UDC 004.942:669.013.6

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SYSTEM MODEL FOR THE MULTIPLE-CRITERIA DECISION ANALYSIS OF THE RECYCLABLE ENERGY RESOURCES USE TECHNOLOGIES AT THE METALLURGICAL PRODUCTION

There was proposed the general vision of system model to solve the issue of the rational recyclable energy resources use at the metallurgical production. It is based on the multiple-criteria decision analysis and optimal solutions search methods integration.

Key words: *recyclable energy resources of the metallurgical production, system modelling, methods of multiple-criteria decision analysis, optimal solutions search.*

Запропонована загальна концепція системної моделі, заснована на об'єднанні методів багатокритеріального аналізу та пошукової оптимізації у вирішенні проблеми раціонального використання вторинних енергетичних ресурсів металургійного виробництва.

Ключові слова: *вторинні енергетичні ресурси металургійного виробництва, системне моделювання, методи багатокритеріального аналізу, пошукова оптимізація.*

Предложена общая концепция системной модели, основанная на объединении методов многокритериального анализа и поисковой оптимизации в решении проблемы рационального использования вторичных энергетических ресурсов металлургического производства.

Ключевые слова: *вторичные энергетические ресурсы металлургического производства, системное моделирование, методы многокритериального анализа, поисковая оптимизация.*

Introduction

Iron and steel industry is a formed sector with well-developed techniques of mainline production, replacement or significant upgrade required huge capital costs. Metallurgical plant produces significant amounts of recyclable energy resources (RER) – fire gases, steam, and heat. Utilization (use) of fire and heat RER at iron and steel industry saves more than 35 ... 50% of the heat demand at the sector. For example, metallurgical complex with complete cycle requires about 8 million tons of equivalent fuel a year, including 2.5 million tons of blast-furnace gas and 1.5 million tons of coke-oven gas (internal fuel resources) [1, 2].

However, the problem of rational RER use at the metallurgical production remains relevant in the following areas: manufacturing, energetic, economic, and environmental [1 ... 3]. Progress in solving this problem can reduce primary energy consumption (gas, electricity) and reduce the amount of pollution and, in consideration of the primary energy cost increasing, get an essential economic effect [1 ... 3].

Mathematical modelling of the RER distribution and use allows optimizing these processes, increasing the validity of the project and organizational decisions. This simulation, taking into account the complexity of the system, should be based on the methods of multiple-criteria decision analysis and modern information technologies [4, 5].

Multiple-criteria decision analysis (MCDA) using modern information technologies implemented as a decision support system allows comparing different variants of RER utilization with all the essential factors of the problem.

Model of optimal RER allocation [2] has two scalar criteria – economic and energetic. There was considered the possibility of further (about 15%) reduction of the need for external energy resources – natural gas and electricity [2]. Thus there would be reduced the cost of these resources acquisition too.

It should be noted that the model [2] designed for stable external environmental conditions – resources prices and output of main products. It is more common the volatility of environmental conditions and uncertainty in their changes (a situation of uncertainty) for modern conditions.

There were reviewed the following aspects in the fundamental paper [3]: the current state, problems, resource and energy saving technologies, including the rational use of RER. There were analysed both traditional and new technologies at iron and steel industry (“Iron Metallurgy”). Particular attention was paid to ecology, technology that reduces pollution. There were presented methodology of metallurgical technology choice [3, Ch. 12].

From the multiple-criteria decision analysis point of view, the methodology is the vision of complex multiple-criteria choice problem. The comparison was performed there according to 11 criteria, alternatives estimates (i.e. technologies) were calculated using special techniques. Thus, the analysis showed that it would be appropriate to include the possibility of vector optimization with environmental conditions considering into the system model of the recyclable energy resources use for situations of uncertainty and risk.

We have formulated three tasks of increasing complexity based on the analysis of the problem: comparative multiple-criteria decision analysis of given technologies; optimization of resource allocation; comparative analysis of optimized technologies.

There was validated the use of the integrated MCDA methods and decision support systems NooTron [6] developed in the Information Technology and Systems department at the National Metallurgical Academy of Ukraine.

Recyclable energy resources

The recyclable energy resources (RER) are the potential of production energy, production wastes, by-products and intermediates formed during technological processes at aggregates and installations, that does not be used at the unit, but may be partially or entirely used for energy saving at the other units (processes).

By type of energy RER divide into fuel, heat and excess pressure energy.

Fuel RER are gaseous by-products of technological processes which can be used as energetic or technological fuel.

Heat RER are physical heat of the main and side products, waste gases of technological units, as well as the cooling systems of their elements

RER of excess pressure energy are potential energy of gases emerging from the technological units with the excess pressure that can be used for other types of energy.

General characteristics of RER and methods of their use are in the books [1 ... 3].

Schematic classification of recyclable energy resources which are utilized at the metallurgical complexes is shown in Fig. 1 [3].

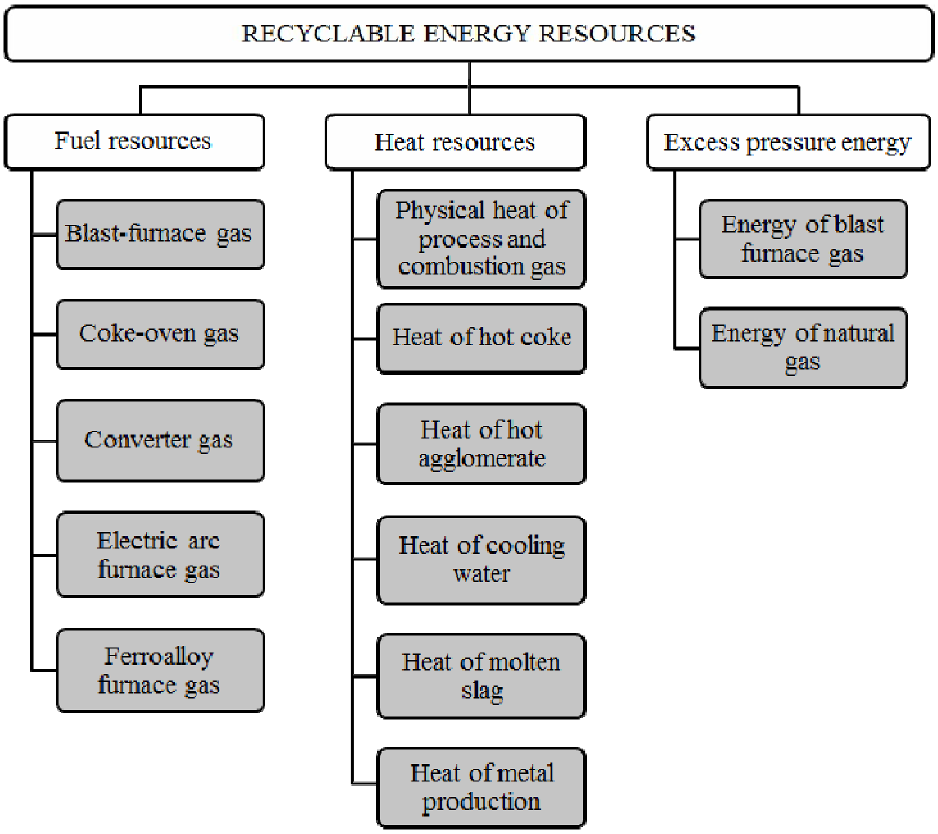


Figure 1. – Recyclable energy resources at the metallurgical production

Systems approach

The systems approach to the rational use of the recyclable energy resources involves the comparative analysis of existing technological schemes and optimization of their use with consideration of all significant factors.

It can be done using multiple-criteria decision analysis methods and system modelling. I.e. it means using multiple-criteria comparative analysis and multiple-criteria (vector) optimization [4 ... 7].

The multiple-criteria decision analysis (MCDA) is the practical implementation of systems research structure in solving complex problems. MCDA provides a rational, systematic and transparent decision-making process in the analysis of impacts and interactions in complex systems. Comparing objects are called alternatives in MCDA. The objects can be understood as existing systems, technologies or projects. Criterion is a quantitative or qualitative characteristic that is essential for judging the object. Estimate – quantitative or qualitative assessment of the estimated object with a certain criterion.

There were developed pretty much MCDA methods. Each of them has advantages and disadvantages, limitations and preferred applications. These methods are divided into cardinal (quantitative) and ordinal [5, 7, 8].

MCDA methods are used for various tasks; the following issues are interesting for us: the best alternative choice, multiple-criteria optimization, making design decisions and estimate of efficiency. These methods are time-consuming, they should be used as part of a computer decision support system (DSS) [7 ... 9].

System model

System modelling can be described as an interactive modelling with decision analysis (MCDA) and optimization methods "embedded" into the model. The system model can be briefly described as an interactive model that uses methods of systems analysis, knowledge domain, and information technologies.

The most universal method of complex systems analysis and optimization is simulation. Analysis of existing approaches to building models (they are called paradigms in simulation modelling) showed that according to the specific subject area (the production and utilization of recyclable energy resources) the most suitable is system dynamics paradigm [4].

Problem analysis includes multiple-criteria decision analysis methods which allow multiple-criteria optimization, comparing alternatives (technologies and recycling schemes in our case) on the set of criteria, evaluating the effectiveness of projects [5, 9]. The necessary component of the system model is interaction with the researcher. It is provided with DSS NooTron [6].

The structure of system model is shown in general in Fig. 2. Let us consider the components of the model.

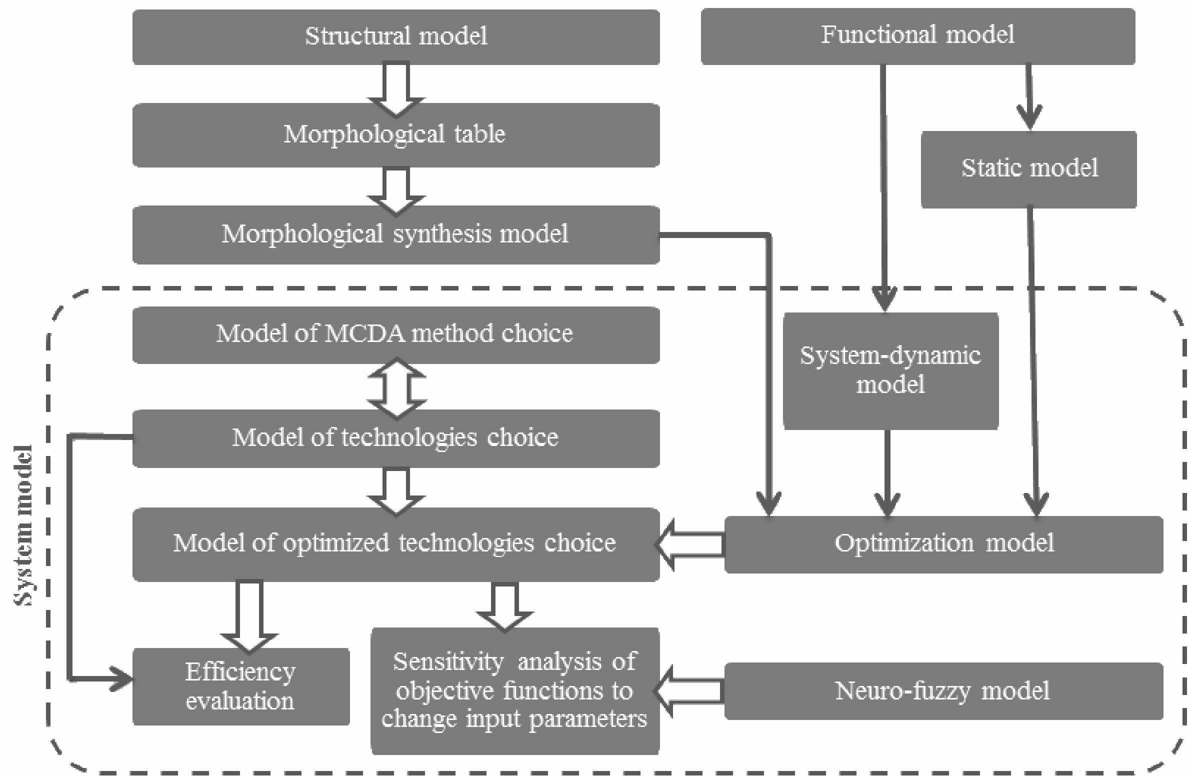


Figure 2. – System model structure

The basis of the structural model is generalized model of metallurgical complex with complete cycle. The complex viewed only (simplification of the real domain) as external energy resources consumer and generator (producer) internal energy resources used within the enterprise, and the surplus released into the environment. The generalized nature of the model is that some steps of the RER use can be included into the general model and excluded from it as well as variants of the RER use in each level.

RER flows correspond to the basic metallurgical technologies and accompanying energy flows. The basis is the basic technology of production and use cases of recyclable energy resources from the books [1 ... 3]. Processing units of metallurgical industry and their products and wastes are considered in the scheme only as sources and consumers of energy. This is the main simplification. There was taken into account that some consumers are sources of RER for consumers of the next level.

All sources, resources types and variants of use were included into the structural model from the books [1 ... 3]. In general structural model is scalable as broadwise and lengthwise by adding new types of sources and consumers, new sublevels.

The structural model is used in the system-dynamic model and optimization model.

Static model. Theoretically, the specificity of steel production, especially in terms of energy is well suited to system-dynamic modelling. But because of the complexity of the task it can be appropriate modelling and, in particular, optimization, not in continuous time, and for some “static” periods with average characteristics. With an increasing of periods number the static model approaching to system-dynamic.

System-dynamic model is used in changing time to calculate parameters, external conditions under various scenarios according to optimize the objective functions or in conjunction with an optimization model, or independently (optimal solutions search).

According to the concept of system dynamics, the main objects of this model are the “storage” and “streams”. Storage is an object that contains (or produces) a “resource”. The value of the resource in the storage is called a “level” or “volume”. Stream is a continuous (or semi-continuous) movement resource among storages. In our case, the storage is a metallurgical production unit that produces recyclable (internal) energy resource. For example, the blast furnace produces (in our model) the fuel resource as blast-furnace gas.

The dynamics of storage (i.e. the unit that consumes / produces energy resources) in differential form can be represented by the formula (1).

$$\frac{dV_{ij}}{dt} = \sum_j I_{ij}^{in} - \sum_j I_{ij}^{out} \tag{1}$$

In integral form:

$$V_{ij}(t) = \int_0^t (\sum_j I_{ij}^{in} - \sum_j I_{ij}^{out}) ds + V_0 , \tag{2}$$

i – unit number; *j* – resource number; *t* – time; $V_{ij}(t)$ – resource j volume in the unit i; I_{ij} – resource j stream in the unit i; *in* – incoming energy resource; *out* – outcoming energy resource; *s* – integral variable.

The model uses a differential form.

RER resource distributed among units of the next level.

Distribution schema of outcoming resource Id_{ij}:

$$Id_{ij} = \delta_{ij} x_{ijk} I_{ij}^{out} , \tag{3}$$

$$\delta_{ij} = \begin{cases} 0, & if \quad the\ unit \quad i \quad doesn't \quad produce \quad the\ resourse \quad j \\ 1, & in \quad the\ opposite \end{cases}$$

$0 < x_{ijk} \leq 1$ – fraction of resource j in the unit i, that is sent to the unit k of the next level, including the environment.

$\sum_j x_{ijk} = 1$ for all i, k – distribution condition.

Thus, metallurgical production units are sources (“storages” in SD terms) of internal energy, the flow (and volume) of which must be optimally distributed between the “storages” of the next level (such as utilization units) according to the distribution variant. Thus, the link between the system-dynamic and optimization models is installed.

Optimization model

Optimization model designed for calculating particular (scalar) objective functions (“criteria”), for finding parameters values which deliver extremes scalar objective function and for multiple-criteria (vector) optimization.

If the basic production technologies are considered as given then the problem of optimal RER use can be presented as a model of optimal resources allocation in the heating system of the metallurgical complex [2]. The model formalized as a vector (multiple-criteria) problem of nonlinear programming. It can be used either independently (based on a static model), or together with system-dynamic model. The optimization part of the model is based on the model from [2], but optimization is vector with flexible structure of criteria and different convolution methods (or converting into several estimates for efficiency evaluating). Later in the article we will discuss the optimization model. There is optimized the distribution of blast-furnace gas and coke-oven gas between RER consumers.

The main differences from the model [2] are the following:

1. Flexible open structure that allows you to include and exclude certain technologies such as primary production and RER use technologies.
2. The multiple-criterion optimization methods is based on MCDA methods integrated into DSS NooTron [6].
3. Taking into account the time factor based on system dynamics [4].
4. Consideration of environmental conditions variants [8, 9].
5. It is the part of the system model.

There are such items in the model:

1. Criteria (generalized scalar objective functions).
2. Constant parameters.
3. Variables in kind (they include being optimized parameters too).
4. Being optimized parameters, in relative form.
5. Balance correlation of linking options from p. 1 and p. 2.
6. Boundary conditions for the parameters from p. 4.
7. External variables.
8. Intermediate calculation variables (used in p. 1-6).

Objective functions do not explicitly be written out because of their inconvenience and they are calculated algorithmically. Optimization is performed for the periods of the annual cycle. The model [2] has two periods (cold and warm). Our model allows increasing the number of periods. Also one can use continuous time i.e. optimization can be performed directly on system-dynamic model. The question of the optimum number of periods and appropriateness of continuous (in time) problem definition requires a separate study with domain experts.

In general, the mathematical formulation of the optimization model can be represented as follows (4).

$$\begin{gathered} Cr_i(\overline{Z}) = \sum_j w_{ij} \cdot Z_j \to \min \ \textit{for all } i, \\ Z_i = Z_i(\overline{y}, \overline{x}, \overline{a}), \\ 0 < x_k \leq 1 \ \textit{for all } k, \end{gathered} \tag{4}$$

Cr_i – scalar criterion (objective function) of upper level; $\overline{Z}$ – vector of aggregated parameters that are optimized; $\overline{y}$ – vector of parameters in kind that are optimized; $\overline{x}$ – vector of relative parameters that are optimized; they are related with particles x_{ijk} in the system-dynamic model; $\overline{a}$ – vector of parameters.

Optimization is to search for each criterion relative parameters sets which deliver a minimum to each criterion. Each of the criteria has its own set in general case. As optimization methods have been chosen optimal solutions search methods. The advantages of search methods are their universality and opportunity of many suboptimal solutions acquisition (for each scalar criterion).

The disadvantages of the methods are laboriousness of calculations and they do not guarantee gaining of explicit (in the mathematical sense) global optimal solution. But first drawback is overcome by increasing computing productivity. The second one is irrelevant for most practical problems, because the original data is usually inaccurate (especially in such industries as metallurgy).

The application of optimal solutions search methods corresponds with the modern analysis and synthesis methodology of complex systems based on models and computer experiments. In combination with the scenario approach it enables to obtain the general view of a problem with the necessary granularity, to reveal not only optimums but the weakest points and reserves, to research the system behaviour in the environment. In this way one can improve the validity of design and organizational decisions, and the synthesis of technologies too.

Multiple-criteria model includes integrated MCDA methods and methodology BOCR ("benefits – opportunities – costs – risks") for estimate of efficiency [5, 9]. These methods are implemented in DSS NooTron [6].

Let us consider the optimization technique based on a common model (4).

The calculation of the objective function of the model is implemented algorithmically and consists of 6 steps:

1. Setting of 25 initial data (a_i).
2. Setting of 26 extra initial data (g_i) for calculating.
3. Specifying the set of 12 relative parameters that are optimized (x_i, $i \in [1;12]$).
   a) Boundary conditions: $0 \le x_i \le 1$.
   b) Every x_i is dimensionless quantity that is expressed in terms of calculated parameters y_i.
   c) Every x_i is set for one season; the next season has its own set and optimization.
   d) Methods of optimization are the following: discretization for every x_i with certain step (Δh_i) and brute force use; discretization and random search: formation of random vectors with random variables x_i, uniformly distributed on [0; 1].
4. Calculating of intermediate data (y_i).
5. Calculating objective functions $Cr_1(\overline{X})$, $Cr_2(\overline{X})$ for every set $\overline{X}$ [2]:
   a) energy criterion is unit discharge of imported equivalent fuel consumed by complex (natural gas and electricity from the regional electric network):

$$Cr_1(\overline{X}) = z_1 + b_{11} \cdot z_2 \to \min \; ; \quad (5)$$

   б) economic criterion is the total cost of the unit discharge of equivalent fuel:

$$Cr_2(\overline{X}) = b_{21} \cdot z_1 + b_{22} \cdot z_2 \to \min . \qquad (6)$$

z_1 and z_2 are annual consumption of natural gas and electricity, respectively (7), (8).

$$z_1 = \sum_{i=1}^{N} y_{86}^{i} \qquad (7)$$

$$z_2 = \sum_{i=1}^{N} y_{87}^{i} \qquad (8)$$

b_{11} – average unit cost of equivalent fuel for electricity delivery (inclusive of power line wastes) in the current consolidated power system, kg / (kWt·h.); b_{21} – the price of natural gas (uah./t); b_{22} – the price of electricity (uah./(MWt·t)).

Ecological criterion (minimum of emissions weighted sum) [3] does not be optimized because of that RER wastes volume is given for the static model.

6. Locating suboptimal values and the corresponding sets $\overline{X}^{opt} = \{x_1, x_2, \ldots x_{12}\}^{opt}$ for further multiple-criteria analysis (for example, the top 10 values for each scalar objective function).

7. Filling in utilities matrix with calculated data. There is performed multiple-criteria decision analysis of suboptimal choices on the basis of using the integrated method AHP + DMM (the analytic hierarchy process and decision matrix method) [8]. A decision about the best variant is made on this basis. Alternatives are suboptimal variants in the utilities matrix. Their number can vary. Variants of environmental conditions are given as a combination of three levels (low – medium – high) for two criteria (energy and economic).

Using decision matrix method allows performing comparative analysis of suboptimal variants which are gained by optimization model subject to possible variants of environmental conditions. For example, variants of environmental conditions may be movement of energy resources cost (gas and electricity in our case). On this basis multiple-criteria optimization is carried out to select the best variants as by each criterion as by the whole set of criteria with using such methods as the analytic hierarchy process (AHP), analytic network process (ANP). Applying the integrated method “analytic hierarchy process method + decision matrix method” (AHP + DMM) provides an analysis with simultaneous use of multiple rules for choosing the best alternative [8].

Decision support system NooTron is used for the multiple-criteria analysis and vector optimization. DSS was developed at the information technology and systems department of NMetAU. It is based on MCDA methods. DSS was realized as a web-application and is freely available at: http://nootron.net.ua. There is on-line help with detail methods explanation and with examples of solving problems in the DSS [6].

DSS NooTron based on modern information technologies allows providing such property of system model as interactivity. Also DSS allows increasing efficiency of multiple-criteria decision analysis performing.

Multiple-criteria optimization of recyclable energy resources allocation

Multiple-criteria optimization of fuel RER allocation at the metallurgical production was performed on the basis of the proposed technique. There were used the following basic input parameters (table 1), 1-3 parameters were taken from [2], energy resources prices were taken by 2014.

Table 1

The input parameters for optimizing of fuel RER allocation

№	Parameter name	Value
1	Blast-furnace gas (tons of equivalent fuel/year)	2556000
2	Coke-oven gas (tons of equivalent fuel/year)	1541000
3	Productivity of rolling mills (tons of steel/year)	8000000
4	Natural gas price (uah./t)	3539,35
5	Electricity price (uah./(MWt·h))	1162,9

There were two phases of multiple-criteria optimization: 1) searching $\overline{X}$ sets (12-component vectors of optimized parameters) which correspond to the best values of the objective functions Cr_1 and Cr_2; 2) multiple-criteria decision analysis of gained $\overline{X}$ sets with environmental conditions considering.

For finding the best values of objective functions Cr_1 and Cr_2 program was developed based on a common model (4) for RER allocation optimization. Optimization method was the brute force method with a certain step of x_i discretization.

During optimization 244140625 $\overline{X}$ sets were searched with increment 0.25 for each x_i. As a result there were found the best values of objective functions Cr_1 = 3214.9 (thousands of equivalent fuel) and Cr_2 = 1068.29 (mln. uah.), and corresponding set $\overline{X}$. This set turns out optimal for both criteria that can be explained by their linear dependence on the intermediate criteria z_1 and z_2 (7, 8).

There was calculated Δ_1 (9) and Δ_2 (10) for analysis of the result among 10, 100 and 1000 the best values of both objective functions (fig. 3, 4).

$$\Delta_1^j = Cr_i^j - Cr_i^1, \qquad (9)$$

Δ_1^j – distance between j-order and the first best values of objective function Cr_i; Cr_i^j – j-order the best value of objective function Cr_i; Cr_i^1 – the first best value of objective function Cr_i.

$$\Delta_2^j = \overline{Cr_i^{[1;j]}} - Cr_i^1 , \qquad (10)$$

Δ_2^j – distance between average value in [1; j] and the first best value of objective function Cr_i; $\overline{Cr_i^{[1;j]}}$ – average value of objective function Cr_i in [1; j]; Cr_i^1 – the first best value of objective function Cr_i.

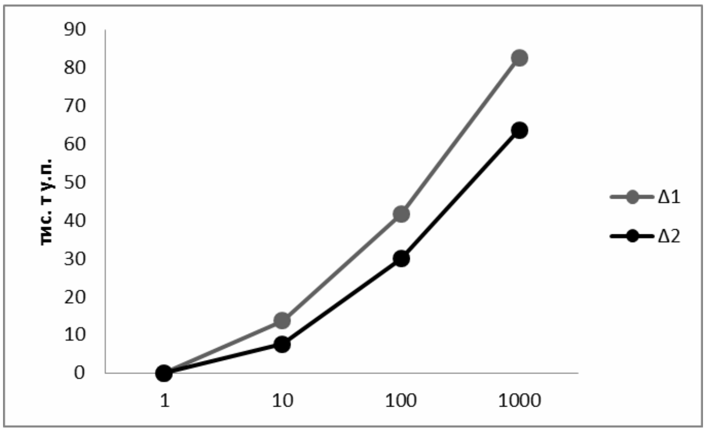


Figure 3. – Chart of the best values Cr_1 distinction

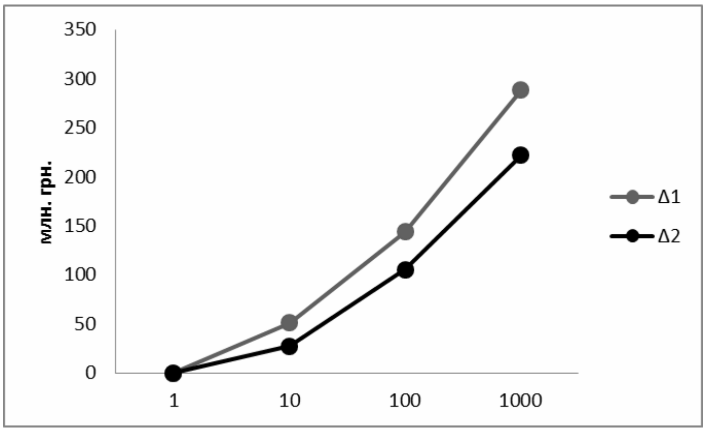


Figure 4. – Chart of the best values Cr_2 distinction

The value of each objective function depends not only on set $\overline{X}$, but also on such parameters as b_{11}, b_{21}, b_{22} (5),(6), which can vary. So it would be reasonable to perform multiple-criteria analysis of the best sets $\overline{X}$ (table 2) with environmental conditions considering.

For this purpose the following extension of integrated method AHP+DMM was proposed: 1) utilities matrix is calculated for each criterion; 2) generalized utilities of alternatives (sets) are calculated with the chosen rules of DMM; 3) priorities of alternatives are synthesized with AHP on the basis of the generalized utilities for each criterion; 4) global priorities of alternatives (sets) are calculated according to the priorities of criteria with AHP.

Table 2

Indicators of sets $\overline{X}$ selected for analysis

Set $\overline{X}$ number	z_1 (tons of equivalent fuel)	z_2 (MWt·h)	Cr_1 (thousands of equivalent fuel)	Cr_2 (mln. uah.)
39687504	5341,94	9170167,97	3214,90	10682,90
40087504	14172,51	9161381,88	3220,66	10703,93
87890629	5279,21	9200527,05	3225,46	10717,98
39062503	33425,05	9128782,69	3228,50	10734,16
88996879	10454,04	9195378,28	3228,84	10730,31
40006253	34829,33	9127385,48	3229,41	10737,51
136718754	5216,49	9230886,12	3236,03	10753,06

It was accepted for calculating the utilities matrix of alternatives (sets in table 2) that the value of the parameter b_{11} can be increased / decreased in 15%, parameters b_{21}, b_{22} can be increased / decreased in 20%. There was obtained the utilities matrix for energy criterion (Cr1, (5)) with 3 variants of environmental conditions: $V_1 = \{b_{11}, b_{11} + 15\%, b_{11} - 15\%\}$, and for economic criteria (Cr2, (6)) with 9 variants of environmental conditions: $V_2 = \{\{b_{21}, b_{22}\}, \{b_{21}, b_{22} + 20\%\}, \{b_{21}, b_{22} - 20\%\}, \{b_{21} + 20\%, b_{22}\}, \{b_{21} + 20\%, b_{22} + 20\%\}, \{b_{21} + 20\%, b_{22} - 20\%\}, \{b_{21} - 20\%, b_{22}\}, \{b_{21} - 20\%, b_{22} + 20\%\}, \{b_{21} - 20\%, b_{22} - 20\%\}$.

Generalized utilities of alternatives were calculated for each criterion by Hurwitz (c = 0.5) (normalized to maximum) and Savage (normalized to minimum) rules, relative estimates are shown in fig. 5, 6.

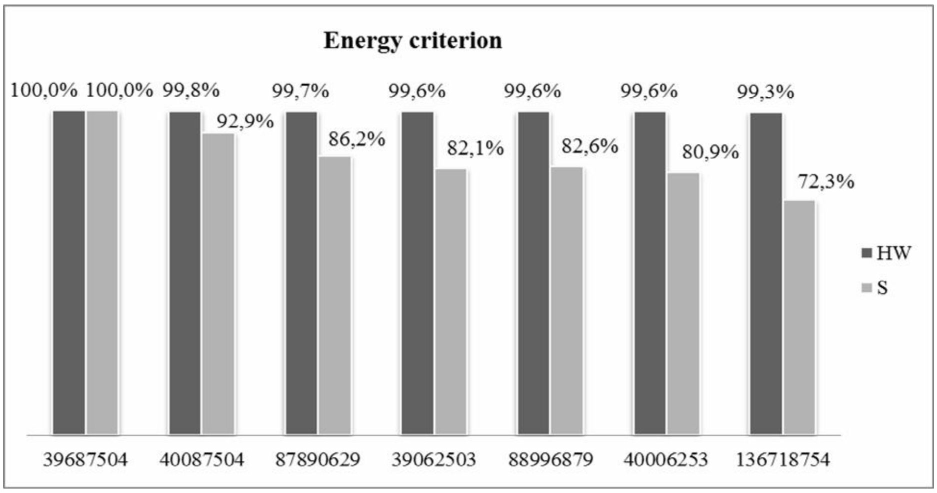


Figure 5. – Relative utilities of sets $\overline{X}$ by energy criterion

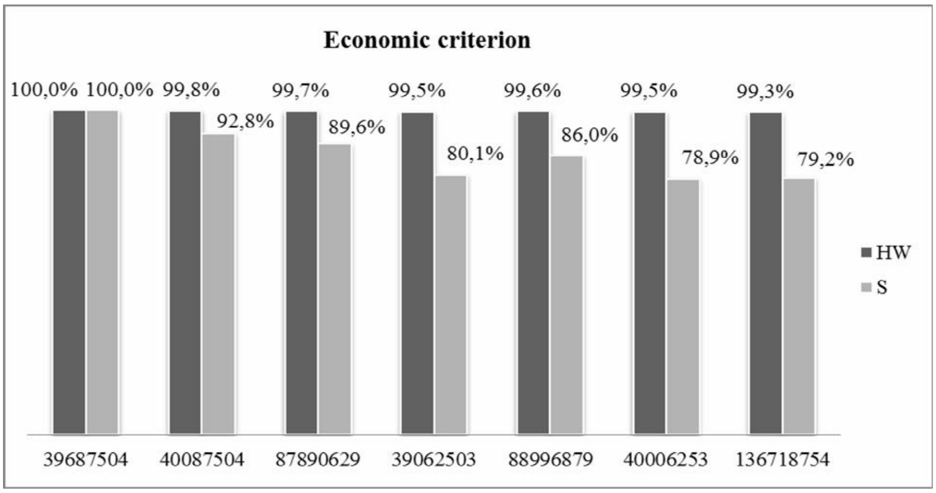


Figure 6. – Relative utilities of sets $\overline{X}$ by economic criterion

There were obtained priorities of alternatives for each criterion at the next step (fig. 7).

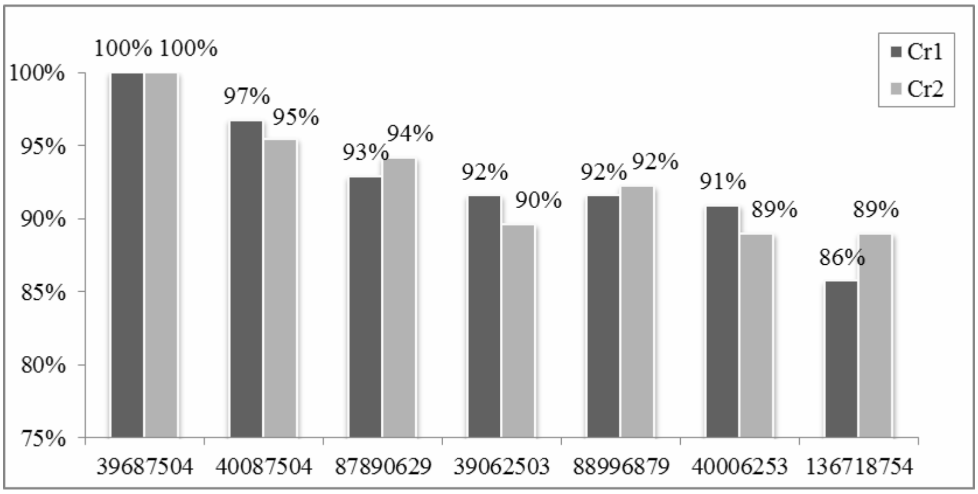
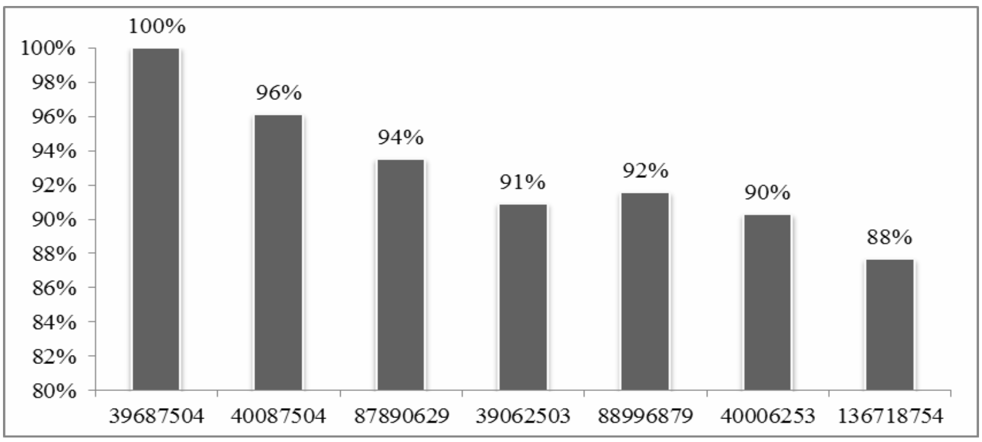


Figure 7. – Relative utilities of sets $\overline{X}$ by Cr_1 and Cr_2 criteria

Finally, global priorities of sets were calculated on the basis of all criteria range (Fig. 8).



ISSN 1991-7848

Figure 8. – Relative global priorities of sets $\overline{X}$

The performed multiple-criteria decision analysis confirmed that the resulting set $\overline{X}$ (39687504) is the best one also with taking into account possible changes of environmental conditions. Thus, the proposed technique allows obtaining general solution of multiple-criteria issue not only for the few rules of DMM as integrated method AHP + DMM, but also generalizes solution for the required number of utilities matrices.

Conclusions

The problem of rational RER use at the metallurgical production remains relevant in the following areas: manufacturing, energetic, economic, and environmental. Mathematical modelling of the RER distribution and use allows optimizing these processes, increasing the validity of the project and organizational decisions. This simulation, taking into account the complexity of the system, should be based on the methods of multiple-criteria decision analysis and modern information technologies.

There was proposed the general vision of system model to solve the issue of the rational recyclable energy resources use at the metallurgical production. It is based on the multiple-criteria decision analysis and optimal solutions search methods integration.

Schema of interconnected mathematical models was constructed according to the system modelling principles with using various mathematical tools and modern information technology. Using the decision support system NooTron (http://nootron.net.ua) provided interactive communication for carrying out a multiple-criteria comparative analysis.

There was designed the new combinatorial approach to accounting of possible environmental conditions changes: large number of suboptimal variants analysis for possible combinations of environmental conditions variations and for several utilities matrices. There was solved the model problem of internal and external (blast-furnace and coke-oven gases) energy resources optimal allocation.

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