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Using DEA models to measure the efficiency of energy saving projects

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Abstract. The paper discusses the approach for multi-criteria estimation of the efficiency of energy saving projects by the Data Envelopment Analysis (DEA) method. The measurement of efficiency of considered projects and the identification of sources of their inefficiency is a very important condition to put the projects into practice in industrial competitive environment. The term “energy saving project” refers to a project resulting in certain output improvements with respect to energy consumption of the technological process by spending certain inputs. Thus, the energy saving project can be treated as a production unit or Decision Making Unit (DMU). The estimation of the efficiency of energy-saving projects by DEA is illustrated here via example of an industrial enterprise for the production of cellular autoclaved aerated concrete. The nine typical inputs/outputs are used and the twelve DEA models are developed that characterize the technological, environmental, economic and comprehensive estimators of the efficiency of energy saving projects. The developed approach for multi-criteria estimation of the efficiency of energy saving projects by the DEA method has the potential of widespread use in practice for making effective management decisions on the formation of investment programs for industrial enterprises.

1. Introduction

The current state of any industrial production is directly related to the efficiency of the use of fuel and energy resources (FER). Implementation of energy saving projects at the enterprises leads to reducing the consumption of fuel and energy resources, thereby decreasing the cost of production, which allows enterprises to remain competitive in the market [1-4]. However, the use of the enterprise asserts or, moreover, borrowed investment funds requires a well-reasoned decision in the choice of the most efficient energy saving projects. For the decision making not only the economic component, but also the efficiency of projects with respect to technological, environmental, logistical and other criteria (indicators) should be taken into account.

In recent years, the investment in the energy saving projects has grown continuously, and there is increasing recognition that measuring the efficiency of these projects becomes a vital important problem [5-8]. A large number of publications devoted to the problem of multi-criteria estimation of efficiency of industrial energy saving projects have appeared in Russia and abroad [9-12]. The use of certain estimation methods described in these publications is determined mainly by the features of the



specificity of implementation objects and the projects themselves, as well as by the characteristics of investment sources [13, 14].

In Russia, «Guidelines for evaluating the effectiveness of investment projects» [15] and the «Guideline for the estimation of the investments efficiency of the United Nations Industrial Development Organization UNIDO» are most often used for measuring the economic efficiency of energy saving projects [16]. The Guideline, published by UNIDO in 1978, is accepted worldwide as a standard. It is relevant to this day both for new investments and for projects devoted to extension of an enterprise, modernization and business process re-engineering. The estimation methods proposed in [17-19] are based on this approach, which determines the benefit by the cost of the projected reduction in energy consumption. However, the implementation of energy saving projects also releases a capacity, the effect of which sometimes turns out to be more significant than the saving of fuel and energy resources (FER); this fact is not always taken into account in the technoeconomic study. Thus, while estimating the efficiency of energy-saving projects, it is necessary to consider not only the savings in fuel and energy resources, but also, for example, the technological effect of the release of capacity, the environmental effect of reducing CO₂ emissions, the social effect of easy operation of equipment, reliability, durability and other criteria.

Another method for measuring the efficiency of an energy saving project is the rapid assessment of equipment and technology [17]. The contribution of energy saving equipment is determined by including the coefficient of its' efficiency into the equation of heat balance of an industrial object (building); this coefficient characterizes the relative value of the reduction in energy consumption. This method is used to determine a class of buildings' energy efficiency and is universal for most projects, however, it gives fairly generalized results and does not take into account economic and operational factors, affecting only the energy indicators of the object of implementation (DMU).

Another approach to estimating the efficiency of implementation of energy saving technologies and energy saving measures is based on analysis of the environmental component of the Kyoto Protocol methodology [20]. For estimation of the contribution of energy saving technologies into the environmental component of efficiency, the author proposes to be guided by the following criteria: greenhouse gas emissions into the atmosphere; total energy consumption; consumption of material resources; emissions of ozone-depleting gases into the atmosphere; water consumption. In addition to the proposed generally applicable criteria, specialized criteria for toxic effects on humans and animals were also considered. The proposed indicators of environmental performance allow one to analyze new technological solutions in terms of their global and local environmental impacts.

In this paper, it is proposed to use the Data Envelopment Analysis (DEA) method for multi-criteria analysis of the efficiency of energy saving projects that allows evaluating projects using heterogeneous criteria having different units of measure [21, 22]. The energy saving project is proposed to be treated as a production unit or Decision Making Unit (DMU). Usage of DEA models provides the values of generalized efficiency indexes, which determine the relative efficiency or degree of inefficiency of each project. Projects with a maximum efficiency index of 1 form the efficiency boundary or efficiency frontier, and, therefore, the objects belonging to this frontier can be considered as the most efficient ones [23]. DMU located below the efficiency maximum in the interval [1], depending on the size of the estimation, are considered as less effective or not effective projects.

Analysis of the criteria for measuring efficiency of energy saving projects by the methods listed above demonstrates that the DEA method provides the most complete estimation (table 1).

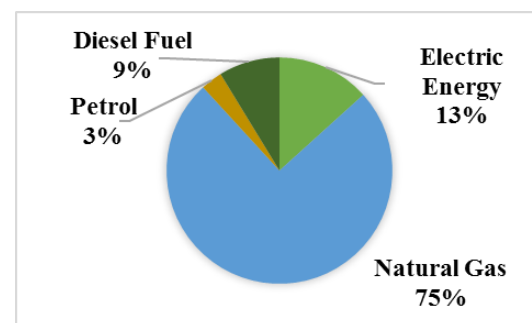
The aim of the presented study is the development of the procedure for multi-criteria estimation of the efficiency of energy saving projects by the DEA method on the example of an industrial enterprise for the production of cellular autoclaved aerated concrete.

2. Object of investigation

In the presented researches an industrial enterprise for the production of cellular autoclaved aerated concrete is considered as an object of investigations. It is located in the Krasnoyarsk district of Samara region, Russia. The total industrial square of the enterprise is 96600 m² (figure 1).

Table 1. Criteria for estimation of efficiency of energy saving projects.

Method of measuring efficiency	Estimation criterion
Rapid assessment	Reducing of energy consumption
Estimation based on the Kyoto Protocol methodology	General energy consumption; Greenhouse gas emissions; Consumption of material resources.
Technoeconomic study	Capital commitments; Return on investment; Pay-off period; Return on average assets; Generalized index of energetic efficiency of enterprise.
DEA	Reducing of energy consumption; Lifetime of equipment; Capital commitments; Exploitation costs; Operating convenience; Service personnel; Reliability growth; Increasing quality of energy resources, etc.

**Figure 1.** Location of main buildings at the enterprise**Figure 2.** Balance of fuel and energy resources consumption at the enterprise in 2016 year

The enterprise contains 15 buildings and units for various purposes (Figure 1): the main workshop (1); finished products storage area (2); emulsol warehouse building (3), boiler house building and compressor station (4), transformer substation building (5), autoscales (6), sand warehouse (7), security posts (8, 15), air drying unit building (9), a lime warehouse with a grinding department (10), a fork-lift parking (12), special equipment garages (11, 13), an administrative building (14). The production technology of cellular aerated concrete by the autoclaved hardening method causes a large amount of natural gas consumption (figure 2). Due to the high energy intensity of production, the need to reduce the consumption of energy resources by an enterprise through the implementation of energy saving projects is obvious.

To identify the potential for energy saving and energy efficiency increasing at the enterprise, an energy consumption survey of the enterprise has been conducted. The analysis of the results shows necessity of implementation of several energy-saving projects (table 2):

1. Implementation of a frequency-controlled drive of an electric motor of a pump for supplying water to the technological chain;

2. Replacing the insulation of the process steam line;
3. Implementation of the energy management system according to ISO 50001 standard;
4. Replacing the burner devices of water boilers;
5. Installation of a heat exchanger of a plate type at the site of concrete mixing;
6. Reconstruction of outdoor lighting of the enterprise;
7. Reconstruction of the internal lighting of the main workshop;
8. Installation of thermal insulation of the heating system pipeline;
9. Warming of the facade of the main workshop;
10. Insulation of the roof of the main workshop;
11. Development of automated system of electric power technical metering (ASTME).

The listed projects allow to save electric and thermal energy, and also natural gas. However, in real-life conditions of limited investments, not all projects are reasonable to be implemented and it becomes necessary to determine the most effective and low-cost ones. Table 2 shows the main technical and economic parameters of energy-saving projects, as well as the specific production indicators and the predicted values of CO₂ emission reduction, which may be considered as criteria for estimation of the projects' efficiency.

The following notations in table 2 are used.

I is investments (in thousands of rubles); this economic index displays the amount of investment required to implement an energy saving project.

C_{OP} is operating expenses (in thousands of rubles); this economic index takes into account production costs associated with maintaining the operating systems, machines and equipment in working conditions.

DPP is discounted payback period (in months); this parameter takes into account the period of refund depending on the time value of money (discount rate) that can be calculated according to expression:

$$DPP = \frac{I}{\sum_{t=1}^T \frac{D_t}{(1+\alpha)^t}}, \quad (1)$$

D_t is the flow of funds, including net income and depreciation for the certain period $t = \overline{1, T}$; $\alpha = 20\%$ is a discount rate.

B is an annual savings of energy resources in terms of their costs (in thousands of rubles); this economic criterion describes the value of saved fuel and energy resources, which can be achieved as a result of the energy-saving project implementation.

NPV is a net present value calculated as follows:

$$NPV = \sum_{t=1}^T \frac{D_t}{(1+\alpha)^t} - I. \quad (2)$$

ΔW is a reduction of power capacity of equipment (in tons of fuel oil equivalent per m³); this technological parameter can be defined as the following ratio of the saved energy resource E (in tons of oil equivalent (TOE)) to the volume of production V_{prod} (m³):

$$\Delta W = \frac{E}{V_{prod}}. \quad (3)$$

Economic parameter ΔP describes increasing of economic efficiency (in thous. Rub·m⁻³) as the ratio of money saved to the volume V_{prod} of end product:

$$\Delta P = \frac{B}{V_{prod}}. \quad (4)$$

Parameter $MTBF$ means a middle time between equipment failures (in hours), characterizing the average time of equipment failure-free operation and determines its reliability.

Em_{CO_2} is a reduction of CO₂ emission (in tons). In addition to reducing the consumption of fuel and energy resources, the energy saving problem solution also leads to the reduction of CO₂ emissions into the atmosphere.

Table 2. Inputs and outputs of energy saving projects.

Pr. No.	$I,$ (th.RUB)	$C_{OP},$ (th.RUB)	$DPP,$ (months)	$B,$ (th.RUB)	$NPV,$ (th.RUB)	$\Delta W,$ (TOE·m ⁻³)	$\Delta P,$ (th.RUB·m ⁻³)	$MTBF,$ (hours)	$Em_{CO_2},$ (tons)
	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
1	313.08	24.08	37	201.02	458.253	60.66	2,801.4	9,635	15.93
2	79.64	6.13	46	39.7	92.162	63.70	553.3	32,604	7.33
3	1650	137.5	48	749.55	1,854.48	224.55	10,445.8	47,424	25.83
4	226.22	17.4	55	94.61	155.16	151.46	1,318.5	10,640	17.42
5	176.3	13.56	63	65.35	59.27	104.87	910.8	11,742	12.06
6	258.46	17.23	41	147.75	360.99	44.60	2,059.1	100,000	11.71
7	1,581.35	105.42	71	533.85	635.82	161.12	7,439.9	100,000	42.3
8	114.64	8.81	48	54.34	120.51	87.20	757.3	96,360	10.03
9	1,713.6	122.36	104	454.63	412.03	653.61	6,335.9	131,400	52.26
10	1,531.87	109.42	78	483.14	727.03	775.23	6,733.1	131,400	66.25
11	2,278	189.833	45	1,148.16	2,534.96	346.94	16,001	105,120	90.9

3. Statement of the problem of multi-criteria estimation using DEA method

Integral efficiency in the original formulation of the DEA method proposed by A. Charnes, W.W. Cooper, E. Rhodes [24] (CCR-model), for the estimated simple one-dimensional DMU [25] with one input X and one output Y , can be characterized as the ratio of the efficient result Y of the DMU to the resources expended X (figure 3):

$$f = \frac{Y}{X}. \quad (5)$$

Based on the relation (5) the numerical values of efficiency f can be defined for the estimated DMU.

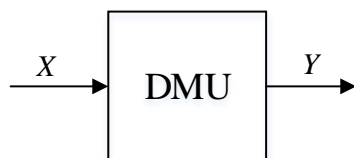


Figure 3. Model of one-dimensional DMU

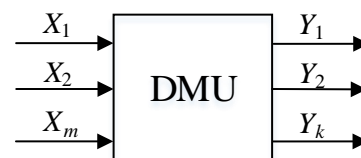


Figure 4. Model of multi-dimensional DMU

Using multi-dimensional DEA model, it is possible to evaluate n productive units, DMUs, where each DMU takes m different inputs to produce k different outputs (figure 4).

Values of inputs $X_j, j=1,2,\dots,m$ represent the costs of resources involved in the implementation of the production process of DMU, the reduction of which leads to an increase in the final index of efficiency. Thus, capital, financial, labor, material, information, energy and other resources can be considered as inputs.

An increase in the input value leads to a decrease in the efficiency of DMU, i.e.:

$$\frac{\partial f(X_1, X_2, \dots, X_m)}{\partial X_j} < 0, j = 1, 2, \dots, m. \quad (6)$$

The choice of outputs $Y_i, i=1,2,\dots,k$ is carried out in such a way that they characterize the factors that positively affect to the overall efficiency of the DMU. This, the income, profitability, volume and quality of the final product, reliability, durability, environmental friendliness, sustainability and other similar characteristics can be considered as outputs. The values of outputs may be not numerically comparable and not related to each other, however, they must be quantified, and their increase should lead to an increase in the overall efficiency:

$$\frac{\partial f(Y_1, Y_2, \dots, Y_k)}{\partial Y_i} > 0, i = 1, 2, \dots, k. \quad (7)$$

According to (5), based on the choice of m inputs and k outputs, the efficiency rate of such a multi-dimensional DMU can be generally expressed as:

$$f = \frac{u_1 \cdot Y_1 + u_2 \cdot Y_2 + \dots + u_k \cdot Y_k}{v_1 \cdot X_1 + v_2 \cdot X_2 + \dots + v_m \cdot X_m}, \quad (8)$$

where $u_i, i=1,2,\dots,k$ are weights assigned to i^{th} output $Y_i, i=1,2,\dots,k$; $v_j, j=1,2,\dots,m$ are weights assigned to j^{th} input $X_j, j=1,2,\dots,m$.

For the definition of numerical indexes of efficiency of each estimated DMU $_z, z=1,2,\dots,N$ it is necessary to demand that the efficiency value belongs to an interval $[0;1]$. The essence of DEA models in measuring the efficiency of productive unit DMU lies in maximizing its' efficiency rate, subject to the condition that the efficiency rate of any other units in the population must not be greater than 1:

$$\frac{\sum_{i=1}^k u_{iz} Y_{iz}}{\sum_{j=1}^m v_{jz} X_{jz}} \leq 1, z = 1, 2, \dots, N; i = 1, 2, \dots, k; j = 1, 2, \dots, m; u_{iz} > 0; v_{jz} > 0 \quad (9)$$

Then the condition of achievement of maximum efficiency f_z for z^{th} DMU can be written as follows:

$$f_z = \frac{\sum_{i=1}^k u_{iz} Y_{iz}}{\sum_{j=1}^m v_{jz} X_{jz}} \rightarrow \max_{u_{iz}, v_{jz} \in G} \quad (10)$$

Solving the $z^{\text{th}}, z = \overline{1, N}$ problem (10) under the constraints (9) gives the z^{th} value of the complex efficiency index f_z and the corresponding set of weights $u_{iz} \in G, i = \overline{1, k}$ and $v_{jz} \in G, j = \overline{1, m}$ providing the maximum of the functional (10).

The formulated problem relates to the problems of mathematical programming that can be solved by standard optimization methods (the method of least squares, the method of conjugate gradients, etc.).

The application of the DEA method allows to:

- identify efficient and inefficient energy saving projects using a quantitative measures of their efficiency (inefficiency);
- indicate effective goals for each project;
- find the best ways to achieve these goals;
- determine the most promising further investment directions for energy saves and energy efficiency improvements at the enterprise while analysing the efficiency of energy saving projects.

4. Algorithm for multi-criteria estimation of energy saving projects based on DEA method

For multi-criteria evaluation based on DEA method, the energy saving project is proposed to be treated as a production unit or DMU.

Then a following algorithm including seven main steps can be used:

1) Definition of a group including N projects, DMUs, for multi-criteria estimation;

2) Selection of DEA models for the z^{th} energy saving project, DMU; choice of input parameters

$X_{jz}, j = \overline{1, m}$, and output parameters $Y_{iz}, i = \overline{1, k}, z = \overline{1, N}$;

3) The formulation of mathematical programming problem in the form (9) - (10) for each DEA model;

4) Solving mathematical programming problem (9) - (10);

5) Analysis of the results;

6) DMUs ranking;

7) Decision making.

At the first stage, a group of N energy-saving projects (DMUs) is formed; the technical and economic justification of the projects is carried out. All projects in the group should meet the same efficiency criteria.

Further, at the second stage, the DEA models are compiled, which are characterized by sets and combinations of input and output parameters (criteria). In this case, the input and output criteria can have different dimensions and estimates (Table 2).

At the third stage, the problems of mathematical programming are formulated: a functional is written in the form (10) under conditions of constraints (9). The solution of mathematical programming problem includes definition of the weights $u_{iz} \in G, i = \overline{1, k}, z = \overline{1, N}$ and $v_{jz} \in G, j = \overline{1, m}, z = \overline{1, N}$, which correspond to the searched values of the relative efficiency indexes $f_z, z = \overline{1, N}$ for the every considered DEA model.

Solving N problems of mathematical programming using the well-known MATLAB software package allows one to present the result as a set of values of the relative efficiency indexes of the investigated projects.

Based on these values, the analysis of the computational results can carried out depending on the direction of the energy saving program at the enterprise (based on economic, technological, environmental effects separately or on a combination of all of them). Then, in the final stage, projects are ranked according to their indexes of efficiency $f_z, z = \overline{1, N}$.

The developed approach allows identifying the advantages and drawbacks of each energy saving project. However, such estimation is relative and must be compared with the corresponding absolute indexes calculated during the feasibility study.

5. DEA models for measuring efficiency of energy saving projects

The nine typical input and output parameters have been selected and the twelve DEA models are developed that characterize the technological, environmental, economic and comprehensive estimators of the efficiency of $N=11$ energy saving projects at industrial enterprise for the production of cellular autoclaved aerated concrete (Figure 5-16).

The input parameters, $X_j, j=\overline{1,3}$ which increasing has a negative impact on the final value of the relative efficiency of the project are the follows: X_1 is investment (I), X_2 is operating expenses (C_{OP}), X_3 is a discounted payback period (DPP). The output parameters, $Y_i, i=\overline{1,6}$ which increasing has a positive impact on the final value of the relative efficiency of the project are follows: Y_1 is the annual savings of energy resources in terms of their costs (B), Y_2 is a net present value (NPV), Y_3 is reduction of power capacity of the equipment (ΔW), Y_4 is increasing of economic efficiency (ΔP); Y_5 is time between equipment failures ($MTBF$); Y_6 is a reduction of CO_2 emission (Em_{CO_2}). Numerical values of inputs $X_{jz}, j=\overline{1,3}$ and output parameters $Y_{iz}, i=\overline{1,6}$ for $z=\overline{1,11}$ projects are reported in table 2.

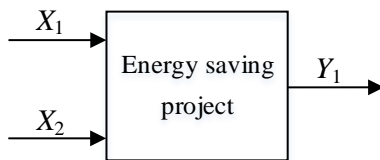


Figure 5. DEA model No. 1 (estimation of annual savings of energy resources).

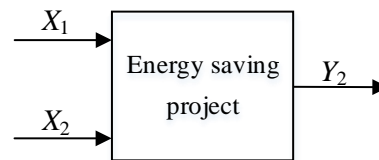


Figure 6. DEA model No. 2 (estimation of NPV).

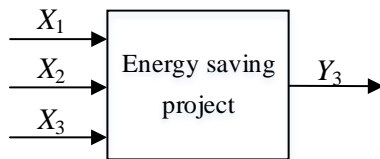


Figure 7. DEA model No. 3 (estimation of decreasing energy consumption by equipment)

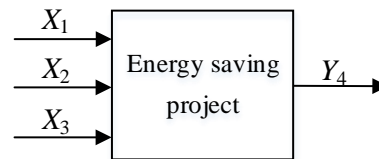


Figure 8. DEA model No. 4 (estimation of increasing economical efficiency)

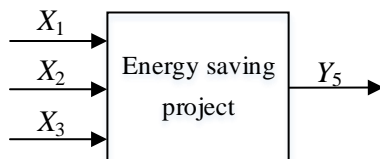


Figure 9. DEA model No. 5 (estimation of increasing reliability)

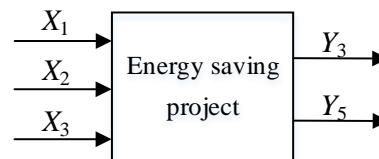


Figure 10. DEA model No. 6 (estimation of decreasing energy consumption by equipment and increasing reliability)

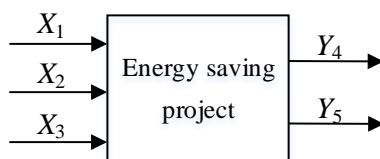


Figure 11. DEA model No. 7 (estimation of increasing economical efficiency and reliability)

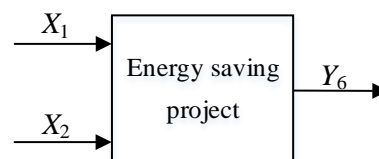


Figure 12. DEA model No. 8 (estimation of decreasing CO_2 emission)

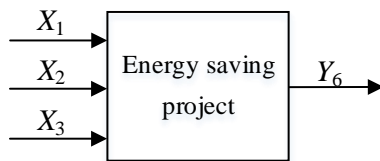


Figure 13. DEA model No. 9 (estimation of decreasing CO₂ emission taking into account DPP)

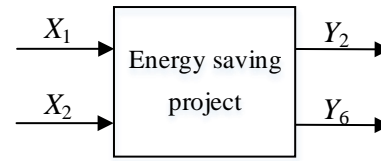


Figure 14. DEA model No. 10 (measuring of economical and ecological efficiency)

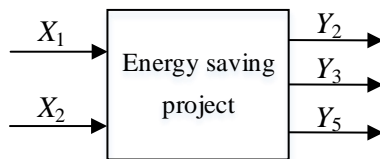


Figure 15. DEA model No. 11 (measuring economical and technological efficiency).

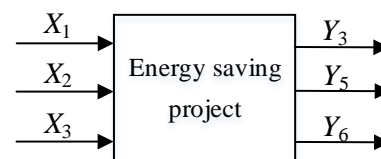


Figure 16. DEA model No. 12 (measuring the ecological and technological efficiency)

For all presented DEA models (figures 5-16) the problem of mathematical programming can be formulated in the form (9)-(10).

6. Results analysis

Mathematical programming problems in the form of (9), (10) have been solved for each energy saving project with respect to all 12 models and the results are shown in table 3. According to the data in table 3, the priority for implementation should be given to energy saving projects having the maximum value of the DEA-index Σf . The most effective projects No. 2, 8, 11 and 6 (from 1 to 4 places in the ranking) demonstrate the highest value of the relative efficiency in the most models. However, each of these projects has its own drawbacks. Thus, projects No. 6 for the reconstruction of outdoor lighting of the enterprise's territory and No. 8 for installing insulation of the heating system's pipeline are not expedient from the point of view of reducing CO₂ emissions. Project No. 2 on the replacement of the steam line insulation should be improved in terms of reliability improving.

Table 3. Computational results for the efficiency of energy saving projects with respect to selected models based on the DEA method.

Pr. No.	Model DEA												DEA-index Σf	Rank.
	1 (Fig.5)	2 (Fig.6)	3 (Fig.7)	4 (Fig.8)	5 (Fig.9)	6 (Fig.10)	7 (Fig.11)	8 (Fig.12)	9 (Fig.13)	10 (Fig.14)	11 (Fig.15)	12 (Fig.16)		
1	1	1	0.344	1	0.107	0.345	1	0.553	0.914	1	1	0.914	9.177	5
2	0.776	0.791	1	0.776	0.487	1	0.896	0.952	1	1	1	1	10.678	1
3	0.708	0.768	0.471	0.878	0.405	0.513	0.878	1	0.378	0.768	0.769	0.513	8.049	8
4	0.651	0.469	1	0.651	0.088	1	0.660	0.336	1	0.838	0.838	1	8.531	7
5	0.577	0.230	0.816	0.577	0.091	0.816	0.592	0.568	0.816	0.744	0.744	0.816	7.387	9
6	1	1	0.316	1	1	1	1	0.170	0.777	1	1	1	10.263	4
7	0.591	0.288	0.228	0.742	0.577	0.605	0.762	0.357	0.674	0.370	0.314	0.710	6.218	11
8	0.739	0.718	1	0.739	1	1	1	0.507	1	0.952	1	1	10.655	2
9	0.439	0.168	0.744	0.521	0.518	0.745	0.547	0.434	0.681	0.357	0.514	0.745	6.413	10
10	0.522	0.332	1	0.641	0.691	1	0.698	0.838	1	0.507	0.682	1	8.911	6
11	0.785	0.760	0.776	1	0.958	1	1	0.744	1	0.765	0.765	1	10.553	3

Projects No. 5, 7, 9 turned out to be ineffective (from 9th to 11th places in the ranking). For none of the models, these projects provide the maximum value of relative efficiency. Thus, they should be excluded from the investment program of the enterprise.

The remaining projects No. 1, 3, 4, 10 (from 5th to 8th places) are suitable for investment only if additional funds are allocated, they need to be improved in terms of technical implementation and the use of better materials.

Conclusions

The paper proposes a successfully tested procedure of multi-criteria evaluation of the efficiency of energy-saving projects using the DEA method on the example of an industrial enterprise for the production of cellular autoclaved aerated concrete. This approach allows measuring the efficiency of energy saving projects proposed for implementation at the enterprise, according to economic, technological and environmental criteria. The developed procedure for multi-criteria evaluation of the efficiency of energy saving projects based on the DEA method has the potential of widespread use in practice for developing effective management decisions regarding the formation of investment programs in industrial enterprises.

Acknowledgments

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