Application of data envelopment analysis for multi-criteria evaluation of system for technogenic waste recycling in oil refining industry

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Abstract. The paper proposes an approach based on the DEA method (Data Envelopment Analysis) to a multi-criteria evaluation of a complex structured system for the processing of technogenic waste in the oil refining industry. The special algorithm is considered for assessing environmental safety and energy efficiency of operating waste processing system facilities, taking into account their resource value and reuse potential. According to the developed algorithm, five interconnected mathematical programming problems are solved. These problems formulated using CCR and Super-efficiency models of DEA method allow to obtain the assessments of the disposal system regarding the chosen efficiency criteria. A new approach to the analysis of the results on the basis of total effectiveness estimates using the Super-efficiency model of the DEA method is proposed. The results of testing the developed algorithm on an oil-containing waste processing system in the Samara region make it possible to form appropriate control decisions in the region’s oil refining industry.

1. Introduction

The oil refining industry is the key sector of the economics of the Russian Federation, the development of which currently represents one of the most important strategic objectives. The reduction of energy costs and the harmful environmental impact of the processes of oily waste refining are of particular importance due to the recognition of the importance of energy-saving and environmental safety of production in modern society. The traditional methods of increasing the technical and economic indicators of oil refining processes are focused on the specific nature of the industries in which they were used in the period before the fast development of modern information technologies and intelligent systems. According to statistics, up to 10 million tons of technogenic oil-contaminated waste (OCW) of the oil refining industry (oil and drilled sludge, oil waste, used oils, etc.) are accumulated in Russia annually, and the volume of their reuse is no more than 10% [1, 2]. At the same time, in western countries OCWs are considered as sources of secondary resources of high value [3-7], and the proportion of their secondary processing reaches 50% [8].
The term «value of secondary resources» includes not only a quantitative assessment of their physical and chemical composition and properties, which determines the degree of suitability of the waste for use as material resources in recycling technologies but also the creation of a wide range of measurable benefits in the environmental, economic, social and technical fields evaluated by groups of relevant indicators [9-13].

A significant part of the production cycle of complex OCW processing is represented by energy-and resource-intensive technological processes that negatively affect the environment. Given the total costs of storage, transportation, treatment, and disposal of TW, it can be argued that due to losses associated with both the fatal features of the oil refining processes and the removable causes of inefficient use of energy resources and their negative impact on the environmental situation in the present and In the future, the effect expected from the optimization of the integrated processing system may be more significant than the effect from the optimization of primary processing processes.

The problem of a comprehensive assessment of the efficiency of OCW utilization by groups of heterogeneous indicators is an urgent task in modern societies. One approach to solving such a problem is based on the DEA method (Data Envelopment Analysis) [14-15]. The concept of measuring the environmental efficiency of companies’ management by aggregating various indicators without explicit values of the coefficients of weight functions using the “input-output” model of the DEA method was proposed in [16].

The environmental performance of a waste recycling system can be measured using the ratio of GDP per capita to greenhouse gas emissions per capita derived from the waste treatment sector [17]. The analysis of the improvement of the environment per unit of investment costs for waste utilization is given in [18], taking into account the separation coefficient of waste during collection and the ratio of the methods used for waste processing.

In [19], on the basis of the DEA method, multifactor analysis of the efficiency of industrial systems at the stage of energy use and the stage of purification from pollution is carried out in order to accurately assess the overall energy efficiency. Three-stage DEA model is used in [20] to measure environmental efficiency and the marginal cost for CO₂ emission decreasing in 37 industries in China during 2005-2014.

In [21], the basic model of the DEA method was used to assess the ecological efficiency of regions by identifying those that are on the boundary of efficiency, and then the Super-efficiency model of the DEA method was used to rank the most effective regions.

To solve the problem of reducing energy consumption and the environmental impact of waste treatment processes, it is necessary to make a comparative assessment of the environmental safety and energy efficiency of the operating of the optimized waste recycling system. Toward this goal, let us assume that the system for OCW recycling includes N storages of wastes and M recycling technologies. According to DEA method terminology, all these objects under consideration will be called further as DMUs (Decision Making Units). The article proposes an approach based on the DEA method to assess heterogeneous indicators characterizing DMUs of a complex structured system for the processing of technogenic oil-contaminated wastes. Based on the proposed approach, an algorithm has been developed for a multi-criteria comparative assessment of environmental safety and energy efficiency of functioning of waste processing system facilities, taking into account assessments of resource value and reuse potential.

In the analyzed system, the waste storage facilities and technologies for waste processing are considered as interrelated objects (DMUs) for comparative evaluation.

2. Multi-criteria assessment based on DEA-method

The paper proposes a unified approach based on the DEA method to solve the problem of comparative evaluation of heterogeneous indicators (criteria) characterizing DMUs of a complex structured system for the processing of technogenic waste from the oil and gas industry.

One of the most important quantitative indicators for estimating the efficiency of the secondary use of the waste is the resource value. The resource value of wastes is a quantitative assessment of their
physicochemical composition and properties, which determines the degree of suitability of waste for use as material resources in recycling technologies associated with their recycling, recovery and regeneration. The original approach to estimating the resource value proposed in [22] is based on the DEA method. In [23], it is suggested to consider the reuse potential as the complex quantitative criterion of the possibility of effective waste recycling, assessed by the combination of heterogeneous indicators (technological, energetic, environmental, economical, social, technical, etc.) and the resource value of OCW. The estimation of the reuse potential is also based on the DEA method.

Similar to assessments of the resource value and the reuse potential on the basis of the DEA method, one can obtain comparative estimates of DMUs of a complex structured system for the recycling of technogenic oil-contaminated wastes according to heterogeneous indicators (criteria) characterizing the overall efficiency of the system operation. It is proposed to consider the waste storage facilities and the technologies for waste processing as interrelated DMUs in the analyzed system for comparative evaluation.

Problem of mathematical programming (MPP) of searching for the maximum of objective function $F_z$ [14], formulated on the basis of CCR model of DEA method that allows one to obtain evaluations of Z DMUs, can be written in the following form:

$$F_z(X_z, Y_z) = \sum_{j=1}^{J} u_{jk} y_{jk} \rightarrow \max \forall \ t, y \in G$$

subject to the following constraint:

$$\frac{\sum_{j=1}^{J} u_{jk} y_{jk}}{\sum_{i=1}^{H} v_{ik} x_{ik}} \leq 1, \forall \left( z = 1, Z; j = 1, J; i = 1, H; u_{jk} > 0; v_{ik} > 0 \right)$$

providing that the numerical values of the relative assessments should belong to the interval [0; 1].

Here the objective function $F_z$ represents the ratio of the weighted sum of the output parameters $y_{jk}, j = 1, J$ that positively affect the estimated indicator, to the weighted sum of the input parameters $x_{ik}, i = 1, H$ that negatively affect the estimated indicator; $u_{jk}, j = 1, J, z = 1, Z$ and $v_{ik}, i = 1, H, z = 1, Z$ are input and output “weights”. The number $H$ of input parameters and number $J$ of output parameters depend on the physical meaning of the evaluated function $F_z$, as well as on the possibility of determining the numerical values of inputs and outputs or the characteristics of the compared DMUs used to calculate values of inputs or outputs in particular cases.

Solution of the problem (1) under constraint (2) gives the relative values $F_z, z = 1, Z$ of efficiency estimation for Z DMUs and appropriate weight coefficients $u_{jk} \in G, j = 1, J, z = 1, Z$ and $v_{ik} \in G, i = 1, H, z = 1, Z$, maximizing the functional (1). Formulated problem (1)-(2) is related to the problems of mathematical programming (MPP) that can be solved by standard optimization methods [24].

As a result of the solution of Z MPPs, several DMUs in the analyzed group can at once have an assessment $F_z = 1$, meaning that these DMUs have maximum efficiency in the system. The remaining DMUs with a rating of $0 < F_z < 1$ are considered as less efficient ones regarding criterion (1). When several DMUs have maximum possible efficiency ($F_z = 1$), the results of MPP (1)-(2) solution can be not representative from point of view of ranking DMUs in the analyzed group regarding criterion (1).

Super-efficiency model of DEA method is used for comparative evaluation in the cases when it is important to determine which DMU demonstrates the highest efficiency according to the chosen criterion [15].

Then, similar to (1)-(2), the following mathematical programming problem based on Super-efficiency model should be formulated for the comparative evaluation of the DMUs:
\[ S_z(X_z, Y_z) = \frac{\sum_{j=1}^{J} \bar{u}_{jz} y_{jz}}{\sum_{i=1}^{I} \bar{v}_{iz} x_{iz}} \rightarrow \max_{\vec{u}, \vec{v}} \]  

\[ \frac{\sum_{j=1}^{J} \bar{u}_{jz} y_{jz}}{\sum_{i=1}^{I} \bar{v}_{iz} x_{iz}} \leq 1 \forall \begin{cases} z = 1, Z; & z \neq k; j = 1, J; \\ i = 1, H; & \bar{u}_{jz} > 0; \bar{v}_{iz} > 0 \end{cases} \]  

where \( \vec{U} = (\bar{u}_{jz}), j = 1, J; \vec{V} = (\bar{v}_{iz}), i = 1, H \) are vectors of unknown weight coefficients for each \( z \)-th DMU, \( z = 1, Z \). It is important to underline that output weights \( \bar{u}_{jz}, j = 1, J \) and input weights \( \bar{v}_{iz}, i = 1, H \) for \( k \)-th DMU with efficiency estimation \( F_k = 1 \) are eliminated from the solution set in problem (1)-(2), where \( k \) is the sequential number of DMU having assessment \( F_k = 1 \).

Solution of the problem (3)-(4) gives the relative value \( S_z, z = 1, Z \) of efficiency estimation belonging to the interval \([0, \infty)\). As a result, the DMU having maximum estimation \( S_z \) can be considered as the most effective one in the analyzed system.

3. Algorithm for evaluation of environmental safety and energy efficiency of the system for waste recycling

Based on the approach described above, the special algorithm has been developed for a multi-criteria comparative evaluation of environmental safety and energy efficiency of waste processing system operating taking into account assessments of resource value and reuse potential of DMUs. This algorithm represented in Figure 1 comprises 5 consecutive stages. On each stage the above-described MPPs (MPPs 1-5 in Figure 1), formulated in the form (1) - (2) on the basis of the CCR model and in the form (3) - (4) on the basis of Super-efficiency model of the DEA method, are solved to obtain comparative assessments of \( N \) waste storage facilities and \( M \) technologies for waste recycling considered as compared DMUs in the analyzed system.

On the first stage in order to determine the comparative significance of \( N \) storages (DMUs) as potential sources of the secondary resources the problem of comparative evaluation of the resource value (Problem 1 in Figure 1) is solved [23].

As DMU’s inputs, those smaller amounts are preferable for the higher relative re-source value, the following waste components have been selected in MPP 1: average weighted content of water, asphalt-tenes and resins, mechanical and mineral impurities, and sulfur (Figure 1, inputs 1-4). As DMU’s outputs, those bigger amounts result in the higher relative resource value of the storage, the following OCW components have been selected in Problem 1: average weighted content of light hydrocarbons and the ratio of the mass of light carbon-hydrogens to the total mass of harmful impurities and water (Figure 1, outputs 5-6).

Solutions of the MPPs formulated in the forms (1)-(2) and (3)-(4) based on CCR and Super-efficiency models of the DEA method provide relative estimations \( F_n \) and \( S_n \), \( n = 1, N \) of resource value of \( n \)-th DMU (OCW’ storage), respectively. These estimations can be obtained for all \( N \) storages of the analyzed group. As a result, the obtained assessments \( S_n, n = 1, N \) can be compared and the storage with the biggest resource value of OCW can be determined in the analyzed group.
On the second stage the resource potential is proposed to be evaluated separately for two types of the compared DMUs: storages and technologies. The resource potential of the n-th storage characterizes the cost of useful products obtained as a result of recycling the stored wastes taking into account the cost of recycling process. The resource potential of the m-th processing technology characterizes the cost of the useful products obtained as a result of this technology application for the waste utilization in specific storage taking into account the cost of recycling process.

To evaluate the reuse potential, Problem 2 (Figure 1) formulated in the forms (1)-(2) and (3)-(4) is solved. As DMU’s inputs, those smaller amounts are preferable for the higher relative reuse potential value of the DMUs, the following parameters have been selected: duration of the recycling process, reagents mass and energy (fuel) consumption (Figure 1, inputs 7–9 and 10–12). As outputs, those bigger amounts are preferable for the higher relative reuse potential value of the DMUs, the following parameters have been selected in the Problem 2: mass of valuable recycling products and estimation of resource values of n-th DMU, obtained as a result of solution of Problem 1 in the form (3)-(4) (Figure 1, outputs 13 and 14).

Solutions of the Problems 2 in the forms (1)-(2) and (3)-(4) based on the CCR and Super-efficiency models of DEA method, respectively, provide the relative values $F_{mn}^2$ and $S_{mn}^{2.1}$, $n = 1, N$, $m = 1, M$ of reuse potential, estimating possibility of effective recycling of OCW in n-th storage (DMU) using m-th
recycling technology. Analysis of the estimations \( S^2_{mn}, m = 1, \bar{M}, n = 1, \bar{N} \) obtained for all \( N \) storages allows to determine the storage with the biggest reuse potential in the in the analyzed system.

Similarly, solutions of the Problem 2 give the relative values \( F^2_{mn}, n = 1, \bar{N}, m = 1, \bar{M} \) of reuse potential, estimating the ability of \( m \)-th recycling technology (DMU) to use the waste in \( n \)-th storage as a resource. These estimations can be obtained for all \( M \) technologies in analyzed system. Analysis of estimations \( S^2_{mn}, n = 1, \bar{N}, m = 1, \bar{M} \) allows to determine the technology with the biggest reuse potential in the in the analyzed system.

On the third stage a multi-criterion assessment of a system for waste recycling according to the criterion of energy consumption is proposed taking into account the energy costs of waste transporting from storage facilities to the locations of stationary recycling plants or the cost of transporting mobile recycling installations to the storage facilities. To determine comparative assessments of the DMUs efficiency regarding the criterion of energy consumption, Problem 3 is solved for two types of compared DMUs (storages and technologies, see Figure 1). The input parameters are the indicated specific energy costs for transportation and its duration (inputs 25, 26 and 27, 28 in Figure 1). The output parameters are the assessments \( S^3_{mn} \) and \( S^3_{mn} \) of resource obtained as a result of the decision of the Problem 2.

Solutions of the Problem 3 formulated in the forms (1)-(2) and (3)-(4) based on CCR and Super-efficiency models of DEA method, respectively, provide the relative assessments \( F^3_{mn} \) and \( S^3_{mn}, m = 1, \bar{M}, n = 1, \bar{N} \) for energy efficiency of waste recycling in the compared storages. Analysis of the assessments \( S^3_{mn}, m = 1, \bar{M}, n = 1, \bar{N} \) allows determining the storage in which the recycling process using all \( M \) technologies requires minimum energy consumption.

Similarly, solutions Problem 3 provide the relative assessments \( F^3_{mn} \) and \( S^3_{mn}, m = 1, \bar{M}, n = 1, \bar{N} \) for energy efficiency of the \( n \)-th technology application for recycling waste in the \( n \)-th storage. Analysis of the assessments \( S^3_{mn}, m = 1, \bar{M}, n = 1, \bar{N} \) allows determining the most energy saving technology for the recycling waste in all \( N \) storages of the analyzed system.

To estimate the environmental safety of the recycling system operation, Problem 4 is formulated and solved on the fourth stage of algorithm for two types of comparison DMUs: storages and technologies (Figure 1). As DMU’s inputs, those smaller values are preferable for the higher environmental safety of DMU, the following parameters have been selected in the Problem 4: the overall emissions of greenhouse gases, sulphur dioxide and minerals, mass of not processed part of mineral and mechanical impurities, and mass of polluted water formed in the recycling process (inputs 15-19 and 20-24, Figure 1). As DMU’s output, those bigger value is preferable for the higher environmental safety, the mass of useful recycling products is considered (outputs 13-14, Figure 1).

Solutions of the Problem 4 in the form (1)-(2) and (3)-(4) based on the CCR and Super-efficiency models of the DEA method give, respectively, the relative values \( F^4_{mn} \) and \( S^4_{mn}, n = 1, \bar{N}, m = 1, \bar{M} \), estimating the comparative environmental safety of waste recycling in \( n \)-th storage using \( m \)-th recycling technology. These estimations can be obtained for all \( N \) storages. The analysis of assessments \( S^4_{mn}, n = 1, \bar{N}, m = 1, \bar{M} \), defines which storage in the analyzed system has the highest environmental safety with respect to all \( M \) recycling technologies.

Similarly, solutions of the Problem 4 in the form (1)-(2) and (3)-(4) based on the CCR and Super-efficiency models of DEA method provide, respectively, the relative values \( F^4_{mn} \) and \( S^4_{mn}, n = 1, \bar{N}, m = 1, \bar{M} \), estimating the environmental safety of usage of \( m \)-th technology for recycling the waste in \( n \)-th storage. These estimations can be obtained for all \( M \) recycling technologies. The analysis of assessments \( S^4_{mn}, m = 1, \bar{M} \) shows which technology has the highest environmental safety for waste recycling in all \( N \) storages of the analyzed system.

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Finally, at the fifth stage of algorithm Problem 5 is formulated and solved to estimate the system for waste recycling regarding either energy efficiency or environmental safety. As DMU’ inputs the same input parameters as in the Problem 3 have been selected in the Problems 5 (inputs 25, 26 and 27, 28, Figure 1). As DMU’ outputs the following parameters have been selected in the Problems 5: the estimations \( S_m^2 \) and \( S_m^2 \) of reuse potential obtained as solutions of the Problems 2 in the form (3)-(4), respectively; the estimations \( S_m^4 \) and \( S_m^4 \) of the environmental safety obtained as solutions of Problems 4 in the form (3)-(4), respectively.

Considering the storages as DMUs, solutions of the Problem 5 in the forms (1)-(2) and (3)-(4) based on the CCR and Super-efficiency models of DEA method provide, respectively, the relative values \( F_n^5, n S_n^5 \), \( m = 1, M, n = 1, N \) estimating energy efficiency and environmental safety of waste recycling in \( n \)-th storage using \( m \)-th recycling technology. These estimations can be obtained for all \( N \) storages of OCW in the analyzed system. Analysis of estimations \( S_m^5, m = 1, M, n = 1, N \), defines the best storage in the analyzed system from the point of view of the energy saving and environmental safety.

Similarly, solutions of the Problem 5 for technologies as DMUs provide the relative values \( F_n^5 \) and \( S_m^5 \), \( m = 1, M, n = 1, N \) estimating the energy efficiency and environmental safety of usage of \( m \)-th technology for recycling waste in \( n \)-th storage. These estimations can be obtained for all \( M \) recycling technologies of the analyzed system. Analysis of estimations \( S_m^5, m = 1, M, n = 1, N \) defines the most energy saving and environmentally safe technology in the analyzed system.

4. Implementation of the developed algorithm and results analysis

The developed algorithm has been tested for the evaluation of the waste recycling system consisting of \( N = 15 \) storages of waste and \( M = 8 \) recycling technologies located in Samara region of Russian Federation. As the results of Problems 1-5 solutions the relative values of assessments \( F_n^5, F_m^5, S_n^5, S_m^5 \), \( n = 1, N, m = 1, M, \gamma = 1, 5, \psi = 2, 5 \) have been obtained (Figure 1).

Generalized analysis of the obtained results can be performed using cumulative assessments calculated by formulas:

\[
DL_n^\gamma = \sum_{m=1}^{N} S_m^\gamma, n = 1, N, \gamma = 1, 5; \tag{5}
\]

\[
D2_m^\psi = \sum_{n=1}^{N} S_n^\psi, m = 1, M, \psi = 2, 5. \tag{6}
\]

Cumulative estimations \( DL_n^\gamma, \gamma = 1, 5 \), obtained by expression (5), for \( \gamma \)-th MPP characterize generalized assessments for \( M \) technologies applied for recycling waste in \( n \)-th storage, \( n = 1, N \) (Table 1). Cumulative estimations \( D2_m^\psi, \psi = 2, 5 \), obtained by expression (6) for \( \psi \)-th MPP characterize generalized assessments for the case of application of \( m \)-th technology \( (m = 1, M) \) for recycling waste in \( N \) storages (Table 2).

To perform the final analysis, it is proposed to formulate MPP on the basis of CCR model of DEA method in the form similar to (1)-(2), that allows to obtain a comparative assessment of \( Z \) DMUs of the recycling system regarding to the efficiency indicators:

\[
Q_\gamma (Y) = \sum_{k = 1}^{Z} u_k Y_k \rightarrow \max_{i \in I}, \tag{7}
\]

The following constraint
\[ \sum_{\varphi=1}^{\phi} u_{\varphi z} y_{\varphi z} \leq 1, \quad \forall \left( z = \overline{1, Z}; \varphi = \overline{1, \Phi}; u_{\varphi z} > 0 \right) \]  

(8)

provides belonging the numerical value of the relative assessments \( Q_z \) to the interval \([0; 1]\). In (7)-(8) \( u_{\varphi z}, z = \overline{1, Z}; \varphi = \overline{1, \Phi} \) are coefficients that characterize “weights” of outputs \( y_{\varphi z}; \varphi = \overline{1, \Phi} \); \( y_{\varphi z}, \varphi = \overline{1, \Phi} \) are output parameters that positively affect the assessment \( Q_z \) and represent cumulative assessments \( D^1_u, n = \overline{1, N}, \gamma = \overline{1, 5} \) obtained by (5) or \( D^2_u, m = \overline{1, M}, \psi = \overline{2, 5} \) obtained by (6). Number of output parameters \( \Phi = 5 \) used for cumulative assessment \( Q_z \) is determined by number of formulated and solved MPP according to algorithm of evaluation of environmental safety and energy efficiency of the waste recycling system, including \( N \) storages and \( M \) recycling technologies (Fig. 1).

If several DMUs have maximum values of assessments \( Q_z = 1 \), then the results of MPP (7)-(8) solution can be not representative from point of view of ranking DMUs in the analyzed system, and therefore, the Super-efficiency model of DEA method is again should be applied for comparative evaluation.

Then, similar to (7)-(8), the following mathematical programming problem based on Super-efficiency model is formulated for the comparative evaluation of the DMUs as follows:

\[ R_z \left( Y_z \right) = \sum_{\varphi=1}^{\phi} \overline{u_{\varphi z}} y_{\varphi z} \rightarrow \max \quad \forall \left( z = \overline{1, Z}; \varphi = \overline{1, \Phi}; \overline{u_{\varphi z}} > 0 \right) \]  

(9)

\[ \sum_{\varphi=1}^{\phi} \overline{u_{\varphi z}} y_{\varphi z} \leq 1, \quad \forall \left( z = \overline{1, Z}; \varphi = \overline{1, \Phi}; \overline{u_{\varphi z}} > 0 \right) \]  

(10)

where \( \overline{U} = \left( \overline{u_{\varphi z}} \right), \varphi = \overline{1, \Phi} \) is vector of weight coefficients for \( z \)-th DMU, \( z = \overline{1, Z} \), that represent unknown parameters excluding coefficients \( \overline{u_{\varphi z}}. \) It is important to underline that “weights” \( \overline{u_{\varphi z}}, \varphi = \overline{1, \Phi} \) for \( b \)-th DMU with estimation \( Q_b = 1 \) are eliminated from the solution set in problem (9)-(10), where \( b \) is sequential number of DMU having assessment \( Q_b = 1 \).

Solution of the problem (9)-(10) gives the relative values \( R_z, z = \overline{1, Z} \) of the assessments belonging to the interval \([0, \infty)\). As a result, the DMU having maximum estimation \( S_z \) can be considered as the most effective one in the analyzed system.

In Table 1, the assessments \( R_{1n}, n = \overline{1, 15} \), obtained as a result of solution of MPP (9)-(10) formulated using Super-efficiency model of DEA method characterize relative efficiency of \( n \)-th waste storage in comparison with other storages of the system taking into account all criteria considered as objective functions in Problems 1-5 (Figure 1).

The results in Table 1 show that it is most effective to utilize the waste in the storage \( \# 12 \), which has maximum evaluation \( R_{12} = 1.907 \), using all recycling technologies of the analyzed system. At the same time, analyzing the cumulative assessments obtained for Problems 1-5, one can see that the storage \( \# 12 \) can be considered as the best one only regarding resource value (\( D^1_{12} = 2.381 \)) and environmental safety (\( D^1_{12} = 8.301 \)). It is conditionally not effective to recycle waste from the storage \( \# 15 \), having minimum value of assessment \( R_{15} = 0.553 \).

In Table 2, the assessments \( R_{2m}, m = \overline{1, 8} \), obtained as a result of solution of MPP (9)-(10) formulated using Super-efficiency model of DEA method characterize relative efficiency of \( m \)-th recycling technology in comparison with other technologies of the system taking into account all criteria considered as objective functions in Problems 1-5 (Figure 1).
Table 1. Cumulative assessments $D^\gamma_n$ of environmental safety and energy efficiency of waste storages.

| Number of waste storage $(n = 1.15)$ | Assessments $D^\gamma_n$ | Assessment $R^\gamma_n$ |
|-------------------------------------|--------------------------|-----------------------|
|                                     | $\gamma = 1$ | $\gamma = 2$ | $\gamma = 3$ | $\gamma = 4$ | $\gamma = 5$ | |
| 1                                   | 1.249 | 5.789 | 2.708 | 6.435 | 3.097 | 0.909 |
| 2                                   | 0.850 | 4.550 | 2.692 | 6.059 | 3.264 | 0.839 |
| 3                                   | 0.682 | 3.299 | 1.857 | 4.828 | 2.182 | 0.623 |
| 4                                   | 0.806 | 5.035 | 1.113 | 5.417 | 1.245 | 0.764 |
| 5                                   | 0.440 | 3.710 | 1.346 | 3.878 | 1.541 | 0.555 |
| 6                                   | 0.837 | 3.811 | 1.776 | 5.181 | 2.024 | 0.650 |
| 7                                   | 0.687 | 4.367 | 2.182 | 5.477 | 2.439 | 0.724 |
| 8                                   | 0.629 | 7.380 | 1.113 | 5.417 | 4.791 | 1.068 |
| 9                                   | 0.527 | 3.794 | 0.775 | 4.061 | 0.856 | 0.574 |
| 10                                  | 0.860 | 4.448 | 3.186 | 6.393 | 4.791 | 1.068 |
| 11                                  | 0.653 | 4.106 | 1.717 | 4.873 | 1.993 | 0.654 |
| 12                                  | 2.381 | 5.631 | 2.745 | 8.301 | 3.078 | 1.907 |
| 13                                  | 1.063 | 7.92 | 2.719 | 5.578 | 2.778 | 1.106 |
| 14                                  | 0.548 | 4.015 | 1.073 | 4.897 | 1.233 | 0.647 |
| 15                                  | 0.440 | 3.047 | 1.804 | 3.994 | 2.132 | 0.553 |

The results in Table 2 show that it is most effective to apply the technology №6, which has maximum evaluation $R^\gamma_n = 1.608$, for recycling waste in all storages of the analyzed system. At the same time, analyzing the cumulative assessments obtained for Problems 2-5, one can see that the technology №6 can be considered as the most energy saving ($D^\gamma_6 = 9.42$) and environmentally safe ($D^\gamma_6 = 9.51$). It is conditionally not effective to recycle waste using technology №4, having minimum value of assessment $R^\gamma_4 = 0.815$.

Obtained results (Tables 1 and 2) can be applied to make the decisions for the optimization recycling system in Samara region in order to improve its operating efficiency. Developed algorithm of multi-criteria evaluation can be considered as a basis for optimization of complex structured recycling system regarding environmental safety and energy efficiency taking into account the resource value and reuse potential of the system elements.
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