Mathematical modeling of synergetic aspects of machine building enterprise management

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Abstract. The multivariate method of determining the optimal values of leading key performance indicators of production divisions of machine-building enterprises in the aspect of synergetics has been worked out.

1. Introduction
Despite the large number of methods and tools of machine-building enterprise management we should note the lack of efficiency of their use.

According to the authors, this inefficiency is largely due to lack of implementation or complete lack of synergetic components in the concept of the investigated tools and approaches. While implementing the tasks of machine-building enterprise management it is necessary to rely not only on organization, but also on self-organization. In this case, there is a non-trivial and important issue of the transition from classical methods of econometrics to modern techniques, implementing the principles of synergetics.

2. Results and discussion
Exploring production divisions of enterprises as a dissipative structure, it is necessary to highlight such components that accompany self-developing systems in synergetics as an attractor, a fluctuation and, in particular, a fractal.

According to the authors’ opinion the most relevant and effective method of management of a machine-building enterprise that allows taking into account synergetic effects is the logical-metric modeling. The logical-metric modeling is a systematic set of procedures for the development of metrics, which are interconnected with stochastic and/or functional dependence and allow providing coordinated functioning of production subsystems of a business entity.

In the authors’ opinion a fractal as an object that has the property of self-similarity, i.e. consisting of several elements, each of which is similar throughout the whole object. It appears in the logical-metric model of development of a socio-economic system (SES) in the form of a top level balanced scorecard as well as in the procedure of cascading the system to the structural units (Figure 1).
Figure 1. A fractal in the logic-metric model of socio-economic system development.

The authors have investigated the ways of selecting the desired invariant conditions of production systems in accordance with the target as directed self-organization. Therefore, according to the authors, the attractor as the ideal end state of the system development in a logical-metric model of development of a machine-building enterprise manifested in the form of a balanced system of key performance indicators.

In this case, the problem of determining the values of the leading indicators when determining the target value of the indicator at the top level arises. This problem is caused by the presence of stochastic relationships between key performance indicators.

The authors propose the following approach to the determination of target values of key performance indicators of the logical-metric model of the economic entity strategy. At the first stage of the analysis, it is necessary to identify the presence of stochastic relationships using a correlation and regression analysis. If the statistical data necessary for a factor analysis are not available in the development of the logical-metric model of an economic entity evolution, then it is recommended to use expert assessment methods to obtain values of the regression coefficients.

The target value of the resulting financial indicator \( y \) is set by top managers using methods of forecasting and taking into account the results of a strategic analysis. At this stage, it is necessary to define the planned percentage change in the result indicator \( \Delta y \).

The target values of the other factor scores are calculated through their corresponding planned changes needed to achieve target value \( y \):

\[
x_k = x_k \left(1 + \frac{\Delta x_k}{100}\right),
\]

where \( x_k \) is the target value of the indicator; \( \Delta x_k \) is the necessary planned changes in the indicator, %.

To determine the required planned change of an indicator the authors propose the following approach.

At first we determine elasticity coefficients which present the percentage change in an average effective index change in \( y \) when an \( x_i \) factor changes by one percent. These coefficients are calculated by formula

\[
a_k = a_k \frac{\Delta x_k}{x_k},
\]
where \( e_k \) is the elasticity coefficient of factor \( x_k \); \( a_k \) is a coefficient of multiple linear regression.

Thus, we obtain:

\[
\Delta x_1 \times e_1 + \ldots + \Delta x_k \times e_k = \Delta y.
\]  

(3)

From the viewpoint of rationality and economy of resources factor indicators should vary according to the degree of their influence on the resulting indicator. To determine the percentage change of the factor indicator it is supposed to do the following:

A regression equation is transferred to the standardized form:

\[
t_0 = \beta_1 \times t_1 + \beta_2 \times t_2 + \ldots + \beta_n \times t_n.
\]  

(4)

Factors and the regression coefficients are related with the respective averages and dispersions by the following relations:

\[
t_k = \frac{x_k - \bar{x}}{\sigma_x},
\]

\[
a_k = \frac{\beta_k \sigma_x}{\sigma_k},
\]

\[
t_0 = \frac{y - \bar{y}}{\sigma_y},
\]

\[
a_0 = \frac{y - a_1 \bar{x}_1 - \ldots - a_n \bar{x}_n}{\sigma_y}.
\]  

(5)

\( \beta \)-coefficients allow one to give a comparative description of factor significance: the higher the value of a \( \beta \)-coefficient is, the more significant factor is in terms of its influence on the resulting indicator. Thus, the \( \beta \)-coefficients can be used for calculating the degree of change of the factor indicator. In our opinion, the percentage change in factor indicators should relate so as the relationship between their \( \beta \)-coefficients:

\[
\frac{\beta_1}{\beta_2} = \frac{\Delta x_1}{\Delta x_2}.
\]  

(6)

It turns out that any change of the factor indicator can be expressed through any change (for example, through the change of the last indicator) and the ratio of the corresponding \( \beta \)-coefficients. Having done this, we can solve equation (3) and calculate the necessary changes of all indicators:

\[
\Delta x_k = \frac{\Delta y}{\frac{\beta_1}{\beta_k} \times e_1 + \ldots + \frac{\beta_{k-1}}{\beta_k} \times e_{k-1} + e_k}.
\]  

(7)

In order to take into account the cases when the increase in the result value represents a negative change of the factor, we need to slightly transform equation (7):

\[
\Delta x_k = \frac{\Delta y \times \left| e_k \right|}{\frac{\beta_1}{\beta_k} \times \left| e_1 \right| + \ldots + \frac{\beta_{k-1}}{\beta_k} \times \left| e_{k-1} \right| + \left| e_k \right|}.
\]  

(8)

For enlarging the economic analysis, the authors recommend using the determination coefficient that describes the proportion of variation in dependent variable \( y \), which can be explained by attributes included in the factor model and calculated as follows:

\[
D = R^2,
\]

where \( R^2 \) is the coefficient of multiple correlation.

The coefficient of multiple correlation is calculated by the following formula:

\[
R^2 = \beta_1 \times r_{y x_1} + \beta_2 \times r_{y x_2} + \ldots + \beta_n \times r_{y x_n},
\]  

(9)

where \( r_{y x_k} \) is the coefficient of correlation between \( y \) and \( x_k \).

According to the calculation of the determination coefficient, we can conclude that \( D \times 100 \% \) is due to variation included in the model factors and \( (1 - D) \times 100 \% \) is due to the activities aimed at achieving the target, the extent of which is defined as resulting indicator \( y \).
For the purposes of testing the proposed methodology, we determine the optimal values of the KPI of the production hall of the Klintsovskiy truck crane plant.

Let us consider the index of output per shift \( y \), the target value for 2015, which is equal to 4.5 million rubles. In the developed logical-metric model the factor indicators are:

- an integrated indicator of product quality \( x_1 \);
- an integrated indicator of equipment failure \( x_2 \);
- actual implementation of replacement outfit, % \( x_3 \);
- non-recoverable waste for recycling, % \( x_4 \);

The values of these indicators for 2014 are presented in Table 1.

| \( y \) | \( x_1 \) | \( x_2 \) | \( x_3 \) | \( x_4 \) |
|-------|-------|-------|-------|-------|
| 3400000 | 3.671 | 2 | 93 | 0.533 |

The parameters of the regression equation were calculated using the method of least squares:

\[
y = 231887.14 \times x_1 + 23972.1 \times x_2 + 63469.72 \times x_3 + 509053.53 \times x_4 - 3644209.78.
\] (10)

For determination of the percent change of the factor indicator it is necessary to calculate the \( \beta \)-coefficients for standardized linear regression. The results of the calculation are presented in Table 2.

| The dispersion of the factor indicator (\( \sigma_k \)) | \( \beta \)-coefficient | Elasticity coefficient |
|-----------------------------------------------|-----------------|-------------------|
| \( \sigma_k \)                               | value           | \( e \) value     |
| 0.4545                                       | \( \beta_1 \)   | 0.3915            | 0.2348           |
| 0.4517                                       | \( \beta_2 \)   | 0.0402            | 0.0103           |
| 2.1665                                       | \( \beta_3 \)   | 0.5107            | 1.9021           |
| 0.0494                                       | \( \beta_4 \)   | 0.0935            | 0.0817           |

As it was mentioned above, the \( \beta \)-coefficients are used to calculate the change degree of the factor indicators, that is, to define each change of the factor indicator through the change in this index and finding the change of the factor:

\[
\Delta x_1 \times \frac{\beta_1}{\beta_4} \Delta x_4 = 4.184 \times \Delta x_4
\]
\[
\Delta x_2 \times \frac{\beta_2}{\beta_4} \Delta x_4 = 0.4299 \times \Delta x_4
\]
\[
\Delta x_3 \times \frac{\beta_3}{\beta_4} \Delta x_4 = 5.4585 \times \Delta x_4.
\] (11)

Substituting the values from Table 2, let us find value \( \Delta x_4 \):

\[
\Delta x_4 = \frac{\Delta y}{\frac{\beta_1}{\beta_4} e_1 + \frac{\beta_2}{\beta_4} e_2 + \frac{\beta_3}{\beta_4} e_3 + e_4} = 4.184 \times 0.2348 + 0.4299 \times 0.0103 + 5.4585 \times 1.9021 + 0.0817 = 2.8252.
\] (12)

Using (11) the change of the following factor indicators can be found:

\[
\Delta x_1 = 4.184, \quad \Delta x_4 = 11.821
\]
\[
\Delta x_2 = 0.4299, \quad \Delta x_4 = 1.214
\]
Thus, the following logical-metric model can be obtained:

\[ \Delta x_3 = 5.4585, \Delta x_4 = 15.421 \]  \hspace{1cm} (13)

Figure 2. Optimal values of factor indicators of the Klintsovskiy truck crane plant production division

In case of functional dependency between leading indicators and high-level indicators the optimal values of leading indicators are supposed to be calculated using system dynamics methodology.

Mathematically, the basic structure of a formal system dynamics computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations:

\[ \frac{dx(t)}{dt} = f(x, p), \]  \hspace{1cm} (14)

where \( x \) is a vector of levels (stocks or state variables), \( p \) is a set of parameters, and \( f \) is a nonlinear vector-valued function.

Basic elements of a system dynamics model are of four kinds: stocks, flows, variables and links. An application of the system dynamics approach assumes the distribution of the logical-metric model indicators for object classes mentioned above.

System dynamics has ample opportunity for simulating modeling and forecasting based on a stochastic approach that should increase the efficiency of management of the machine-building enterprise.

Further research of the existence of elements of synergetics in the management of production divisions of the machine-building enterprise makes it possible to note that fluctuation as a random deviation from the average values of physical quantities, which characterize the system of a huge amount of particles, can extend (on the results of the correlation analysis) the logical-metric model of indicators for monitoring of operating activities.

3. Conclusion

In summary, it can be noted that the proposed multivariate method of determining target values of leading indicators of the logical-metric models of development of the business entity based on the elements of synergetics should allow one to raise efficiency of management of production divisions of the machine-building enterprise.

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