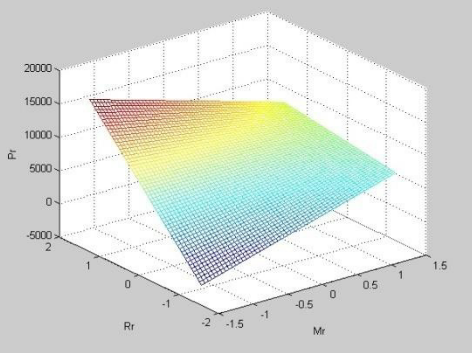

Fig. 3. The 3D-surface of the function Pr=f(Mr, Rr).

The maximum value of the production is 17.056 kg/month.

4. Conclusions

The optimization method used in this work gives a quick solution for approaching the production strategy in terms of Safety in Operation. The method is explained and tested on a production system including 13 drawing frames from two distinct unit, and can be generalized with small modifications to any production system.

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