Automated control system functions for complex structured technological processes

A M Korneev, T A Smetannikova, T V Lavrukhina and F A Al-Saeedi
Lipetsk State Technical University, Lipetsk, Russia

E-mail: lavrukhina_tv@mail.ru

Abstract. A system for determining the optimal technology and process control has been developed. The system provides identification of global and local technologies, flexible management of end-to-end technology with the issuance of appropriate recommendations about the further progress of the production process. The data obtained during the operation of the system is recorded by the report generation subsystem for further analysis. The developed system allows you to implement optimal process control, both at the level of an individual product and for a batch of products. The system provides the ability to adapt to changing production conditions. A procedure for selecting the most effective optimization method for managing local technology has been developed.

1. Introduction
The approach to process of modeling and management focuses on building models of quality indicators, determining the optimal values of technological factors that provide the highest level of output properties. In this paper we consider an automated system that allows to identity global and local technologies, as well as to control the progress of the production process [1-9].

The main features of this automated system are:

- the ability to analyze end-to-end technology;
- universal system of modeling;
- independence from the type and structure of the technological process for which statistical information is available;
- finding the optimal technology and monitoring its implementation, and when the factors deviate from the recommended values, a forecast of the quality characteristics for this technology is made, and its adjustment is made in order to increase the level of output properties.

Proposed automated system consists of several subsystems. The information about technology is included into data base. Moreover, relevant characteristics of finished product quality are also included into it. Then all information goes to the subsystem of pre-processing of data, where it is analyzed. The obtained data is used in the identification subsystems of global and local technologies.

Identification of the global technology consists in choosing the optimal technological modes that ensure obtaining the required properties with the maximum probability [2, 4-8]. After identifying the global technology, the output properties prediction subsystem determines the values of the quality indicators of the finished product, provided that rational boundaries are observed.
2. Research method

The process modeling subsystem provides the construction of mathematical models of metric and non-metric quality indicators. For this purpose, models of the dependence of quality characteristics on technological factors are built on the basis of regression analysis. At the same time, the researcher can control the complexity of the resulting models at his own discretion. The following types of models can be constructed:

- a linear model, which can be written in the general form as follows: $f(x) = a_0 + a_1x_1 + \cdots + a_nx_n$, there $a_0, \ldots, a_n$ - model parameters;
- a nonlinear model: $f(x) = a_0 + \sum_{k=1}^{K} a_k f_i(x_j)$, where $(K + 1)$ - the number of parameters of the model, $j = 1, \ldots, n$ - the number of the factor, $i = 1, \ldots, r$ - the number of the function, and there is a linear function in the set of functions $f_i$;
- with using the products of linear functions of factors: $f(x) = a_0 + \sum_{k=1}^{K^1} a_k x_j + \sum_{k=1}^{K^2} a_{K+k} x_j x_k$;
- with using products and nonlinear functions of factors: $f(x) = a_0 + \sum_{k=1}^{K^1} a_k f_i(x_j) + \sum_{k=1}^{K^2} a_{K+k} f_i(x_j) f_k(x_j)$.

The subsystem for modeling technological processes allows you to obtain mathematical models of individual quality indicators. However, when managing the technology, the problem arises of determining the optimal values of technological factors that ensure the minimum deviation of all quality indicators from the required values [2]. The local technology identification subsystem allows us to obtain point optimal values of technological factors that provide the highest level of output properties, based on the obtained models. For optimization, a weighted complex criterion is used – the root-mean-square convolution function. The system provides for the use of expert evaluation methods to determine the weight coefficients of quality indicators, which allows you to get the smallest deviation of the most important indicator from the optimal value.

The resulting nonlinear least squares problem in the system is solved by the following methods: Gauss-Newton, Levenberg-Marquardt, DFP and BFGS, which are described in detail in [2]. Then the problem of choosing a solution method occurs that allows to get the most accurate approximation to the optimum for certain class of models. The researches help come to the conclusion that it is impossible to uniquely determine the most optimal procedure among the listed ones for the considering types of models. That’s why the automatic selection of the most rational method in each specific case is used in the developed system. Below you can see the results of calculation for 4 models of quality indicator, reflecting the dependence on six technological factors. The following models of the form were obtained:

- a linear model $f(x) = 7.383 + 11.077x_1 + 9.496x_2 - 4.449x_3$;
- a nonlinear model $f(x) = 9.003 + 1.282x_1^2 + 18.672\sqrt{x_2} - 3.723x_2^3 - 5.737\sqrt{x_3}$;
- with using the products of linear functions of factors $f(x) = 7.477 + 10.681x_1 + 1553.591x_2 x_4 - 12598.549x_4 x_5 - 34.004x_2 x_6$;
- with using products and nonlinear functions of factors $f(x) = 7.932 + 20.441\sqrt{x_2} - 3.987x_2^3 + 1.291x_1^3 - 293.477x_3 x_4^2$.

Table 1 shows the average values of relative deviations of quality indicators from the specified optimal values.
The given example demonstrates that for different types of models, different methods show the best results. In this case, these are the BFGS methods for nonlinear models and the Levenberg-Marquardt methods in the other cases. This allows us to conclude that the chosen strategy for finding the optimal method in each particular case is correct. After the identification of the local technology, the forecast of the values of the quality characteristics is carried out on the basis of the constructed models for the obtained optimal values of the technological factors.

3. Results and analysis
The problem of choosing optimization boundaries becomes an important step, because they determine the possibility of finding acceptable values of technological parameters. Consider an example of the influence of factors on the properties of products. An example of such a model:

\[
y_1 = 0.027 + \frac{16311.738}{x_1^2} - \frac{85.295}{x_2^2} + \frac{0.0003}{x_3^2} + 0.033x_4 + 1.73 \times 10^{-12}x_5^3 + 2.64 \times 10^{-8}x_6^3 + \frac{528.898}{x_7^2} - \frac{437.947}{x_8^2}
\]

As constraints, we take:

\[
\begin{align*}
1310 & \leq x_1 \leq 1465 \\
236 & \leq x_2 \leq 294 \\
0.4 & \leq x_3 \leq 1.03 \\
0.006 & \leq x_4 \leq 0.088 \\
1580 & \leq x_5 \leq 1710 \\
18 & \leq x_6 \leq 23.67 \\
550 & \leq x_7 \leq 1290 \\
250 & \leq x_8 \leq 1250
\end{align*}
\]

Let's set the point value that we need to get at the output to 0.048. Then the optimization problem will look like this:

- find the minimum value of the function

\[
y_1 = 0.027 + \frac{16311.738}{x_1^2} - \frac{85.295}{x_2^2} + \frac{0.0003}{x_3^2} + 0.033x_4 + 1.73 \times 10^{-12}x_5^3 + 2.64 \times 10^{-8}x_6^3 + \frac{528.898}{x_7^2} - \frac{437.947}{x_8^2}
\]

- under the following conditions

\[
g_1(x) = 1310 - x_1 \leq 0, g_2(x) = x_1 - 1465 \leq 0,
g_3(x) = 236 - x_2 \leq 0, g_4(x) = x_2 - 294 \leq 0,
g_5(x) = 0.4 - x_3 \leq 0, g_6(x) = x_3 - 1.03 \leq 0,
g_7(x) = 0.006 - x_4 \leq 0, g_8(x) = x_4 - 0.088 \leq 0,
g_9(x) = 1580 - x_5 \leq 0, g_{10}(x) = x_5 - 1710 \leq 0,
\]
\[ g_{11}(x) = 18 - x_6 \leq 0, g_{12}(x) = x_6 - 23.67 \leq 0, \]
\[ g_{13}(x) = 550 - x_7 \leq 0, g_{14}(x) = x_7 - 1290 \leq 0, \]
\[ g_{15}(x) = 250 - x_8 \leq 0, g_{16}(x) = x_8 - 1250 \leq 0, \]
\[ g_{17}(x) = 0.021 - \frac{16311.738}{x_1^2} + \frac{85.295}{x_2^2} - \frac{0.0003}{x_3^2} - 0.033x_4 - 1.73 * 10^{-12}x_5^3 - 2.64 * 10^{-8}x_6^3 - \frac{528.898}{x_7^2} + \frac{437.947}{x_8^2} \leq 0 \]

The restriction \( g_{17}(x) \) shows that the range of acceptable values from the bottom is limited by the number 0.048, reaching it during optimization, we will find the necessary values of the technological parameters.

1) We will set \( x^0 = (1310; 294; 0.4; 0.088; 1710; 18; 550; 1250)^T; f(x^0) = 0.05 \)
\[ \epsilon_1 = -0.01; \epsilon_2 = 0.0001; M = 5. \]

2) Set \( k = 0 \)
3) Check the condition \( k \geq M: 0 < 5 \).
4) Calculate \( g_j(x^0), j = 1, 2, ..., 17: g_1(x) = 0, g_2(x) = -155, g_3(x) = -58, g_4(x) = 0, \)
\[ g_5(x) = 0, g_6(x) = -0.63, g_7(x) = -0.082, g_8(x) = 0, g_9(x) = 0, \]
\[ g_{10}(x) = -130, g_{11}(x) = -0.032, g_{12}(x) = -5.638, g_{13}(x) = 0, g_{14}(x) = -740, g_{15}(x) = -1000, \]
\[ g_{16}(x) = 0, g_{17}(x) = -0.005 \]

5) Check \( \epsilon_1 \leq g_j(x^0) \leq 0 \)
Restrictions with numbers 1, 4, 5, 8, 10, 13, 16, 17 fall under this condition. Table 2 shows components of the gradient vector.

**Table 2. Components of the gradient vector.**

| \( \frac{df}{dx_1} \) | \( \frac{df}{dx_2} \) | \( \frac{df}{dx_3} \) | \( \frac{df}{dx_4} \) | \( \frac{df}{dx_5} \) | \( \frac{df}{dx_6} \) | \( \frac{df}{dx_7} \) | \( \frac{df}{dx_8} \) |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| -1               | -1               | -1               | -1               | -1               | -1               | -1               | -1               |
| 1                | 0.05             | 1                | 0.05             | 1                | 0.05             | 1                | 0.05             |
| 0.06             | 0.03             | 0.02             | 0.05             | 0.05             | 0.06             | 0.07             |

6) Calculate \( \Delta x^k = - \left[ E - A_k^T \left( A_k A_k^T \right)^{-1} A_k \right] \nabla f(x^k) \), where \( A_k \) presented in the table 3.

**Table 3. Matrix \( A_k \).**

| \( \frac{df}{dx_1} \) | \( \frac{df}{dx_2} \) | \( \frac{df}{dx_3} \) | \( \frac{df}{dx_4} \) | \( \frac{df}{dx_5} \) | \( \frac{df}{dx_6} \) | \( \frac{df}{dx_7} \) | \( \frac{df}{dx_8} \) |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| -1               | 0                | 0                | 0                | 0                | 0                | 0                | 0                |
| 0                | 1                | 0                | 0                | 0                | 0                | 0                | 0                |
| 0                | 0                | -1               | 0                | 0                | 0                | 0                | 0                |
| 0                | 0                | 0                | 1                | 0                | 0                | 0                | 0                |
| 0                | 0                | 0                | 0                | 1                | 0                | 0                | 0                |
| 0                | 0                | 0                | 0                | 0                | -1               | 0                | 0                |
| 0                | 0                | 0                | 0                | 0                | 0                | 1                | 0                |
| 1.45E-05         | -6.71E-06        | 8.56E-03         | -3.30E-02        | -1.52E-05        | -2.57E-05        | 6.36E-06         | -4.48E-07        |

7) Check the condition \( \| \Delta x^k \| \leq \epsilon_2 \) : the condition is met \( \Delta x^k = 0 \)
8) Calculate \( \lambda^0 = -\left( A_k A_k^T \right)^{-1} A_k \nabla f(x^k) \) the components of which are presented in the table 4.
We remove the constraint number 8 from the list of active constraints, because the largest element of the negative values by modulus corresponds to it.

9) Calculate \( \Delta x^k = - \left[ E - A_k^T (A_k A_k^T)^{-1} A_k \right] \nabla f(x^k) \), where \( A_k \) presented in the table 5 and the components of \( \Delta x^k \) are presented in the table 6.

### Table 5. Matrix \( A_k \).

| \( A_k \) | -1.43E-11 | -6.60E-12 | -8.41E-09 | -3.24E-08 | -1.49E-11 | 2.53E-11 | 6.25E-12 |
|----------|------------|------------|------------|------------|------------|------------|------------|

### Table 6. The components \( \Delta x^k \).

| \( \Delta x^k \) | -1.0E-14 | 0 | -2.5E-17 | -3.3E-02 | 0 | 0 | 0 | 1.09E-03 |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|

Calculate \( t^*_k \), in this case, this parameter can not be obtained the function increases monotonically, the components of \( \Delta x^k \) will be in this case presented in the table 7.

### Table 7. The components \( \Delta x^k \).

| \( \Delta x^k \) | -1000 | -155 | 0.63 | 0 | 2.49 | 0.09 |
|-----------------|-------|------|------|---|------|-----|

As you can see, the single increment can be estimated as \( t^*_k = 2.49 \). Get a new point and check it \( x^0 = (1310; 294; 0.4; 0.06; 1710; 18; 550; 1250)^T \); \( f(x^0) = 0.048 \). As you can see, we have reached the optimal point and these parameters are optimal.

The functions of monitoring and correcting the technology are performed by tracking technology execution subsystems for optimal ranges and values of factors, issue recommendations on the continuation of the process and predict the output properties. By means of these subsystems, it is possible to adapt the technology to the changing conditions of the production process.

In the production of a batch of products, for some reason, the values of technological factors at one of the stages may go beyond the calculated rational limits, which will entail a change in the predicted level of output properties. If it turns out to be significant, the system issues recommendations on the transfer of products to another grade or defects. The adjustment of the technology is carried out as...
following. At the $k$-th step of the used iterative method, the technological space, from which the part corresponding to the already implemented stages of the production process is excluded, is divided into $k_n$ subspaces, where $n$ is the number of factors. For each subspace, the value of the criterion for the amount of shared information between factors and quality indicators is calculated. The area with the highest criterion value is selected. The procedure continues for $k = 1, 2, 3, \ldots$, until the amount of information begins to decrease. As a result, we get rational limits of changes in the still unrealized technological factors.

After adjusting the global technology, new optimal "point" values of factors and corresponding values of quality indicators are determined. In this case, the existing values of quality indicators corresponding to the previous stages are substituted into the statistical models of quality indicators. This allows you to reduce the forecast error for models, and therefore determine the values of technological factors that will improve the quality of this product.

In the conditions of real production, several classes of situations may arise that lead to the task of correcting the found optimal technology. Let’s consider several similar situations and illustrate their solution in the framework of an automated process control system. If one of the following cases occurs, the system adjusts the found technological limits and finds the optimal continuation of the production process.

1. Violation of technology, which corresponds to a situation where the values of technological factors do not correspond to the calculated optimal values.

The values of the technological factors obtained after the violation of the technology and further adjustment are shown in figure 1 and in table 8.

Note. In the figures: ● - before the state change; ■ - after the state change; the left rectangle is the original optimal technology; the right rectangle is the changed ranges.

![Figure 1](image1.png)

**Figure 1.** The values of technological factors obtained after the technology violation and adjustment.

**Table 8.** The values of technological factors obtained after the technology violation and adjustment.

| technological factors | $X1$ | $X2$ | $X3$ | $X4$ | $X5$ | $X6$ |
|-----------------------|------|------|------|------|------|------|
| before adjustment      | min  | 0.03 | 0.19 | 830  | 577  | 10   | 11   |
|                        | max  | 0.05 | 0.22 | 855  | 610  | 19   | 28   |
|                        | opt  | 0.038| 0.18 | 843  | 597  | 15   | 24   |
| after adjustment       | min  | 0.03 | 0.19 | 850  | 597  | 12   | 10   |
|                        | max  | 0.05 | 0.22 | 863  | 614  | 17   | 33   |
|                        | opt  | 0.04 | 0.2  | 859  | 608  | 16   | 31   |

2. Change in production conditions. After changing the temperature range of the end of rolling in the hot rolling mill, an adjustment was made and the following values of the factors were obtained (figure 2 and table 9).
3. Raw material drift. The following results were obtained when the properties of raw materials drifted (figure 3).

4. Changing the requirements for the quality indicators of finished products. In fact, this change corresponds to the transition to a different type of product.

4. Conclusion
The data obtained during the operation of the system is recorded by the report generation subsystem for further analysis. The developed system allows you to implement optimal process control, both at the level of an individual product and for a batch of products. The system provides the ability to adapt to changing production conditions. A procedure for selecting the most effective optimization method for managing local technology has been developed.

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