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Modified Criterion for Economic Efficiency Estimation of Heat Pumps

Stanislav Boldyryev[a], Andrey Garev[a], Oleg Ilunin[a], Anatolij Shamraev*[b], Olexandr Selyakov*[,b], Olena Leshchenko*[b], Petro Kapustenko[a]

[a]AO "SODRUGESTVO – T" Company, per. Krasnoznamenny, 2 ,off. 19, 61002 Kharkiv, Ukraine, e-mail: petro.kapustenko@kpi.kharkov.ua
[*b]Kharkiv National University of Radio & Electronics, av.Lenina,14 ,off.33z, 61166 Kharkiv, Ukraine, e-mail: Shamraev.Anatolij@gmail.com

In this work the cost-effectiveness of coal mine waste water low potential heat utilization and integration in the enterprise local heating network by the bivalent parallel scheme is investigated. It is shown that the additive criterion of economic efficiency is not always sensitive to the target value because of the reason of non-linear coupling between the arguments of the target function. Several cases were considered from the viewpoint of cost-effectiveness criterion. Moreover, the arguments of the target function are also non-linear, depending on technological parameters of the heat pump (HP) equipment. As a more effective criteria were proposed the modified canonical additive-multiplicative function and Kolmogorov-Gabor polynomial function to obtain the generalized multivariate estimation of alternatives in two stages procedure.

1. Introduction

The Ukrainian heating systems, which use the boiler houses, consume large amounts of fossil fuels. This leads to high levels of carbon dioxide emissions, to negative impacts on the environment and a negative impact on the enterprise economy. But the regions of the coal and mining industry in Ukraine have the alternative low potential heat sources, namely the mine water. And the integration of the heat pumps to the heating systems of the enterprises makes significantly better emissions and economic indicators. The methods of utilization of low-potential heat are known and described by Klemeš at al. (2008). In our case, the topology of the scheme was determined at the preliminary stage of the project as the most effective, according to the minimum capital costs criterion under the existing heat generator (HG). Synthesis of complex structured systems, which include HP, leads to the necessity of solving the vector optimization problems, which are also called multicriterion. The fundamental difference of these tasks from the classical (one-criterion extremum) is in the impossibility of exact optimization of vector functions, describing the object, in the sense of mathematical programming , i.e. it is impossible in the general case, to find the value of argument , in which each component of the vector criterion would be the optimal value. This involves computational difficulties when solving applied tasks. The rules of the optimality conditions and a measure of preference-quality indicators are the basis for the optimal option searching. Assessment of effectiveness is required for a variety of operations, projects and processes, performance indicator should link the basic indicators, which are common for any operation and processes. It's a variety of estimation of input and output operations. This means that in the general case, the efficiency is a cross-cutting measure. When replacing the estimations of the cost indicators performance indicator turns into a tool of estimation of economic operations.

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2. Methodology

2.1 Stages of rational choice of alternatives

HP as a technical system is characterized by the principles of work, structure, and nonlinear parameters, which characterizes the process performance. The task of searching for effective and optimal parameters in the set limits belongs to the tasks of parametric optimization. Solving we use formalized indicators, presented by Khoroshev (1999) - quantitative evaluation, which is also called as the efficiency criteria of an object. The design of the HP can be formally represented as a process of narrowing the set of alternatives decisions on the basis of the available information. Rational choice of alternatives can be divided into the following stages:

(1) Situational analysis;
(2) Identification of the problem and targeting;
(3) Searching of the necessary information;
(4) Formation and formal presentation of alternatives;
(5) Formation or correction of criteria for evaluating of alternatives;
(6) Assessment;
(7) Selection of the best alternative;
(8) Assessment of the result.

This process is repeated in a loop until effective, satisfying the designer (expert).

The general problem is reduced to the problem of parametric optimization namely to select t components of HP, which will be effective in scope of the limitations. Taking into account a lot of input information availability to the technical characteristics, it is necessary to establish procedures accelerated the search for satisfactory solutions. This leads to the demand for the synthesis of effective criteria, which aggregates in itself all the requirements and objectives of the technical system. It can be presented in the form of a two-stage procedure suggested by Arrow (1963):

- First stage: selection from initial set the number of N effective solutions;
- Second stage: selection the best solution from N effective solutions.

2.2 Formal description of HP

A comprehensive heat installation of Complex Heating Unit (CHU) after decomposition of the installation units, aggregates, units, components (subclasses), can be described as an object, or an object class in the form of rectangular pieces, forming many formally implemented solutions $R_i(U)$, where i = card(HG)•card(NP)•card(HP) is the number of all technically possible implementations of the installation. In CHU implemented is introduced the peak thermal generator, therefore, card(HG)=g=1. The power of sets of all technically possible implementations of network and heat pumps accept the card(NP)=p and card(HP)= h, respectively. With a certain depth of formalization of HP, as an object or a class of objects, just as you can imagine in the form of many implementations of the decisions or records in the database field, the structure of which is formed on the basis of tuples of the form: HP=<Compressor, Evaporator, Condenser,...,Refr; V_{ref}, Q_{ab},...,T11 ,T21 ,T1,COP,CC,OC>,where the variables V_{ref}, Q_{ab} ,...,T11 ,T21 ,T1, represent a specific numerical limitations, COP,CC,OC - numeric values, and the variables of the Compressor, Evaporator, Condenser,..., Refr are linguistic , such as Evaporator =NB14-20 Alfa Laval, Refr =R134a.

More detailed, each term - element tuple can be presented in the form of a record of the following structure:

Compressor=:<$T1=f_1(Refr,V_{ref},T_{src},\Delta P_{cp},Q_{ab},)$,…,$COP=f_{k1}(N(\Delta P_{cp}),T1)$,$OC_{HP}=f_k(COP,N(P_{cp}))$,$CC_{HP}$>,
NP=:<$G=y_1(Q_{ab},T11,T21)$,…,$OC_{NP}=y_m(G,N(H_{pump},\Delta P)$,$CC_{NP}$>,where:

Refr - type refrigerant, T1, T11, T21 – values of corresponding temperature flows, V_{ref} - volume refrigerant, ΔP_{cp} - required differential pressure to compress the refrigerant, $N(P_{cp})$ - electric power consumption of the compressor, COP – coefficient of performance electricity consumption for heat energy (compression of the working medium HP),G – mass flow rate in the heating network, $N(H_{pump})$ - consumption of power of the network pump, H_{pump} - necessary head, ΔP - pressure drop in the network, CC,OC- the capital and operating costs respectively.

All the elements of records interconnected sets of computational methods of { f_k },…,{y_m }, characterizing physical dependence between the elements of the subclasses in the form of formulas, systems of equations, etc. These methods are implemented in the form of a software application, developed by designers or provided by the HP manufacturers. Due to the fact that many technically feasible aggregates, units, etc.(instances of subclasses) are finite, the number of implemented decisions defined as $card(R_L(U))=L$, $L \le g•h•p$.

2.2 Analysis of used criteria

The authors offered a classical route information vector problem to one-criterion, on the basis of the vector criterion in a modified canonical additive-multiplicative (AM) function of the overall efficiency. This criterion because of its clarity widely used for the evaluation of technical systems, economic, environmental and social components at all levels. A more accurate assessment of complex systems requires a more detailed description, and thus leading to a multi-objective optimization problem, as illustrated by De Benedetto and Klemeš (2009). It should be expert ordering criteria in importance, as well as the choice of the weight of each factor (each partial criterion). Approach in its basis is informal: the appointment of the number and type of criteria is carried out by the experts, which makes the procedure heuristic nature. For transition to the scalar representation of the target function of the economic efficiency of formally present the i-th copy of the decision in the next form : CHU_i =<$Compressor_i$, CC^i_{cp} ,$Evaporator_i$, CC^i_{ev} ,…, $NetPump_i$, CC^i_{NP}, HG_i, CC^i_{HG}, COP_i, OO_i^{SUM} >, where the CC^i - capital costs (prices) of the relevant nodes ,and OO_i^{SUM} - overall operating costs of the i-th instance. Excluding the non-numeric fields of the record, we get CHU^s_i =<CC^i_{cp} ,CC^i_{ev} ,…, CC^i_{HG}, COP_i, OO_i^{SUM} > and go to a scalar presentation of the target function in the form of weighted multiple criterion:

$$C_i = \sum_{j=1}^{m} \lambda_j \cdot c_j \tag{1}$$

where λ_j is weighting factor the impact of the *j*-th factor (unit, node) on the efficiency of the system as a whole, the c_j is the value expression of one (CC_j), for example CHU_i. CHU contains a large number of factors, it is difficult to the expert determine which one has the most significant impact on the entire system, and it is with this starts the analysis of the system for the synthesis of criteria of assessment of attaining the desired solution. When solving the problem of 1) the factors ranked by importance method of pairwise comparison, which gives a maximum objectivity in the formation of a number of preferences. Further to the transition from the binary representation of preferences to the scalar, 2) the matrix of quantitative estimates of e_{ij} is formed: each expert E_i assesses the score weight the importance of the factor of the c_j on its significance, as noted by Arrow (1963) and later described by Saaty at al. (1983).Converting evaluation to norm by method of arithmetic mean ranks get the weights λ_j impact of the c_j (Table 1):

Table 1: Weights of the factors

Expert№	Factor (c_1)	Factor (c_2)	Factor (c_j)	Factor (c_m)	∑
E_1	e_{11}	e_{12}	e_{1j}	e_{1m}	
E_2	e_{21}	e_{22}	e_{2j}	e_{2m}	
E_i	e_{i1}	e_{i2}	e_{ij}	e_{im}	
E_n	e_{n1}	e_{n2}	e_{ij}	e_{nm}	
$\lambda_{j\,,\,j=1,\ldots m}$	$\lambda_1 = \sum^n_i e_{i1} / S$	$\lambda_2 = \sum^n_i e_{i2} / S$	$\lambda_j = \sum^n_i e_{ij} / S$	$\lambda_m = \sum^n_i e_{im} / S$	$S=\sum^n_i \sum^m_j e_{ij}$

where e_{ij} is assessment of the weight of the importance of the factor of the c_j-expert E_i on a points scale; λ_j - importance weight of the c_j - in criteria of efficiency. By introducing additional restrictions on the OC and the CC apply to the set of implemented solutions $R^{pxh}(U)$ modification AM, researched by Soboleva (2012), of the form :

$$C_{AMm} = a \cdot \sum_{j=1}^{m} \lambda_j c_j + b \cdot \prod_{j=1}^{m} c_j^{\lambda_j} + c \cdot \prod_{j=1}^{m} c_j^{(1/\lambda_j)}, \tag{2}$$

where *a* , *b* , *c* - additional ratios that take into account the importance of the factors, making pre-classification of them, as reviewed by Romesburg (2004): *a* =[0, 0.4]- main (significant), *b* =[0, 0.8] - additional, *c* =[0, 0.05] informative (insignificant), and following constraints have to be applied: $a + b + c = 1$, $\{\lambda_j \neq 0 \mid j = 1, 2, \ldots m\}$. The presented criterion C_{AMm} softens the canonical form of C_{AM} by adding a third member, taking into account the weight of insignificant λ_j factors inverse degrees, and increases the card ($R_K(U)$) of decisions set in comparison with canonical form (K<L).

Clustering algorithms (CA) are used extensively to organize and categorize data, for data compression and model construction. CA put a data set into several groups such that the similarity within a group is larger than among groups. Specifically, in the simulation of a fuzzy control to a heat exchanger, presented by Vasickaninova and Bakosova (2011), one of CA was used to determine the boundaries of fuzzy intervals of input parameters have to be clustered.

The authors proposed a more precise and fast criterion. From the set m of factors $\{q^m\}$ is allocated cluster factors q^{Im}, which are necessary to describe real processes (objects) and sufficient for the construction of the criterion of alternative solutions comparison. Clustering is performed in accordance to the importance and frequency of factor in the process of the relationship preferences analysis by means of the method, offered by Saaty (2006) and named “Analitycal Hierarchy Process” (AHP). As a rule, the number of factors considered as $|q^{Im}|=5\div7$ is enough. Other factors q^{Ad} and q^{Ins}, we will consider additional and insignificant, the use of which increases the sensitivity and completeness of synthesizable criterion for the evaluation of the alternative (an instance of the real system) only:

$$C_{AMc} = \sum_{j=1}^{q^{Im}} \lambda_j^{Im} c_j + \prod_{j=q^m-q^{Im}+1}^{q^{Ad}} c_j^{\lambda_j^{Ad}} + \prod_{j=q^m-q^{Im}-q^{Ad}+1}^{q^{Ins}} c_j^{\left(1/\lambda_j^{Ins}\right)} , \tag{3}$$

and following constraints have to be applied: $|q^{Im}| + |q^{Ad}| + |q^{Ins}| = |q^m|$, and $\{\lambda_j \neq 0 \mid j= 1, 2,\ldots m\}$. As a result of the application of criterion get a subset of the $R_L(U)$ is truncated number of alternatives $R_K(U)$,card($R_K(U)$)= N. In the case of loved ones, «indistinguishable» of the results and the inability to make a single decision, go to the 2nd stage of the search method of the group account of arguments with the use of polynomial of the Kolmogorov - Gabor (PKG) of the second degree, offered by Ivakhnenko and Madala (1994). PKG takes into account the pairwise influence of the factors on each other in team systems:

$$C_{PKG} = \sum_{j=1}^{m} \lambda_j c_j + \sum_{i=1}^{m} \sum_{j=1}^{m} \lambda_{ij} \cdot c_i \cdot c_j \tag{4}$$

where formal (canonically) $\lambda_{ij} = \lambda_i \cdot \lambda_j$ that does not take into account the impact of the relationship factors on weight coefficients λ_j received ranking or pairewaise comparisons. Big dimensionality of the variables space, describing complex system, represents the main difficulty in the construction of the objective criterion, as shown Pozo et al. (2012). Therefore, as a rule, the studies are limited to taking into account the mutual influence of the two and not more than three factors. Methodology of the development of linear and nonlinear correlations among different factors within a multi-objective optimization approach was presented by Čuček et al. (2012a). Analysis of cross-influence allows us to identify the group of factors, which have a simultaneous impact on the technical system, and helps to reduce the area for possible solutions. Ratio measurement of pairs of factors and overlap of it by using the ε-constraint method was proposed by Čuček et al. (2012b). This paper offers the following procedure, which is accounting linear or nonlinear factors correlations by experts’ evaluations.

To determine the coefficients λ_{ij} - weight the influence c_i on c_j in the system, using L-experts it is necessary to prepare L pair comparison matrices (PCM), where at the intersection of the corresponding rows and columns fit - e_{ij} assessment of the impact factor of the c_i on the c_j-in criteria, e_{ij} =[0 ,1]:

Table 2: Matrix of cross-influence factors

Factor №	Factor c_1	Factor c_2	Factor c_j	Factor c_m
c_1	1	e_{12}	e_{1j}	e_{1m}
c_2	e_{21}	1	e_{2j}	e_{2m}
c_i	e_{i1}	e_{i2}	1	e_{im}
c_n	e_{n1}	e_{n2}	e_{ij}	1

Converting L copies of expert evaluations by means of the geometric averages of ranks method the matrix of weight coefficients $\hat{e}_{ij}$ of impact of the c_i on c_j will be obtained:

$$\hat{e}_{ij} = \left(\prod_{l=1}^{L} e_{ijl}^{\omega_l} \right)^{1/\sum_{l=1}^{L} \omega_l} , \tag{5}$$

where ω_l is a real number, which the rank of the l-th expert in the expert group determines. As shown by Porhinčák and Eštoková (2012), setting of factors weights is an important, because it may influence the final results. It is necessary to understand the user’s needs to designed HP in order to maximum correctly integrate their needs to the process of project evaluation and make a synthesis of criterion in accordance with the specified constraints.

Using the obtained matrix we can modify PKG to the following form:

$$C_{PKGm} = \sum_{j=1}^{m} \lambda_j c_j + \sum_{i=1}^{m} \sum_{j \neq i=1}^{m} \hat{e}_{ij} \cdot \lambda_i \cdot \lambda_j \cdot c_i \cdot c_j \qquad (6)$$

3. Case study

3.1 Input data

A bivalent parallel circuit integration compressor HP of «water-water» type to the existing heating system for heat generation for heating of the trunks of mines was offered (Figure.1).The restrictions and initial source data (ISD) for the analysis and solution of tasks are the characteristics of the low potential source, the load consumption and temperature charts T1(T11) /T21: <V_{src} , T_{src} ,Q_{ab} ,T11 ,T21 ,T1 >.In particular, JSC «Zaporozhskiy ZRK» iron-ore plant constantly pumped mine water in a volume V_{src}=2000 m^3/h with the source temperature of the T_{src}≈22 ºC with the existing needs in heat Q_{ab}= 4.167Gcal/h.

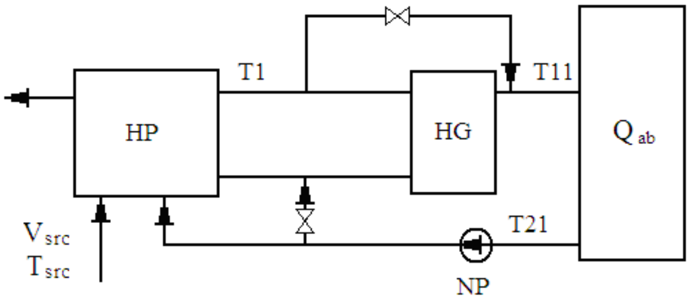

Figure.1. Integration of HP on a Bivalent Parallel Scheme to the Local Heating Network

In Table 3 are presented the results of case study of a summary table of weight coefficients significance of factors λ_j and weight coefficients of cross-influence factors $\hat{e}_{ij}$, received with the help of expert procedures.

Table 3: A summary table of weight coefficients $\hat{e}_{ij}$, λ_j

J	Factors	λ_j	Grading	T1	COP	α_{refr}	N_{cp}	ρ^{-1}_{refr}	ΔP_{cp}	T_{src}	CC	OC
1	T1 ,ºC	0.710	Im	1	0.6	0.2	0.81	0.87	0.91	0.3	1	0.7
2	COP	0.426	Im	0.6	1	0.2	0.87	0.7	0.95	0.4	0.9	0.85
3	α_{refr} ,w/ (m^2·ºC)	0.142	Im	0.3	0.2	1	0.5	0.2	0.1	0.3	0.9	0.9
4	N_{cp} ,kw	0.575	Im	0.9	1	0.5	1	0.4	0.4	0.7	0.9	0.9
5	ρ^{-1}_{refr} , m^3 /kg	0.618	Im	0.9	0.5	0.2	0.4	1	0.45	0.8	0.5	0.7
6	ΔP_{cp} ,Pa	0.646	Im	0.9	0.2	0.1	0.85	0.6	1	0.8	0.6	0.7
7	T_{src} ,ºC	0.213	Add	0.3	0.1	0.4	0.7	0.8	0.8	1	0.5	0.6
8	CC, euro	0.400	Ins	1	0.92	0.2	0.9	0.2	0.9	0.9	1	0.9
9	OC, euro/year	0.710	Add	0.3	0.2	0.8	0.2	0.2	0.6	0.8	1	1

There are two decisions: (A) Viessmann AG Vitocal 300G pro-3 and (B) Hotjet cz s.r.o. RZ1-50, as meet to the restrictions and ISD, after stage 1 of searching procedure were offered for consideration at the Technical Council of JSC «Zaporozhskiy ZRK». Analysis of the structure of prices was conducted, the cost value of the equipment functional groups was estimated by modified AHP, and relation "HP node's cost value=C (Factor)" was built. It is presented in Table 4.

Table 4: Factors and their cost projections

C(Factor)	C(T1), EUR	C(COP), EUR	C(α_{refr}), EUR	C(N_{cp}), EUR	C(ρ^{-1}_{refr}), EUR	C(ΔP_{cp}), EUR	C(T_{src}), EUR	CC, EUR	OC, EUR
A	77.220	154.440	51.480	208.400	223.400	233.640	428.800	991.800	254.206
B	75.210	125.430	58.480	185.560	195.490	189.430	64.560	894.150	401.140

3.2 Results

The results of testing criteria and numerical values for the two decisions (A) and (B) are listed below.

Table 5: Values of criteria

Criteria	C_{ADD}	C_{AMm}	C_{AMc}	C_{PKG}	C_{PKGm}
A	1123.340	5.943965592E+46	7.833768742E+47	1.263016141E+06	6.415098850E+05
B	1121.239	6.047025545E+47	5.404751161E+48	1.258297506E+06	6.157804141E+05

4. Conclusions and future work

The results shows that the additive criteria C_{ADD} is practically does not distinguish between alternatives, the criterion C_{AMc} is more sensitive and has more high speed in comparison with the basical C_{AMM}. The criteria C_{PKGm} and C_{PKG} due to its cumbersome are in the same class of accuracy and speed searching. Approach, proposed for the synthesis of the criterion C_{AMc}, also can be extended for economic efficiency estimation Local Heating Networks in general and can be applied for the assessment of mathematical models adequacy to the real systems. The long-term objective for this research direction is the software application development of expert procedures with clustering factors on formal signs and the calculation of factors weighting coefficients using the AHP method. For the future work, computerized procedures of effective implemented solutions searching should also be investigated and developed.

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