NEW METHODOLOGICAL APPROACH IN TECHNO-ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF SUSTAINABLE ENERGY PRODUCTION

by

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Among its other objectives and principles, sustainable development concept includes finding the optimal technical solutions that will enable exploitation of the resources of energy with minimal environmental damage. The main goal of this paper is to demonstrate methodological approach by using several operational research methods for selecting the optimal solution for complex, multipurpose power-plants construction concept problem with taking the sustainable development aspects into account. These methods are: ELECTRE I-IV, PROMETHEE I-IV, method of analytic hierarchy process, and linear programming. The aim of this research was to find out highly efficient, but relatively simple methods of defining environmental-friendly and socio-politically acceptable technical solution. The new methodology is developed and tested by case studies of determining the optimal choice for the construction of thermal and hydro power plants in the areas extremely exposed to conflict of economic, environmental, and socio-political interest.

Key words: *operational research, power plants, optimal construction concept, thermal power plant, hydro power plant case study*

Introduction

Growing need for energy, high level of environmental awareness, as well as the importance of the role that local community has in the process of making technical and economical decisions, require high efficiency in the choice of optimal concept and key parameters for large power plant facilities. Therefore, this remarkably complex and challenging problem demands adequate application and development of operational research and artificial intelligence.

This problem appears very frequently during the process of planning and designing any kind of power plant facilities, especially for large systems such as thermal power plants [1-5] and nuclear power plants [6], where conflict between environmental, socio-political, and economic interest is obvious and justified, but also in the field of hydro-energetic facilities [7], wind, and biomass power plants [8].

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The idea of this paper was initiated by the real problem in practice [7], in which firstly adopted technical solution for power plant construction with extremely high benefit-cost ratio was rejected because of ignoring the environmental aspects. Similar example was HPP Buk Bijela, when community lost total amount of $50,000,000 during 50 years of planning and designing due to not having the adequate methodological approach.

New methodological approach presented in this paper is tested on hydro system on Drina river on the border between two entities and on the TPP 2100MW in the Kosovo and Metohia region, both with extreme conflict of interest between techno-economical, social, political, and environmental criteria.

It is obvious that in the very near future, renewable sources will have to play much more important role in the energy production in the Balkan region [9-13] than today, not only because of the general trend of including the renewable resources in the energy balance in the European Union [14], but also because it will in the long run contribute to the energy efficiency improvement, diversification of production and supply safety, domestic production and consequently lesser import of energy sources and significant reduction of the environmental influences. All of above-mentioned aspect were included in the methodology presented in this paper.

Designers and engineers do not deal only with issues of constructional, geological, and technical stability of a given facility, but also have to consider complex relationships between human built facilities and natural environment [15, 16] and to present them in appropriate ways – via energy consumption, optimal use of mineral and renewable sources[17-19] and impact on nature [20], as well as to find the optimal solution considering the facility's purpose with respect to environmental and socio-political aspects [21].

Choice of the optimal constructional concept [22] for such a facility includes following conditions and constraints:

– unavoidable conflict of interest, because these are multipurpose facilities and therefore have more than one user,

– imperative of saving natural environment as much as possible [23], and

– sustainable development principles [24].

This paper presents algorithms for application of several operational research methods in process of evaluating different possible constructional concepts and choosing the optimal one. Important advantage of proposed models is their applicability in any power-plant case study that includes socio-political and environmental aspects of any given facility or facilities complex, which consequently would enable experts to find out the optimal conceptual solution for great variety of problems in the field of energy production.

Case study and defined criteria

During the research of which this paper is one of results, different methods [25] were tested on the same case – the choice of optimal hydro-energetic exploitation concept of Drina river between towns Srbinje and Goražde [26, 27]. Although given methodology is applicable on any kind of power production facility, this particular problem has been chosen because of the presence of very strong conflict of interest, not only in technical and economic issues, but also in environmental and socio-political criteria in determining the optimal solution [28].

Considered locality is placed in the valley, between two towns, which belong to different entities, after serious social, political, and even war perturbances. Previously, there was a request for a single dam to be built there, and that facility would have great energetical and economical effects. In spite of its great energetic and economic benefits, such a large dam and belonging accumulation would have a disastrous environmental effect. The goal of this paper was to find another optimal solution by using operational research methods, with simultaneous incorporation of technical, economical, socio-political, and environmental criteria.

This region's topology and hydrodynamic characteristics allow construction of several different hydro-energetic facilities with different head and consequently different technical, environmental, and economic effects. Further researches brought out six possible solutions:

I – HP Gorazde 375 (G375): One concrete dam on the profile Gorazde II, with attached hydroelectric power plant and normal top water level at 375.00 m.a.s.l.

II – HP Gorazde 383 (G383): One concrete dam on the profile Gorazde II, with attached hydro-electric power plant and normal top water level at 383.00 m.a.s.l.

III – HP Gorazde 352 (G352), HP Sadba 362 (S362), HP Ustikolina 373 (U373), HP Paunci 384 (P384): four cascaded concrete overflowing dams with normal top water levels as given, respectively.

IV – HP Gorazde 375 (G375), HP Paunci 384 (P384): two concrete overflowing dams with normal top water levels as given, respectively.

V – HP Gorazde 362 (G362), HP Ustikolina 373 (U373), HP Paunci 384 (P384): three cascaded concrete dams with discharging hydro-electric power plants with normal top water levels as given, respectively.

VI – HP Sadba 362 (S362), HP Ustikolina 373 (U373), HP Paunci 384 (P384): three identical cascaded concrete overflowing dams with normal top water levels as given, respectively, and the falls of 11 m each.

These alternatives have been created by combining seven dam constructions with different top water levels and adjoining hydro-energetic plants. Relevant criteria for the choice of the optimal combination were: benefit/cost ratio (*B/C*), annual energy production (*E*), socio-political factor (*CQ*), and environmental influence (*ENV*) [29], which are all given in tab. 1, where *X*1-*X*7 are variables which show total number of given dam type in combination, while the second row shows type of construction (G – Goražde, S – Sadba, U – Ustikotlina, and P – Paunci) with adjacent top water level (384, 383, 375, 373, 362, 352 m.a.s.l.).

Table 1. Relevant criteria for the choice of the optimal alternative

Alternatives	X_1	X_2	X_3	X_4	X_5	X_6	X_7
Constructions	G383	G375	G362	G352	S362	U373	P384
B/C	1.57	1.53	1.73	0.74	1.44	1.50	1.45
E	501.7	407.2	126.3	73.2	140.4	147.4	156.3
CQ	0	0	1	1	1	1	1
ENV	1.57	2.57	3.64	5	4.57	4.21	4.28
Δh (fall)	36 m	28 m	15 m	5 m	10 m	11 m	11 m

Linear programming method

The very nature of this problem and its variables implied that integer linear programming should be appropriate method for finding optimal solution. Linear programming has been used very often in the civil engineering for solving the organizational and economical problems [30] and it is also usable in solving of such a complex problem such hydro development optimization.

Standard form, as the usual form of describing a linear programming problem [31], consists of the following two parts.

Objective function in the form of linear function to be maximized or minimized (eq. 1):

$$\min/\max Z = \sum_{i=1}^{n} c_i x_i \tag{1}$$

Problem constraints in the form of linear equality or inequality (eq. 2):

$$\sum_{j=1}^{n} a_{ij} x_j \;(\le, =, \ge)\; b_i; \quad x_j \ge 0; \quad i = 1,\dots,n; \quad j = 1,\dots,n \tag{2}$$

The final values of the non-negative variables x_j, found by some of the linear programming algorithms are optimal solution of the problem (1) that meets all given requirements defined by the problem constraints (2). Variables $X_{1\text{-}7}$ in this problem present the number of given types of facilities in combination that will meet all the given constraints. Therefore, in order not to have the same facility twice in the same combination, this problem can be solved only in integer binary mode, in which variables can only have values 0 or 1 [32].

The first and the basic constraint is that sum of the falls in any given combination must not exceed the biggest possible fall (37.0 m), in order to eliminate all impossible combinations from further consideration (eq. 3):

$$\sum_{i=1}^{n} \Delta h_i X_i \le 37.0 \tag{3}$$

The second constraint considers the main purpose of the dam/dams, which is annual energy production. Therefore, it is defined as request that sum of annual energy production for any given dam or dams combination has to be greater than adopted minimal energy production (eq. 4):

$$\sum_{i=1}^{n} E_i X_i \ge E_{\min} \tag{4}$$

The third constraint is defined in a way which would ensure that average environmental influence grade of any given combination will be higher than adopted minimal value (eq. 5):

$$\frac{\sum_{i=1}^{n} ENV_i X_i}{\sum_{i=1}^{n} X_i} \ge ENV_{\min} \tag{5}$$

This constraint can also be represented as (eq. 6):

$$\sum_{i=1}^{n} (ENV_i - ENV_{\min}) X_i \ge 0 \tag{6}$$

The fourth and fifth constraints are defined in the same way as the third, but they consider average values of the socio-political factor (eq. 7) and the benefit/cost ratio (eq. 8):

$$\sum_{i=1}^{n} (CQ_i - CQ_{\min}) X_i \ge 0 \tag{7}$$

$$\sum_{i=1}^{n} (B/C_i - B/C_{\min}) X_i \ge 0 \tag{8}$$

In accordance to which criterion is chosen to be "the most important", left side of its inequality will become the objective function while the other inequalities will be problem constraints. This can not be applied on the first constraint because its purpose is to eliminate the impossible solutions from further consideration. Determination of minimal acceptable value of numerical quantifiers which describe environmental and socio-political acceptability, as well as the choice of criterion which will be taken as the objective function, is based on knowledge and objective estimation of an expert in this field.

Parametric analyses

Parametric analyses of given problem has been conducted for the whole variety of minimal acceptable values of numeric quantifiers and for different choices of objective functions. Results converged in such a way that they can be divided into three characteristic cases.

In case 1, the objective function is inequality (8) and the chosen minimal parameter values for constraints are: $E_{min} = 250$, $ENV_{min} = 2.5$, $CQ_{min} = 0.5$, and $B/C_{min} = 1$. This set of data gives the optimal solution $X_3 = X_6 = X_7 = 1$; $X_1 = X_2 = X_4 = X_5 = 0$ (solution model V), and the objective function value $B/C = 1.68$.

In case 2, the objective function and the constraints remain the same, but the minimal annual energy production is risen to much higher value $E_{min} = 440$. This set of data gives the optimal solution $X_5 = X_6 = X_7 = 1$; $X_1 = X_2 = X_3 = X_4 = 0$ (solution model VI), and the objective function value $B/C = 1.39$.

In case 3, the objective function is maximum annual energy production, while the minimal parameter values for the constraints remain the same as in case 2. This set of data gives the optimal solution $X_4 = X_5 = X_6 = X_7 = 1$; $X_1 = X_2 = X_3 = 0$ (solution model III), and the objective function value $E = 517.3$.

Discussion and conclusion

All above-mentioned criteria and constraints that show functional relationship between facilities are result of the given optimal concept model and the objective function. Comparison of different objective function values gives logical and authentic picture of results. The conclusion is that optimal solution can be achieved by alternatives VI, V, and III. Because of the approximately same equipment, alternative VI – system that consists of three identical facilities, (PP Sadba 362, PP Ustikolina 373, and PP Paunci 384), with the optimal solution value $B/C = 1.39$, has 30% lower total cost of hydro-mechanical and electrical equipment and maintenance. At the same time, these three low concrete dams have minimal influence on the environment and are perfectly fitted in this area's territorial dividedness between different entities, because PP Paunci belongs to one entity and the other two facilities belong to the other one.

Alternative V, that consists of facilities PP Gorazde 362, PP Ustikolina 373, and PP Paunci 384, has optimal solution value $B/C = 1.68$.

The third given solution – III, that consists of four facilities – PP Gorazde 352, PP Sadba 362, PP Ustikolina 373, and PP Paunci 384 and has optimal solution value $E = 517.3$ – practically is a combination of the previous two alternatives.

Multi-attribute decision making

This type of problem can also be solved by multi-attribute decision making, which is appropriate for making a choice among several known solutions with numerically defined attributes, implicit objective and inactive constraints (included in attributes). The research was aimed to develop appropriate multi criteria decision making (MCDM) model [33, 34] for selection of some environmental friendly solutions for structure as well as construction technology of hydro facilities in accordance with local natural, economic and socio-political conditions and limitations.

Depending on nature of any given problem, multi-attributive decision making uses one of three main approaches [35]:

(1) range-based approach in order to range all possibilities from the best to the worst,
(2) problem of choosing the best alternative, and
(3) problem of choosing several alternatives:
   - by choosing previously determined number of acceptable top ranked alternatives, or
   - by choosing one alternative that meets some other conditions that were not included in the starting model.

The most commonly used methods in multi-attributive decision making in the field of optimal construction choice [36] are ELECTRE I-IV, PROMETHEE I-IV, method of analytic hierarchy process (AHP), and multi-compromise ranking method (VIKOR) [37].

This paper presents use of PROMETHEE I and II and ELECTRE in the same case study as used in example of linear programming. The main characteristic of the PROMETHEE methods is application of six generalized criteria (preference functions) for defining the decision maker's preferences among all given criteria in problem. Besides that, user can also include new types of generalized criteria for defining the rules in given problem and to put his/her own preferences according to given criteria.

PROMETHEE I and II methods

Algorithm for methods PROMETHEE I and II is defined in the same way:

- defining the task and setting the weight coefficients,
- defining potential alternatives a_i with corresponding evaluation criteria (eq. 9), tab. 2:

$$f_j(a_i), \quad i = 1, 2, ..., m; \quad j = 1, 2, ..., n \tag{9}$$

- ranging the alternatives. Every criterion f_j gets appropriate weight coefficient w_j. If two criteria have the same significance, their weight coefficients are $w = 1$ in case of maximisation, or $w = -1$ in case of minimisation. In the particular problem all criteria are maximised.

The values of weight coefficients are as follows: 0.16, 0.21, 0.21, 0.21, and 0.21.

Besides task definition and setting the weight coefficients, this method includes following steps: defining specific preference function $P_j(a_i, a_j)$ and preference index for each criterion, calculating positive and negative flows, finding out the partial and the total pre-order for each pair of units (a_i, a_j), forming the higher rank matrix, construction of the higher rank graph, calculating the net flow value for each alternative, and ranking the alternatives. Higher rank matrix defines domination in each pair of units and therefore allows the construction of the higher rank graph, which is also the end of the PROMETHEE I method. PROMETHEE II method includes two more steps: calculating net flow value for each alternative and adjacent ranking of the alternatives. The results showed that the best solution of the given problem is alternative a_5, *i. e.* solution V.

ELECTRE method

ELECTRE I method, often called "basic method", uses iterative approach in finding the optimal solution. Data given in the tab. 2 were used in the following steps: normalizing the decision matrix, weighting the normalized decision matrix, determining the concordance and discordance sets, construction of the concordance and discordance matrices, determining the concordance and discordance dominance matrices, determining the aggregate dominance matrix, and elimination of the less favourable alternatives.

Table 2. Relevant criteria for the choice of the optimal alternative

	f_1 (Ev)	f_2 (B/C)	f_3 (Eu)	f_4 (E/A)	f_5 (CQ)	f_6 (IK)
a_1 (A)	251.1000	1.5310	407.2000	2.4100	0.0000	251.1000
a_2 (B)	308.3000	1.5690	501.7000	1.4100	0.0000	308.3000
a_3 (C)	291.9000	1.2880	504.0000	4.4200	1.0000	291.9000
a_4 (D)	339.3000	1.4790	559.5000	3.3600	0.7500	339.3000
a_5 (E)	297.7000	1.5740	514.1000	4.0400	1.0000	297.7000
a_6 (F)	250.6000	1.4870	432.8000	4.3600	1.0000	250.6000

If the value of element e_{ks} of aggregate dominance matrix is 1, then this means that alternative a_k is preferred to alternative a_s by using both the concordance and discordance criteria. On the other hand, this does not mean that some other alternative is not preferred to a_k. Therefore, a_k would not be dominated only if:

– $e_{ks} = 1$ for at least one s; $s = 1, 2,\ldots, m$; $s \quad k$
– $e_{ks} = 0$ for every i; $i = 1, 2,\ldots, m$; $i \quad k$; $i \quad s$

In practice, in order to eliminate less favourable alternatives it is necessary to examine domination in every possible pair of alternatives. In given example, it would be as follows:

– a_1 does not dominate any other action,
– a_2 does not dominate any other action,
– a_3 dominates a_1 and $a_{2,}$
– a_4 dominates a_1 and a_2,
– a_5 dominates a_1, a_2, a_3, a_4, and a_6,
– a_6 dominates a_1.

It is obvious that the best list of actions is a_5, *i. e.* alternative VI, which represents the cascade made of three identical dams and hydro-power plants: HP Sadba with normal top water level at 362.00 m.a.s.l, HP Ustikolina, with normal top water level at 373.00 m.a.s.l., and HP Paunci with normal top water level at 384.00 m.a.s.l.

Results and discussion of PROMETHEE and ELECTRE method

All the above-mentioned approaches and described methods gave the same solution for the complex problem of choosing the optimal concept in hydro power facilities construction: the alternative F, followed by the alternatives V and III.

This solution is both logical and satisfying according to all given and defined criteria. HP Sadba with normal top water level at 362.00 m.a.s.l, HP Ustikolina with normal top water level at 373.00 m.a.s.l., and HP Paunci with normal top water level at 384.00 m.a.s.l make optimal combination for several reasons:

– minimal deterioration of the river bed natural environment,

- natural head is used in its total extent, which leads to maximal annual production of energy and consequently maximal economic effect,
- all three dams and power-plants have the same head, which allows uniformity of mechanic, hydro-technical and electrical equipment and spare parts, which lessens total investments and maintenance costs,
- dynamics of building works on all three facilities can be made with agreement of different sociopolitical entities, but if such agreement could not be achieved, facilities also can be built separately and independently.

The fact that solution VI was ranked as best one, in all three methods used in this research, confirms usability and quality of these operational research methods for solving even very complex problems within the scope of choosing the optimal building concept for hydro power facilities.

Case study for the 2100 MW fossil-fueled power plant

Model application on fossil-fueled power plant

Developed methodological approach was analyzed and tested on the case study of 2100MW fossil-fueled power plant in the region of Kosovo and Metohia, characterized by high technical, economical, environmental, and socio-political conflict of interest. The problem has been analyzed by the ELECTRE method by ranking 6 possibilities for construction of fossil-fueled power plant considering 21 criteria. Thermal power plant's location suitability and sustainability have been analyzed according to geological composition and structure stability, geomorphology, neotectonicts, seismic, hydro-geology, and engineering geology criteria for the site, as well as according to environmental and socio-political impact, as relevant criteria too.

Criteria relevant for decision-maker, their weight coefficients and numerical values for all 6 possible alternative solutions for the thermal power plant are given in tab. 3.

Domination relationships between alternatives are:

- a_1 does not dominate any other action,
- a_2 dominates a_4,
- a_3 dominates a_2, a_4, a_5, and a_6,
- a_4 does not dominate any other action,
- a_5 dominates a_1, a_2, a_4, and a_6, and
- a_6 does not dominate any other action.

The best actions list is: a_3, a_5.

Results and discusion of the ELECTRE method aplication on fossil-fueled power plant

Application of the ELECTRE method gave the following ranks of the alternatives: (1) TPP 13, (2) TPP 31, (3) TPP 12, and (4) TPP 21, TPP 11, TPP 32.

The last three alternatives do not dominate any other. These results show that the best solution for the 2100 MW fossil-fueled power plant TPP 13, which is confirmed by the sensitivity analysis with respect to empirically defined weight coefficients' values and by the sensitivity

Table 3. Relevant criteria for the choice of the optimal alternative

Criteria	lim	Weight	TPP11	TPP12	TPP13	TPP21	TPP31	TPP32
Basic rock type	max	1	3	3	3	1	1	1
Basic rock depth	min	1	7	36	80	120	100	100
Model depth	min	0.1	55	55	80	600	600	600
Tectonics	min	0.1	3	1	1	1	1	1
Ruptures	min	1	4	1	1	1	1	2
Jump	min	0.1	20	15	25	40	50	50
Dominant process	min	0.1	2	2	3	2	4	4
Stability	max	1	2	3	3	2	2	2
Geo-mechanics	min	0.1	1	3	1	4	1	1
Water table	min	0.1	3	2.5	5	1.5	2	2
Filtration	min	0.1	0.0770	0.0037	0.0023	0.0100	0.0010	0.0010
Horizon depth	min	0.1	6	7	6.5	9	9.5	7.5
Collector type	max	0.1	2	2	3	3	3	3
Drainage	max	1	3	3	3	1	2	1
Seismicity	min	1	7	7	7	7	7	7
Seismic acceleration	min	1	105	105	115	115	85	85
Seismic accretion	min	1	1.00	1.46	1.46	1.34	0.97	1.23
Settlement	min	1	6.5	7.5	9	6.75	5.6	5.6
Capability	max	1	325	275	280	255	292.5	292.5
Environmental aspect	max	1	3	0	5	2	4	1
Socio-political aspect	max	1	4	1	5	1	4	1

analysis with respect to the number of criteria. Both analyses showed stability of results, which implies their credibility.

Conclusions

This paper improves the knowledge, algorithms, and software tools in the field of optimal renewable and mineral resources utilization.

Expert knowledge and specific methodological approach in defining the objective function, problem constrains and criteria applied and presented through the above-mentioned methods offer not only achievable, but also very efficient solution of this problem. The main purpose for the application of described methods is to reach the balance between conflicted criteria in order of fulfillment of the highest standards in the renewable and mineral energy sources exploitation in accordance with environmental, social, and political demands.

The main advantage of the proposed methodology is its applicability for all kinds of power plants, especially for the environmentaly questionable facilities, such as thermal and nuclear power plants. Further researches on above analyzed methods of application of sustainable concept selection in thermal, wind, and biomass power plants case studies are recommended.

Presented methodological approach would enable designers to reach the optimal sustainable technical solutions in relatively easy and fast way and consequently to meet the energy production demands with simultaneous protection and preservation of the natural sources and potentials from techno-economical devastation.

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