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ANALYSIS OF SCENARIOS FOR TRANSFORMING THE OBJECT "UKRYTTYA" INTO AN ENVIRONMENTALLY SAFE SYSTEM BY THE METHOD OF MULTICRITERIA OPTIMIZATION

Based on the criteria for comparative analysis of scenarios grouped into factors, the value of scenarios was determined using the multicriteria optimization methodology. The evaluation methodology includes indicators of weights of factor groups and weights of criteria for the relevant factors. Scenario value assessment is determined by calculating a generalized weighted additive function. It is used to rank the scenarios with the established parametric characteristics of the criteria. The results of the scenario assessment and their ranking are recommendations for making decisions on the sequence of scenario implementation.

Keywords: object "Ukryttya", environmentally safe system, factors and criteria for evaluating scenarios multicriteria optimization, generalized weighted additive function, ranking of scenarios, decision making.

1. Introduction

Transformation of the object "Ukryttya" into an environmentally safe system includes the task of determining optimal scenarios for Shelter transformation into an environmentally safe system.

The analysis of literature sources on decommissioning of nuclear power facilities showed that the bulk of publications is devoted to the problems of decommissioning only nuclear power plants.

In [1], the authors point out the problems of creating models for analysis and decision-making during decommissioning of nuclear power plants with multiple sites. The problem lies in the inability to take into account the relationships between a large amount of data and obtaining consistent results. The paper proposes a mathematical model based on the cost estimation of decommissioning costs and conducts a sensitivity analysis of the model in order to reduce costs. However, the model does not include other categories of factors, assess their mutual influence on the choice of strategies, or determine their impact on decision-making.

Paper [2] developed a model for assessing radiological risks after decommissioning of nuclear facilities. Sets of input parameters have been identified that can be used at the stage of preliminary risk analysis, but only for a specific site.

In their review, the authors of [3] provide a detailed overview of strategies for decommissioning nuclear power plants with a sustainable perspective using a systematic approach involving meta-analysis. The authors emphasize that the main tasks of decommissioning nuclear facilities are focused on achieving the restoration of the environmental condition of the sites. Despite the fact that different strategies are considered that focus on heterogeneous factors, they are mainly evaluated through monetary values.

Thus, it can be concluded that, first, the bulk of publications are focused on creating models that take into account different groups of factors separately – financial, radiation, environmental, etc. Second, their valuation is mainly described by monetary equivalents. Therefore, we consider it promising to develop comprehensive models for assessing scenarios for transforming object "Ukryttya" into an environmentally safe system based on factors that are qualitatively heterogeneous in their meaning. In addition, such models can be aggregated both at different levels of decision-making and at the level of decision management.

Since the object of study is a complex system [4], a generalized assessment of its states should include as input data a set of qualitatively and quantitatively different variables A systematic analysis of the problem of comparative scenario analysis is presented in [5]. The paper proposes to use a set of methodologies – expert methods, multicriteria analysis, and multifactor models. This approach makes it possible to analyze, compare, formulate management decisions, and manage their implementation at different levels of aggregation of the relevant models.

The paper [6] presents the first stage of comparative scenario analysis based on expert assessments of their factors and criteria. At this level of research, a generalized assessment of technical, technological, economic, and financial criteria is carried out.

In order to detail the assessments of scenarios, to take into account their parametric characteristics – factors groups and their criteria – a multicriteria optimization (MCO) methodology is proposed. The implementation of the proposed methodology makes it possible to assess the scenario parameters at a deeper level of detail, to formulate optimal management decisions in the implementation of scenarios for transforming the object “Ukryttya” into an environmentally safe system.

2. Problem statement and research objectives

By analogy with [7 - 13], to build a MCO model for the transforming of the object “Ukryttya”, we took into account existing strategies and main categories of factors when selecting scenarios for decommissioning nuclear power objects. In the document [14], the strategies and criteria for analyzing the environmental safety of scenarios for the implementation of phased removal of spent fuel assemblies specified in the main IAEA documents are defined by eleven indicators (Table 1).

Table 1. **Criteria for the comparative analysis of scenarios of phased extraction of fuel-containing material (FCM)**

No. of criteria	The name of the indicator	Unit of measurement	Marking
1.	Operating costs to ensure the current safety of the object “Ukryttya”	thousand UAH	OE_{ECS}
2.	Costs of creating protective barriers for localization and FCM isolation after New Safe Confinement (NSC) decommissioning	thousand UAH	OE_{PB}
3.	Costs of creating additional infrastructure for retrieval and further FCMs management and other radioactive waste after NSC decommissioning	thousand UAH	OE_{CAI}
4.	The degree to which NSC infrastructure is used for retrieval and further management of FCM and other radioactive waste	%	L_{IU}
5.	Risks of unreadiness of facilities storage for retrieved FCM interim storage	%	R_{USF}
6.	Risks of unreadiness of the geological repository for final disposal of FCM	%	R_{UGR}
7.	Risks of FCM properties change (degradation) over time	%	R_D
8.	Risks of destruction of barriers protective around FCM accumulations over time	%	R_{DPB}
9.	Risks of underfunding the work on phased retrieval of FCM and further management	thousand UAH/year	R_{UDW}
10.	Radiological risks	person/year	R_{rad}
11.	Project (scenario) implementation time	years	T

It should be noted that in the case of using parametric criteria, detailing their groups in relation to the array of scenarios, qualitative comparisons [4 - 6] are insufficient to make a reasoned decision on the sequence of scenarios implementation.

Therefore, the comparative values of the scenarios (if needed by the decision-maker) can be detailed using MCO methods. At the same time, it is possible to refine the assessments of scenarios ranked by relative values by determining their parametric characteristics. – radiation, infrastructural, and financial (with their parametric detailing). The advantage of the MCO methods is the parametric detailing of ranked scenarios by the factors groups and their criteria, the possibility decision-making algorithm forming by a decision-maker based on such estimates. Disadvantages include the necessity and difficulty of determining the scenario's parametric characteristics both according to the relevant factors groups and according to their criteria.

The object of the study is to assess scenarios for transforming the Shelter into an environmentally safe system.

The subject of the study is a comprehensive analysis of the scenarios using the method of MCO. Based on the definition of the object and the research subject, it is possible to formulate research tasks: calculation generalized of the values scenarios, taking into account the parametric criteria characteristics, criteria weights, and the factors weights to which they belong; ranking the scenarios by the value of the generalized value indicator; formulation of the management decisions on the scenarios sequence implementation for the object “Ukryttya” transformation into an environmentally safe system.

The tasks set make it possible to realize the main goal of the research – to evaluate the object “Ukryttya” transformation scenarios based on the parametric characteristics for criteria; to rank the scenarios according to their value; to take into account the decision-maker requirements; to receive recommendations for making decisions about the scenarios implementation sequence.

It should be noted that the proposed work is a logical continuation of the authors’ published works [4 - 6] on the study subject matter. Therefore, the paper actively uses the general approaches and results obtained in previous works. In turn, the results of this study will be used in further publications.

3. Formation of the array of input data and formalization of the methodology

For the comparative scenario analysis of the FCM phased extraction, environmental safety criteria [14] are determined using 11 criteria (see Table 1). Criteria 1 - 11 can be represented by three groups of factors (numbers indicate the numbers of criteria from Table 1):

Factor Φ_1 *– radiation safety components of the scenarios:*

7. Risks of FCM properties change (degradation) over time R_D, %.

8. Risks of destruction barriers protective around FCM accumulations over time R_{DPB} %.

10. Radiological risks R_{rad}, person/year.

11. Project (scenario) implementation time T, years.

Factor Φ_2 *– financial components of scenarios:*

1. Operating costs to ensure the current safety of the object “Ukryttya, OE_{ECS}, thousand UAH.

2. Costs of creating protective barriers for localization and FCM isolation after NSC decommissioning, OE_{PB}, thousand UAH.

3. Costs of creating additional infrastructure for retrieval and further FCMs management and other radioactive waste after NSC decommissioning, OE_{CAI}, thousand UAH.

9. Risks of underfunding the work on phased retrieval of FCM and further management, R_{UDW}, thousand UAH/year.

Factor Φ_3 *– infrastructural components of scenarios:*

4. Degree to which NSC infrastructure is used for retrieval and further management of FCM and other radioactive waste, L_{IU}, %.

5. Risks of unreadiness facilities storage for retrieved FCM interim storage, R_{USF}, %.

6. Risks of unreadiness of the geological repository for final disposal of FCM, R_{UGR}, %.

The criteria grouped in this way are the basis for using MCO methods for evaluation and further comparison of scenarios [5]. By analogy with [5, 6], the concept of “value of the scenario” V_i is introduced based on the significance function definition SF_i. The value of the scenario is identically equal to the predicted level of environmental safety during the implementation of the i-th scenario with the corresponding factor groups Φ_{1-3} and their components – indicators (criteria):

$$\left\{V_i\right\} \equiv SF_i\begin{pmatrix} \Phi_{1,i}\left\{R_{D,i}, R_{DPB.i}, R_{rad,i}, T_i\right\} \\ \Phi_{2,i}\left\{OE_{ECS,i}, OE_{PB,i}, OE_{CAI,i}, R_{UDW,i}\right\} \\ \Phi_{3,i}\left\{L_{IU,i}, R_{USF,i}, R_{UGR,i}\right\} \end{pmatrix}, \quad (1)$$

where: V_i – is the value of the i-th scenario, $i=\overline{1,p}$, p – is the number of scenarios.

Input data for the implementation of the MCO methodology are the criteria presented in Table 1 and “values of scenario” V_i are formalized in (1). Then, in general, by analogy with [5], the multi-criteria problem of evaluating FCM production scenarios can be viewed as a problem of simultaneous optimization of several objective functions on a given set of admissible plans:

$$\begin{cases} V_i = f_i\left(x_i\right) \to max, i=\overline{1,p} \\ x_i \in X \end{cases}, \quad (2)$$

where V_i – target function “value of a certain scenario”; f_i – a separate i-th function from indicator set (i = 1, …, p); $x_i = \left\{R_D, R_{DPB}, R_{rad}, T, OE_{ECS}, OE_{PB}, OE_{CAI}, R_{UDW}, L_{IU}, R_{USF}, R_{UGR}\right\}_i$ – is separate from the set of admissible scenarios X; X – is the set of admissible scenarios; p – number of target functions to be optimized.

Depending on the decision-maker person’s preferences and the factors composition Φ_{1-3}, according to which the value of the scenario is determined, the objective function in (2) can be both maximization and minimization of the value V_i (value of the scenario) on a defined scenarios set.

Sets of scenarios are acceptable plans for FCM extraction. At the same time, they have appropriate parametric estimates of criteria that can be implemented in relation to the ensuring environmental safety task. The admissible scenario sets are formed by comparing the values of the criteria in the scenarios, taking into account the possible/acceptable variation limits. Moreover, the evaluation of an arbitrary admissible plan (scenario) for the multi-criteria problem is a vector value $f_i(R_{D,i}, R_{DPB.i}, R_{rad,i}, T_i, OE_{ECS,i}, OE_{PB,i}, OE_{CAI,i}, R_{UDW,i}$ $L_{IU,i}, R_{USF,i}, R_{UGR,i})$ in the i-th scenario general evaluation by all indicators without their grouping by factors. Or $\begin{cases} f_{1,i}\left\{R_{D,i}, R_{DPB.i}, R_{rad,i}, T_i\right\} \\ f_{2,i}\left\{OE_{ECS,i}, OE_{PB,i}, OE_{CAI,i}, R_{UDW,i}\right\} \\ f_{3,i}\left\{L_{IU,i}, R_{USF,i}, R_{UGR,i}\right\} \end{cases}$ when evaluating scenarios by selecting the factor groups Φ_{1-3}.

Then, in order to solve the multi-criteria problem and implement the MCO technique in relation to determining the values V_i of scenarios, it is advisable to consider the following auxiliary single-criteria problem along with the original multi-criteria problem [15]:

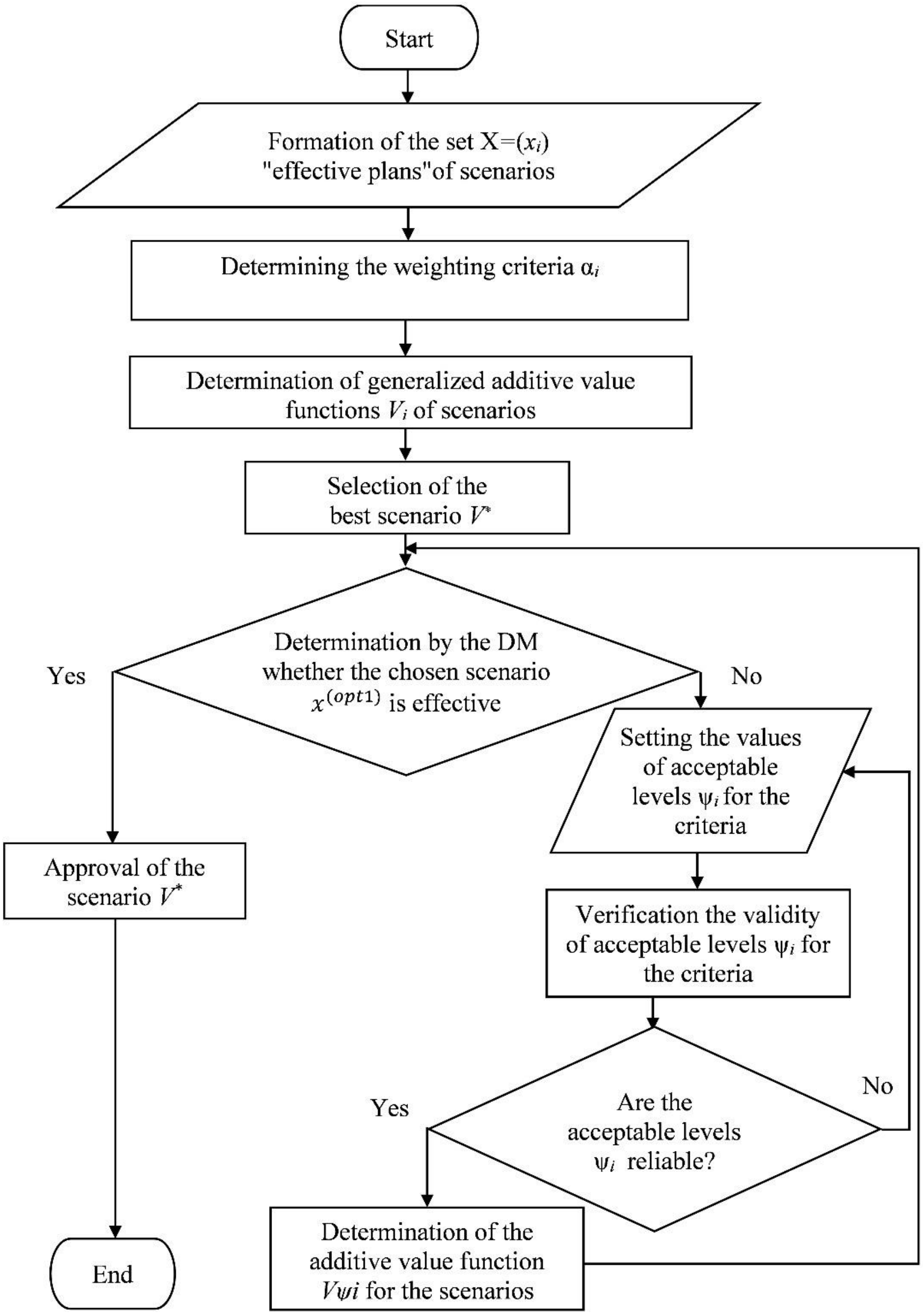
$$\begin{cases} V_i = \sum_{i=1}^{p} \alpha_i f_i(x_i) \to extr, \\ f_i(x_i)\{\geq\leq\}\psi_i, \ i=\overline{1,p}, \\ x_i \in X \end{cases} \tag{3}$$

where α_i, ψ_i – some real numbers and vector parametric criteria characteristics.

Moreover, the signs of the first of them, and the inequalities signs of the criteria limits variations, are consistent with the optimization orientation (to the maximum or minimum) of the objective functions corresponding.

4. Algorithm for comparative analysis of scenarios based on MCO methodology

The algorithm for selecting scenarios based on the MCO methodology is shown in Figure.



Scenario selection algorithm based on the MCO methodology.

A generalized methodology for assessing scenarios for transforming the object "Ukryttya" into an environmentally safe system based on MCO consists of the following steps.

Stage 1. Determination of the scenario implementation plans set, the screening out ineffective plans, the set of acceptable (effective) plans *X* formation and determination (or approximate estimation) of the variation limits for each the objective functions x_i based on the criteria parametric characteristics of the effective plans set. Within the variations of each criterion, the best x_i^* and worst x_i^0 scores are determined:

$$\begin{cases} x_i^* = \left(R^*_{D(i)}, R^*_{DPB(i)}, R^*_{rad(i)}, T_i^*, OE^*_{ECS(i)}, OE^*_{PB(i)}, OE^*_{CAI(i)}, R^*_{UDW(i)}, L^*_{IU(i)}, R^*_{USF(i)}, R^*_{UGR(i)} \right) \\ x_i^0 = \left(R^0_{D(i)}, R^0_{DPB(i)}, R^0_{rad(i)}, T_i^0, OE^0_{ECS(i)}, OE^0_{PB(i)}, OE^0_{CAI(i)}, R^0_{UDW(i)}, L^0_{IU(i)}, R^0_{USF(i)}, R^0_{UGR(i)} \right). \end{cases} \quad (4)$$

Within the array of criteria, target functions are formed for each effective plan. If for each of the objective functions its best value on the efficient plans coincides with its worst value on this set ($x_i^* = x_i^0$ для всіх $i = 1, \ldots, p$), then we conclude that all efficient plans – scenarios for the FCM extraction – are equivalent. Any of them can be chosen to solve the problem. In a typical case, which requires further study, the inequality $x_i^* \neq x_i^0$ will be satisfied for at least two objective functions. The Stage 1 result of the methodology is the numerical limits of the criteria variation determination $\left[x_i^*; x_i^0 \right]$ for each of the objective functions $i = \overline{1, p}$ on the effective plans set.

Stage 2. Determining parametric weights for the indicators that form the overall value function V_Σ of the scenarios:

$$\alpha_i = \left| \frac{1}{x_i^* - x_i^0} \right|, i = \overline{1, p}. \quad (5)$$

The result – is the numerical values of the parametric weighting coefficients for the criteria, with the corresponding units measurement:

$$\begin{cases} \langle \alpha \rangle = \left\langle \alpha_{R_D}, \alpha_{R_{DPB}}, \alpha_{R_{rad}}, \alpha_T, \alpha_{OE\,ECS}, \alpha_{OE\,PB}, \alpha_{OE\,CAI}, \alpha_{R_{UDW}}, \alpha_{L\,IU}, \alpha_{RUSF}, \alpha_{RUGR} \right\rangle \\ \langle [\alpha] \rangle = \Big\langle [\%]^{-1}, [\%]^{-1}, \left[\frac{pers}{year} \right]^{-1}, [year]^{-1}, [thousand\,UAH]^{-1}, [thousand\,UAH]^{-1}, \\ \qquad [thousand\,UAH]^{-1}, \left[\frac{thousand\,UAH}{year} \right]^{-1} [\%]^{-1}, [\%]^{-1}, [\%]^{-1} \Big\rangle. \end{cases} \quad (6)$$

Stage 3. Determination of the generalized weighted additive value functions (GWAVF) of scenarios V_Σ for the admissible plans entire set *X*:

$$V_{\Sigma(i)} = \sum_{i=1}^{p} \left(\alpha_i f_i(x) w_i^{\Omega j} \right), \quad (7)$$

where $j = \overline{1, 3}$ is the corresponding factors group for the criterion.

The GWAVF for the scenarios is carried out taking into account the criteria weights ω_i and the factor weights Ω_j to which the criteria belong. These weights, ω_i and Ω_j, were determined by the expert evaluation method in [6]. As the Stage 3 of the methodology result of the implementation, each individual scenario is described by the unambiguously dimensionless value of its value function V_Σ; it is possible to rank scenarios by their value function criterion and to select the "best" and "worst" scenarios based on their numerical estimates.

Stage 4. On the scenarios (admissible plans) set the one that corresponds to the maximum/minimum of the GWAVF is determined, depending on the optimization orientation of the parametric characteristics of the criteria: $x^{(opt1)} \equiv \max \left(SF_{\Sigma(i)} \right)$, $i = \overline{1, p}$ when the optimization orientation of the criteria parameters is directed to the maximum; $x^{(opt1)} \equiv \min \left(SF_{\Sigma(i)} \right)$, $i = \overline{1, p}$ when the optimization orientation of the criteria parameters is directed to the minimum. As a Stage 4 result, the plan $x^{(opt1)}$ evaluation is determined within the variation of the objective function on the effective plans set. Its estimate

$x^{(opt1)}$ together with the parametric values of the criteria, is transmitted to the decision maker (DM) for coordination and management decision-making.

All subsequent Stages 5 - 8 are focused on agreeing with the DM on the parameters of the criteria in the proposed optimal plan. The content of the stages is described in detail in [15]. The content of the stages based on [15] in relation to the scenario selection task is presented further in the text.

Stage 5. If the DM agrees to choose the scenario $x^{(opt1)}$ as the solution to the multicriteria problem, the specified scenario is proposed for implementation. If the DM does not agree with the parameters of the criteria for the defined scenario $x^{(opt1)}$, it should indicate for each of the indicators such parametric permissible levels $\psi_i\{R_{D,i}, R_{DPB.i}, R_{rad,i}, T_i, OE_{ECS,i}, OE_{PB,i}, OE_{CAI,i}, R_{UDW,i} L_{IU,i}, R_{USF,i}, R_{UGR,i}\}^{AsL1}$ that it considers acceptable. At the same time, the DM must comply with the requirement $\psi_i^{AsL1} \neq x_i^*$ for all $i = \overline{1,p}$. If the DM disregards some of the criteria $\in \overline{1,p}$, then $\psi_i^{AsL1} = x_i^0$ is assumed for them. As a Stage 5 result, the following options are possible: 1) the best scenario selection (in case the DM agrees with the parameters of the indicators) – the scenario evaluation process is completed; 2) the formation of the acceptable level $\psi_i^{AsL1} \in [x_i^*; x_i^0]$, $i = \overline{1,p}$ for the criteria (when the DM does not agree with the characteristics of the scenario) - transition to the next stage.

Stage 6. Determining the reality for the criteria parametric ψ_i^{AsL1}, that the DM has determined as acceptable in the previous step and correcting them either upward if they are real or downward to make them realistic. To do this, it is necessary to solve a one-criterion problem with respect to the conditional parameter *t*, which determines the reality of the acceptable levels:

$$\begin{cases} t \to max \\ \dfrac{f_i(x) - \psi_i^{AsL1}}{x_i^* - \psi_i^{AsL1}} \geq t \ , i = \overline{1,p}. \\ x \in X \end{cases} \tag{8}$$

In this case, for the objective functions directed to the maximum, the inequality $x_i^* > \psi_i^{AsL1}$ is fulfilled and the criterion constraint takes the form:

$$f_i(x_i) \geq \psi_i^{AsL1} + t\left(x_i^* - \psi_i^{AsL1}\right). \tag{8.1}$$

For minimizing objective functions, the criterion constraint is slightly different:

$$f_i(x) \leq \psi_i^{AsL1} - t\left(x_i^* - \psi_i^{AsL1}\right). \tag{8.2}$$

The case $t > 0$ indicates the reality of the acceptable levels, and $t < 0$ the contingency indicates their unreality. For real admissible levels $\psi_i^{AsL1} = \psi_i^{real}$, the value of the value function $V_{\Sigma\left(\psi_i^{real}\right)}$ is estimated. For unrealistic acceptable levels, the parametric characteristics of the indicators are adjusted, and their reality is redefined. As a Stage 6 result implementation, a conclusion is made about the reality or unreality of the initial permissible levels and the value for the value function $V_{\Sigma\left(\psi_i^{real}\right)}$ is estimated for them.

Stage 7. Based on the previous stage results, the scenarios (admissible plans) set $x^{(opt2)}$ is used to find an effective plan that is as close as possible to the real admissible levels of all criteria specified by the DM in the value function terms. As a result of the Stage 7, recommendations are made to approve the plan $x^{(opt2)}$ as a solution to a multi-criteria problem. All this information is sent to the DM.

Stage 8. If the DM does not agree with the recommendation to select an effective plan $x^{(opt2)}$ as a solution to the multicriteria problem the best scenario choosing, it must again adjust the initial permissible levels of the objective function ψ_i^{AsL2}. To ensure the convergence of the method, the new levels of ψ_i^{AsL2}, $i = \overline{1,p}$ must be weaker than the previous ones. As an Stage 8 result, either a conclusion is made about the completion of the process or a return to Stage 5 is made, taking into account the new values permissible levels of the objective functions $\psi_i^{AsL2} \in [x_i^*; x_i^0]$, $i = \overline{1,p}$.

The algorithm ends when the DM approves the determined effective plan $x^{(optDM)}$ with the corresponding indicator parameters. The effective plan $x^{(optDM)}$ is the basis for making management decisions based on the analysis of its indicator parameters.

It should be noted that the algorithm implementation stages are also valid for a separate assessment of scenarios for individual factor groups Φ_{1-3} and their respective criteria arrays.

5. The practical implementation of the scenarios complex analysis algorithm on the MCO methodology based

The input data for the methodology implementation is a criteria array (see Table 1) and an assessment of the factors and criteria weights by on the expert evaluation scenarios results [6] (Table 2).

A prerequisite for implementing the methodology is to establish the parametric characteristics of the scenario assessment criteria. It should be noted that it is impossible to calculate the actual values of the selected criteria without developing a preliminary works design. In addition, the preliminary works design development for all 11 variants of FCM phased removal scenarios requires significant financial and time costs. Therefore, the methodology was implemented on the basis of relative rather than absolute criteria assessments, which were set by an expert collective group. The criteria were assessed in relation to the baseline – the first – scenario, whose parametric criteria were conditionally assessed as “1”. The results of the collective criteria expert assessment parameters for the 11 scenarios are presented in Table 3.

Table 2. **Estimates of weights of factors and criteria of the scenarios [6]**

Factors and their criteria		The scenarios set (factors and criteria weights)										
		sc1	sc2	sc3	sc4	sc5	sc6	sc7	sc8	sc9	sc10	sc11
Φ_1		**0.360**	**0.375**	**0.364**	**0.636**	**0.350**	**0.368**	**0.353**	**0.294**	**0.250**	**0.250**	**0.267**
7.	R_D	0.257	0.273	0.250	0.759	0.222	0.231	0.222	0.214	0.185	0.192	0.200
8.	R_{DPB}	0.257	0.242	0.250	0.759	0.259	0.269	0.222	0.214	0.185	0.192	0.280
10.	R_{rad}	0.229	0.242	0.250	0.759	0.259	0.269	0.222	0.214	0.185	0.192	0.200
11.	T	0.257	0.212	0.250	0.759	0.222	0.192	0.259	0.286	0.333	0.346	0.320
Φ_2		**0.280**	**0.292**	**0.273**	**0.727**	**0.300**	**0.263**	**0.294**	**0.353**	**0.438**	**0.438**	**0.400**
1.	OE_{ECS}	0.233	0.226	0.241	0.778	0.240	0.238	0.211	0.222	0.214	0.214	0.200
2.	OE_{PB}	0.290	0.290	0.276	0.704	0.320	0.333	0.316	0.333	0.357	0.357	0.333
3.	OE_{CAI}	0.258	0.258	0.276	0.741	0.240	0.238	0.316	0.333	0.357	0.357	0.333
9.	R_{UDW}	0.218	0.226	0.207	0.778	0.200	0.190	0.158	0.111	0.071	0.071	0.133
Φ_3		**0.360**	**0.333**	**0.364**	**0.364**	**0.350**	**0.368**	**0.353**	**0.353**	**0.313**	**0.313**	**0.333**
4.	L_{IU}	0.609	0.609	0.625	0.652	0.729	0.700	0.667	0.667	0.667	0.653	0.750
5.	R_{USF}	0.217	0.217	0.292	0.696	0.400	0.350	0.444	0.444	0.500	0.513	0.563
6.	R_{UGR}	0.391	0.391	0.333	0.348	0.671	0.350	0.222	0.222	0.167	0.141	0.188

Table 3. **The results of the collective criteria expert assessment parameters**

Factor	Scenarios criteria (marking)	The scenarios set (set of effective plans)											Best and worst values	
		sc1	sc2	sc3	sc4	sc5	sc6	sc7	sc8	sc9	sc10	sc11	y_i^*	y_i^0
Φ_1	7. R_D	1	1.1	1.2	1.2	1.3	1.35	1.4	1.4	1.35	1.5	1.45	1	1.5
	8. R_{DPB}	1	1	1.1	1.1	1.2	1.4	1.5	1.4	1.3	1.5	1.4	1	1.5
	10. R_{rad}	1	0.95	0.9	0.95	0.9	0.85	0.8	0.75	0.7	0.6	0.5	0.5	1
	11. T	1	0.7	1.1	0.8	1.2	1.25	1.5	1.45	1.4	1.5	1.4	0.7	1.5
Φ_2	1. OE_{ECS}	1	1	1.1	1.1	1.3	1.4	1.5	1.4	1.3	1.4	1.3	1	1.5
	2. OE_{PB}	1	1.1	1.2	1.2	1.3	1.4	1.5	1.4	1.3	1.4	1.3	1	1.5
	3. OE_{CAI}	1	0	1.3	1.2	1.4	1.5	1.7	1.5	1.5	1.7	1.5	0	1.7
	9. R_{UDW}	1	1	0.9	0.9	0.8	0.7	0.6	0.6	0.6	0. 5	0.5	0.5	1
Φ_3	4. L_{IU}	1	1	0.9	0.9	0.8	0.7	0.6	0.6	0.6	0.5	0.5	1	0.5
	5. R_{USF}	1	1	0.9	0.9	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.5	1
	6. R_{UGR}	1	1	1	1	0.95	0.95	0.95	0.95	0.95	1	1	0.95	1

Based on the determined best y_i^* and worst y_i^0 values of the criteria scores, the parametric weighting coefficients of the criteria were determined (Stage 2) using formula (5). The results are shown in Table 4.

The determination of the scenario value functions (Stage 3) was carried out by taking into account the weights of the factors and the according criteria weights by formula (7). The results of the calculations are presented in Table 5.

Table 4. **Parametric weights of the criteria**

Factor	Scenarios criteria (marking)	Parametric weights of the criteria
Φ_1	7. R_D	$\alpha_{R_{DPB}}$ = 1/abs(1.5 – 1) = 2.00 $[\%]^{-1}$
	8. R_{DPB}	α_{RD} = 1/abs(1.5 – 1) = 2.00 $[\%]^{-1}$
	10. R_{rad}	α_{Rrad} = 1/abs(1 – 0.5) = 2.00 $\left[\frac{person}{year}\right]^{-1}$
	11. T	α_T = 1/abs(1.5 – 0.7) = 1.250 $[year]^{-1}$
Φ_2	1. OE_{ECS}	$\alpha_{OE\,ECS}$ = 1/abs(1.5 – 1) = 2.00 $[thousand\,UAH]^{-1}$
	2. OE_{PB}	$\alpha_{OE_{PB}}$ = 1/abs(1.5 – 1) = 2.00 $[thousand\,UAH]^{-1}$
	3. OE_{CAI}	$\alpha_{OE\,CAI}$ = 1/abs(1.7 – 0) = 0.59 $[thousand\,UAH]^{-1}$
	9. R_{UDW}	$\alpha_{R_{UDW}}$ = 1/abs(1 – 0.5) = 2.00 $\left[\frac{thousand\,UAH}{year}\right]^{-1}$
Φ_3	4. L_{IU}	α_{LIU} = 1/abs(1 – 0.5) = 2.00 $[\%]^{-1}$
	5. R_{USF}	α_{RUSF} = 1/abs(1 – 0.5) = 2.00 $[\%]^{-1}$
	6. R_{UGR}	α_{RURG} = 1/abs(1 – 0.95) = 20.00 $[\%]^{-1}$

Table 5. **The determination of the scenario value functions with account the factors weights and the according criteria weights**

$\alpha_{cr} \cdot [criterio] \cdot \omega_{cr}^{\Omega\Phi}$	The scenarios set										
	sc1	sc2	sc3	sc4	sc5	sc6	sc7	sc8	sc9	sc10	sc11
$\alpha_7 \cdot [7] \cdot \omega_7^{\Omega\Phi1}$	1.176	1.176	1.208	1.247	2.384	1.233	1.176	1.271	1.312	1.324	1.302
$\alpha_8 \cdot [8] \cdot \omega_8^{\Omega\Phi1}$	1.227	1.229	1.208	1.181	2.384	1.165	1.176	1.271	1.312	1.324	1.302
$\alpha_{10} \cdot [10] \cdot \omega_{10}^{\Omega\Phi1}$	1.227	1.176	1.208	1.247	2.384	1.233	1.176	1.271	1.312	1.324	1.424
$\alpha_{11} \cdot [11] \cdot \omega_{11}^{\Omega\Phi1}$	0.767	0.699	0.755	0.738	2.384	0.681	0.776	0.865	0.950	0.959	0.922
$\alpha_1 \cdot [1] \cdot \omega_1^{\Omega\Phi2}$	1.331	1.296	1.357	0.980	2.401	1.371	1.265	1.176	1.019	1.019	1.051
$\alpha_2 \cdot [2] \cdot \omega_2^{\Omega\Phi2}$	1.415	1.394	1.408	1.131	2.582	1.498	1.425	1.357	1.275	1.275	1.289
$\alpha_3 \cdot [3] \cdot \omega_3^{\Omega\Phi2}$	0.403	0.396	0.414	0.288	2.488	0.403	0.419	0.399	0.375	0.375	0.379
$\alpha_9 \cdot [9] \cdot \omega_9^{\Omega\Phi2}$	1.306	1.296	1.301	0.894	2.401	1.293	1.162	0.921	0.630	0.630	0.893
$\alpha_4 \cdot [4] \cdot \omega_4^{\Omega\Phi3}$	0.836	0.847	0.843	0.895	2.336	0.877	0.867	0.867	0.881	0.875	0.909
$\alpha_5 \cdot [5] \cdot \omega_5^{\Omega\Phi3}$	1.155	1.203	1.278	1.452	2.282	1.358	1.502	1.502	1.610	1.623	1.651
$\alpha_6 \cdot [6] \cdot \omega_6^{\Omega\Phi3}$	14.267	14.629	13.413	17.392	2.936	13.585	11.762	11.762	11.425	10.832	11.447
GWAVF V_Σ	**25.107**	**25.339**	**24.394**	**27.447**	**26.965**	**24.698**	**22.707**	**22.663**	**22.102**	**21.562**	**22.569**

According to the condition of maximizing the GWAVF, the best plan is $x^{(opt1)}$ with the maximum value $V_{\Sigma(i)}$ = max = 27.447 – “Scenario 4” with the criteria parameters (The list of criteria is given in the order as in Table 1):

$$\text{Scenario 4} = \begin{pmatrix} \mathrm{OE}_{ECS} = 1.1\ from\ the\ basic\ version, thousand\ UAH \\ \mathrm{OE}_{PB} = 1.2\ from\ the\ basic\ version, thousand\ UAH \\ \mathrm{OE}_{CAI} = 1.2\ from\ the\ basic\ version, thousand\ UAH \\ L_{IU} = 0.9\ from\ the\ basic\ version.\ \% \\ R_{USF} = 0.9\ from\ the\ basic\ version.\ \% \\ R_{UGR} = 1\ from\ the\ basic\ version.\ \% \\ R_{rad} = 0.95\ from\ the\ basic\ version.\ \frac{person}{year} \\ R_{D} = 1.2\ from\ the\ basic\ version.\ \% \\ R_{UDW} = 0.9\ from\ the\ basic\ version.\ \frac{thousand\ UAH}{year} \\ R_{DPB} = 1.1\ from\ the\ basic\ version.\ \% \\ T = 0.8\ from\ the\ basic\ version.\ year \end{pmatrix}$$

The results scenarios ranking by the value of the GWAVF are presented below.

$$\begin{cases} V^{*}{}_{\Sigma(i)} = max\left(V_{\Sigma(i)}\right) = 27.447 - \text{scenario 4} \\ V^{*-1}{}_{\Sigma(i)} = 26.965 - \text{scenario 5} \\ V^{*-2}{}_{\Sigma(i)} = 25.339 - \text{scenario 2} \\ V^{*-3}{}_{\Sigma(i)} = 25.107 - \text{scenario 1} \\ V^{*-4}{}_{\Sigma(i)} = 24.698 - \text{scenario 6} \\ V^{*-5}{}_{\Sigma(i)} = 24.394 - \text{scenario 3} \\ V^{*-6}{}_{\Sigma(i)} = 22.707 - \text{scenario 7} \\ V^{*-7}{}_{\Sigma(i)} = 22.663 - \text{scenario 8} \\ V^{*-8}{}_{\Sigma(i)} = 22.569 - \text{scenario 11} \\ V^{*-9}{}_{\Sigma(i)} = 22.102 - \text{scenario 9} \\ V^{0}{}_{\Sigma(i)} = min\left(V_{\Sigma(i)}\right) = 21.562 - \text{scenario 10} \end{cases} \quad (9)$$

The worst scenario according to the $min\left(V_{\Sigma(i)}\right)$ principle is "scenario 10", the value of the relative complex value of which is minimal and amounts to $V^{0}{}_{\Sigma(i)} = min\left(V_{\Sigma(i)}\right) = 21.562$; a scenario estimate, ranked by the GWAVF, is as follows:

$$\begin{Bmatrix} V^{*}{}_{\Sigma(i)} = V_4 > V_5 > V_2 > V_1 > V_6 > V_3 > V_7 > V_8 > V_{11} > V_9 > V^{0}{}_{\Sigma(i)} = V_{10} \\ 27.447 > 26.965 > 25.339 > 25.107 > 24.698 > 24.394 > 22.707 > 22.663 > 22.569 > 22.102 > 21.562 \end{Bmatrix}.$$

The numerical experiment was carried out in MS Excel. In the future, it is planned to create our own software product – a decision support system based on the created algorithms.

6. Discussion and conclusions

Thus, based on our calculations, we can draw the following conclusions:

determination of the best and worst case scenarios using a GWAVF is similar to the results in [8];

the values of the scenarios calculated using the proposed methodology take into account the criteria parametric estimates, the factor weights $\Omega_i^{\Phi j}$ and the criteria weights ω_i^j for the corresponding factors Ω^j;

the additive values array of the scenarios (9) is the basis for the DM formation on the scenarios implementation sequence, taking into account the criteria parametric characteristics.

Therefore, with proper funding for the phased withdrawal of spent fuel, Scenario 4 is the priority. It provides that during the NSC life cycle, it is mandatory to remove FSMs and associated radioactive waste from zones: 1 through part 3 (steam discharge corridor), as well as 4 (part of the turbine hall within the object “Ukryttya”) and 6 (debris under the cascade wall). After the NSC decommissioning retrieval of FCM and co-waste radioactive materials will be performed in part of the third zone (bubler tank) and in the fifth zone (space behind the pioneer walls).

FCMs of the seventh zone (local zone object “Ukryttya”), in this case, cannot be deleted. And after the end of the NSC life cycle, they will be considered buried in the same place. This scenario largely utilizes the NSC infrastructure, reduces the cost of creating protective barriers for FCM containment and isolation, as well as the cost of creating additional infrastructure for retrieval and further management of FCM and other radioactive waste after NSC decommissioning.

Since the values of the GWAVF for all scenarios do not differ significantly, under certain circumstances (mostly due to the financial component), other scenarios that provide for the deferred withdrawal of individual FCM clusters may be preferable. Therefore, to detail the influence of factors and their components on the decision-making process, it is advisable to continue research by building partial scenarios value functions.

The proposed algorithm can also be extended: for factor groups Φ_1-Φ_3 – value functions for groups, for the criteria within the selected group – partial (selected) value functions.

In the first case, the generalized value function for groups makes it possible to determine the values of scenarios by aggregated characteristics – radiation safety, financial, and infrastructure factors. Based on the factor assessment results of scenarios, the DM can make decisions on scenarios taking into account their radiation safety, financial or infrastructure components.

In the second case, partial value functions allow for a more detailed determination of the “best” scenarios within individual factors groups according to their criteria defined for a particular group. At the same time, the DM, in accordance with its own preferences as defined in case 2, may formulate decisions based on the parameters variation of specific criteria within each (or a defined) group. Thus, decisions on the choice of scenarios and their ranking can be made at three generalization levels.

It should also be noted that the proposed methodology of MCO does not explicitly take into account the relationships between the analyzed parameters. Determining the weighting coefficients only partially compensates for the analysis of relationships, which is the subject of further research.

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АНАЛІЗ СЦЕНАРІЇВ ПЕРЕТВОРЕННЯ ОБ'ЄКТА «УКРИТТЯ» НА ЕКОЛОГІЧНО БЕЗПЕЧНУ СИСТЕМУ МЕТОДОМ БАГАТОКРИТЕРІАЛЬНОЇ ОПТИМІЗАЦІЇ

На основі згрупованих у фактори критеріїв порівняльного аналізу сценаріїв проведено визначення цінності сценаріїв на основі методики багатокритеріальної оптимізації. У методику оцінки включено показники ваги груп факторів та ваги критеріїв для відповідних факторів. Визначення цінності сценарію проводиться за допомогою розрахунку узагальненої зваженої адитивної функції. На її основі проведене ранжування сценаріїв із встановленими параметричними характеристиками критеріїв. Результати оцінки сценаріїв та ранжування їх є рекомендацією для прийняття рішень щодо послідовності реалізації сценаріїв.

Ключові слова: об'єкт «Укриття», екологічно безпечна система, фактори та критерії оцінки сценаріїв, багатокритеріальна оптимізація, узагальнена зважена адитивна функція, ранжування сценаріїв, прийняття рішень.

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