Multicriteria analysis of product operational effectiveness at design stages

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Abstract. The multicriteria rapid assessment method of techno-economic parameters of new products is developed. It avoids expensive engineering changes during the operational stages through the analysis of external and internal factors at an early stage in the design that affect the maintainability and manufacturability of the product. The expert selection of the initial multitude of indicators from the five enlarged criteria groups and their subsequent pairwise comparison allow one to distinguish the complex compliance criteria of product design with the average and optimum values of the operational effectiveness. The values comparison provides an opportunity to decide on the continuation of the process for designing and preparation of the product manufacture.

1. Introduction
Modern machine building products are complicated technical complexes, which ownership cost for the exploiter might be several times their acquisition cost. The more complex the system, the higher the cost of service, damage control and maintenance in operational condition. The high operational effectiveness of the technical system can be achieved only by the right engineering decision-making at every stage of the life cycle.

The selection process for scientific ideas on shaping the future product includes an analysis of the objectives correspondence assigned to the system and its main features. It identifies the system efficiency, cost and time frame for the production, a degree of risk a low-tech product creating. The tasks being implemented at this stage have a high degree of baseline data uncertainty for the technical system and operating condition [1].

At the design stage, the particular settings of each element are determined on the basis of the system effectiveness as a whole. The efficiency of the designed elements variants is identified by the simulation of application, taking into account the factors and restrictions imposed by the manufacturer's production base and operational conditions.

The expenses for product operation are necessary to optimize so that its maintainability, included during the design process, allows reducing significantly the work cost during maintenance and repair stages [2, 3]. This requires the development of the complex system of rapid assessment of techno-economic parameters of the created products. Certain aspects of this assessment are reflected in several works of researchers [4, 5, 6, 7, 8]; however to date, there are no universal integrated assessment methods for the operational effectiveness of products at early stages during designing, which support a balanced approach in technological, economic and ecological aspects. This method would allow the advance abandoning of the design process and product manufacture which do not
meet the cost minimization criterion during their operational stages.

2. Method for assessing the operational effectiveness of the product
To fill this gap, a method is proposed that may be extended to broad classes of technical objects. The following enlarged criteria groups are suggested using in the evaluation system:

- functional and design criteria that define the properties of the product, its core functions and that affect the operational stage. These include the technical characteristics of the engineering product, functionality, coefficient of efficiency, operating conditions, for example, ambient temperature, the mass and dimensional characteristics, the accuracy measures of output parameters, and design criteria such as design availability, replaceability, unification of constituent parts, openness of measurement points;
- technological criteria affecting the technical efficiency, laboriousness, material consumption and technological processes of the product production, the costs for required quality assurance during manufacturing;
- reliability criteria that characterize the quality parameters of the functional performance by the product and its use efficiency by the consumer. These include service life, the probability of trouble-free operation, mean time between failures, failure cost, maintainability, and failure flow characteristics;
- ergonomic and ecological criteria for the conformity of the product with the environmental requirements, regulated by the standards of ISO 9000-14000 series; with the physical and physiological human capabilities, as well as the field maintainability taking into account health and safety standards;
- economic criteria that include cost parameters, as well as marketing and logistical potential that can be evaluated by the concerned services of the enterprise based on the analysis and market forecasts. These include the cost of materials, energy, information support, product laboriousness, the service and maintenance support costs, the promotional costs, relative market share, production cost and average price.

The method is implemented through the algorithm, consisting of the following steps:

1. The experts, selected in accordance with the recommendations as set out in [9, 10], select the criteria significant for the assessment of the operational effectiveness. If necessary, according to the agreed expert opinion, the criteria may be supplemented, taking account the characteristics of the product.

2. In order to generate a minimum list of information-capacous criteria fully characterizing the operational effectiveness of the product, the \( \Omega = \bigcup_{i=1}^{c} \times_i \) set of all operational effectiveness criteria \( X_i \) is constructed; obtained through the survey of isolated experts \( N \) which are specialists in the subject area.

Matrix \( R = (r_{ij}) \), \( j = 1, c \), \( i = 1, n \) is found, whose elements take the following values:

\[
\begin{align*}
    r_{ij} = 1 & \quad \text{if the } i \text{ criterion belongs to } X_i; \\
    r_{ij} = 0 & \quad \text{otherwise.}
\end{align*}
\]

The probability is calculated as:

\[
P_j = \frac{\sum_{i=1}^{c} r_{ij}}{c},
\]

and finite set \( \Omega^+ \) is formed having included those criteria for which \( P_i > P_0 \) where \( P_0 \) is a some predefined probability ratio close to one.

The degree of experts’ coherence by means of concordance coefficient \( W \) for unstrict ranking is determined. If \( W \) is less than present value \( W_0 \), the experts are offered another stage of a repeated
expertise having introduced the results of the previous stage. Otherwise, finite set \( \Omega^t \) shall be presented to the experts for classifying by the five above-mentioned groups of criteria \( \Omega^t (t = 1, ..., 5) \).

Correction factor \( B_t \) is defined, which takes into account difference between \( \Omega^t \) groups in terms of the number of included criteria to establish the adequacy of the criteria ranks taken from different subsets:

\[
B_t = \frac{f_t}{l_{\text{min}}},
\]

(2)

where \( f_t \) is the number of criteria in the \( t \) group; \( l_{\text{min}} \) is the number of criteria in minimum size group \( \Omega^t \).

Expert pairwise comparisons of the operational effectiveness criteria are carried out separately for each \( \Omega^t \) group using a verbal scale of their relative importance, on the basis of informativity about this indicator (table 1).

| Importance level of the criteria in terms of informativity about operational effectiveness | Corresponding quantitative value |
|------------------------------------------------------------------------------------------|----------------------------------|
| Equal importance                                                                          | 1                               |
| Moderate superiority                                                                     | 3                               |
| Strong superiority                                                                       | 5                               |
| Significant superiority                                                                  | 7                               |
| Very large superiority                                                                   | 9                               |

The expert fills in the comparison matrix where the criteria are located across the rows and columns. The corresponding quantitative value of the comparative assessment of the two criteria is put in the entries of the intersection of rows and columns. The expert can also use intermediate levels of a criterion preference, for example, 2, 4, 6.

The acquired comparison matrix is then processed. The eigenvectors of criteria within each group are calculated by the formula:

\[
A_i = B_i \cdot \sqrt[\text{\# of criteria}]{a_{i1}a_{i2}...a_{in}},
\]

(3)

where \( a_{i1}, a_{i2}, ..., a_{in} \) are the quantitative values of comparison between the \( i \) criterion and others; \( n \) is the number of criteria in the group.

The average criterion vector for the experts is defined using the formula:

\[
\bar{A} = \frac{\sum_{j=1}^{n} A_{ij}}{c}.
\]

(4)

The weight coefficient of the \( i \) criterion is defined as a specified value:

\[
b_i = \frac{\bar{A}_i}{\sum_{j=1}^{n} \bar{A}_j}.
\]

(5)
From the $\Omega^t_1$ groups, those operational effectiveness criteria of products were selected which weight coefficient exceeds some threshold value \( b_i \geq b_{hm} \), the final list of the most significant informative criteria $\Omega^t$ is formed.

3. The necessary input data for calculations from the design-engineering documentation on the product and analogues are collected for each group of criteria.

4. The calculations are carried out for each group of criteria according to table 2.

Table 2. Optimality assessment for one group of criteria

| Criterion name | Criterion value for the designed product | Criterion value for analogues | Average criterion value | Compliance with the average value | Optimal criterion value designated by the expert | Compliance of the criterion with the optimal value |
|----------------|------------------------------------------|------------------------------|-------------------------|----------------------------------|---------------------------------------------|-----------------------------------------------|
| Criterion 1    | $q_{11}$ $q_{12}$ $q_{13}$ ... $q_{1k}$ | $\frac{1}{k} \sum_{i=1}^{k} q_{1i}$ | $q^*_1$ | $\frac{q^*_1}{q_1}$ | $D_1 = \frac{q^*_1}{q_1}$ | 
| Criterion 2    | $q_{21}$ $q_{22}$ $q_{23}$ ... $q_{2k}$ | $\frac{1}{k} \sum_{i=1}^{k} q_{2i}$ | $q^*_2$ | $\frac{q^*_2}{q_2}$ | $D_2 = \frac{q^*_2}{q_2}$ | 
| ... n criterion| $q_{n1}$ $q_{n2}$ $q_{n3}$ ... $q_{nk}$ | $\frac{1}{k} \sum_{i=1}^{k} q_{ni}$ | $q^*_n$ | $\frac{q^*_n}{q_n}$ | $D_n = \frac{q^*_n}{q_n}$ | 
| Complex criterion (for the $t$ group) | $\frac{\sum b_i V_i}{n}$ | $\frac{\sum b_i D_i}{n}$ | $Y_V$ | $Y_D$ |

The following rule applies to the calculations: if the criterion should be maximal, then its values in the $n$ row are considered without changes; if the criterion should be minimal, then the calculation is made according to the values, inversed to its values, i.e. \(1/q_{1i}, ..., 1/q_{ni}\), where $i = 1, n$.

5. The calculated average values of the $Y_V$ and $Y_D$ for all criteria groups are put into table 3 and a comprehensive assessment of the operational effectiveness is then calculated.

6. On the basis of the obtained indicator values of $Y_V$ and $Y_D$, it is possible to conclude about the level of the product operational effectiveness, the expediency of its implementing in the industry, the availability of opportunities for design improvement or manufacturing technology to reduce costs during repair and maintenance stages.

If $Y_V < 1$ and $Y_D < 1$, then the product design is inferior to the average level by the operational effectiveness, and its further implementation is impractical.

If $Y_V \approx 1$ and $Y_D < 1$, then the product design corresponds to the average level, further development and its implementing in the industry is possible.
If $Y_V > 1$ and $Y_D < 1$, then the product design is superior to the average level by the operational effectiveness, and its implementation is recommended.

If $Y_V > 1$ and $Y_D \geq 1$, then the design of the product is close to the most optimal level, the construction is highly effective in operation, its implementing in the industry is recommended.

**Table 3. Summary table of comprehensive indicators for assessing the operational effectiveness of the product**

| Group name of criteria          | Compliance with the average value by the group | Compliance with the optimal value by the group |
|--------------------------------|-----------------------------------------------|-----------------------------------------------|
| Functional and design          | $Y_{V1}$                                      | $Y_{D1}$                                      |
| Technological                  | $Y_{V2}$                                      | $Y_{D2}$                                      |
| Reliability criteria           | $Y_{V3}$                                      | $Y_{D3}$                                      |
| Ergonomic and ecological       | $Y_{V4}$                                      | $Y_{D4}$                                      |
| Economic                       | $Y_{V5}$                                      | $Y_{D5}$                                      |
| Integrated assessment          | $\frac{\sum_{i=1}^{5} Y_{Vi}}{5}$             | $\frac{\sum_{i=1}^{5} Y_{Di}}{5}$             |

3. **Experimental validation of the method**

It was carried out during selection of the optimum design, in terms of operation; when selecting the device for operational control of the technical condition of systems and airborne equipment designed at a serial enterprise.

The assessments involved 12 experts from experienced technologists, engineers and material specialists of the enterprise, familiar with the specific features of the developing product and analogues. The experts were first offered to assess the significance of the operational effectiveness criteria from the enlarged groups. Next, an information-capacious set of criteria was formed, which takes into account the specificities of the designed device. After pairwise comparisons of criteria, using the verbal scale presented in table 1, the criteria with the weight coefficient above the threshold value were allocated. The calculations were carried out for each group of criteria using formulas (1-5). Consolidated data of the experimental validation are listed in table 4.

**Table 4. Results of an integrated assessment of the operational effectiveness of the designed device**

| Group name of criteria          | Criterion for compliance with the average value by the $Y_V$ group | Criterion for compliance with the optimal value by the $Y_D$ group |
|--------------------------------|-------------------------------------------------------------------|------------------------------------------------------------------|
| Functional and design          | 1.24                                                              | 1.07                                                             |
| Technological                  | 1.32                                                              | 1.20                                                             |
| Reliability criteria           | 0.95                                                              | 1.03                                                             |
| Ergonomic and ecological       | 1.05                                                              | 0.82                                                             |
| Economic                       | 0.87                                                              | 0.69                                                             |
| Integrated assessment          | 1.09                                                              | 0.96                                                             |

Based on the studies and the assessments received by enterprise specialists, it was concluded that it is useful to develop and prepare the production of the device as its design is superior to the average level by the operational effectiveness ($Y_V > 1$ and $Y_D < 1$).

4. **Conclusion**

This method allows assessing the operational effectiveness of any complex technical product. The analysis of external and internal factors at an early stage in the design that affect the maintainability
and manufacturability of the product avoids expensive engineering changes in the construction during the operational stages. The involvement of competent experts allows filling the lack of the product information at the design stages and to assess objectively the best design in terms of the operational effectiveness on the basis of engineering experience and knowledge. Merging several criteria, implemented through the weight coefficients of their importance, eliminates the multi-criteria nature of the task and ensures an informed decision on further development and manufacture of the product design.

The method is recommended in machine building enterprises in the product evaluation for production and operational manufacturability.

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