Application of Multi-criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System/ Scenario Options: KIND approach and KIND evaluation tool

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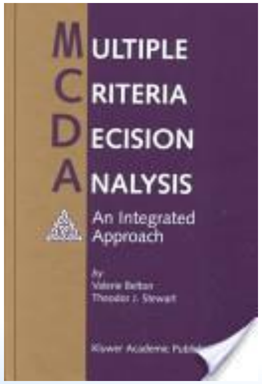
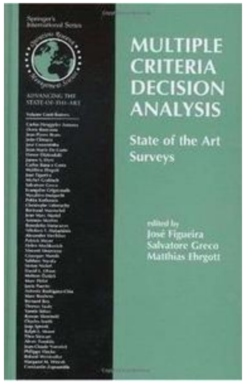
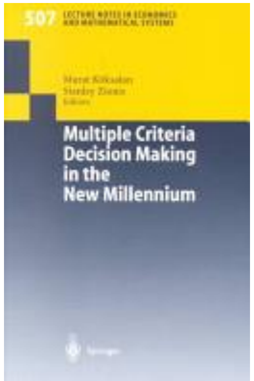
Multi-Criteria Decision Making

Multiple Criteria Decision Making

- *Multiple Criteria Decision Making (MCDM)* techniques are a tool aimed at supporting decision makers faced with making numerous and **conflicting assessments**. MCDM techniques intend to **highlight conflicts** and **find compromises** in the decision making process.
- **Studies** properly **organized** on the basis of the MCDM paradigm represent a process **not only formally** operating with a set of **mathematical methods** and various analytical tools, but **also leading to a comprehensive understanding** of the problem and its elaboration.
- *Multi-Criteria Decision Analysis (MCDA)* **does not provide a ‘right solution’**; in this regard it would be correct to talk **about a compromise or a trade-off solution**, paying special attention to an analysis of the solution stability to various methods used and their model parameters.







MODM & MCDA techniques

- *Multi-Criteria Decision Analysis (MCDA)* and *Multi-Objective Decision Making (MODM)* are the main components of MCDM.
- ***Multi-Criteria Decision Analysis (MCDA).*** These problems consist of a finite number of alternatives, explicitly known in the beginning of the solution process. Each alternative is represented by its performance in multiple criteria. The problem may be defined as finding the best alternative for a decision maker, or finding a set of good alternatives.
- ***Multi-Objective Decision Making (MODM).*** In these problems, the alternatives are not explicitly known. An alternative (solution) can be found by solving a mathematical model. The number of alternatives is either infinite or not countable (when some variables are continuous) or typically very large, if countable (when all variables are discrete).

Comparison of MODM and MCDA approaches (Malczewski, 1999)

Criteria for comparison	MODM	MCDA
Criteria defined by	Objectives	Attributes
Objectives defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constrains defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision maker`s control	Significant	Limited
Decision modelling paradigm	Process-oriented	Outcome-oriented
Relevant to	Design/search	Evaluation/choice

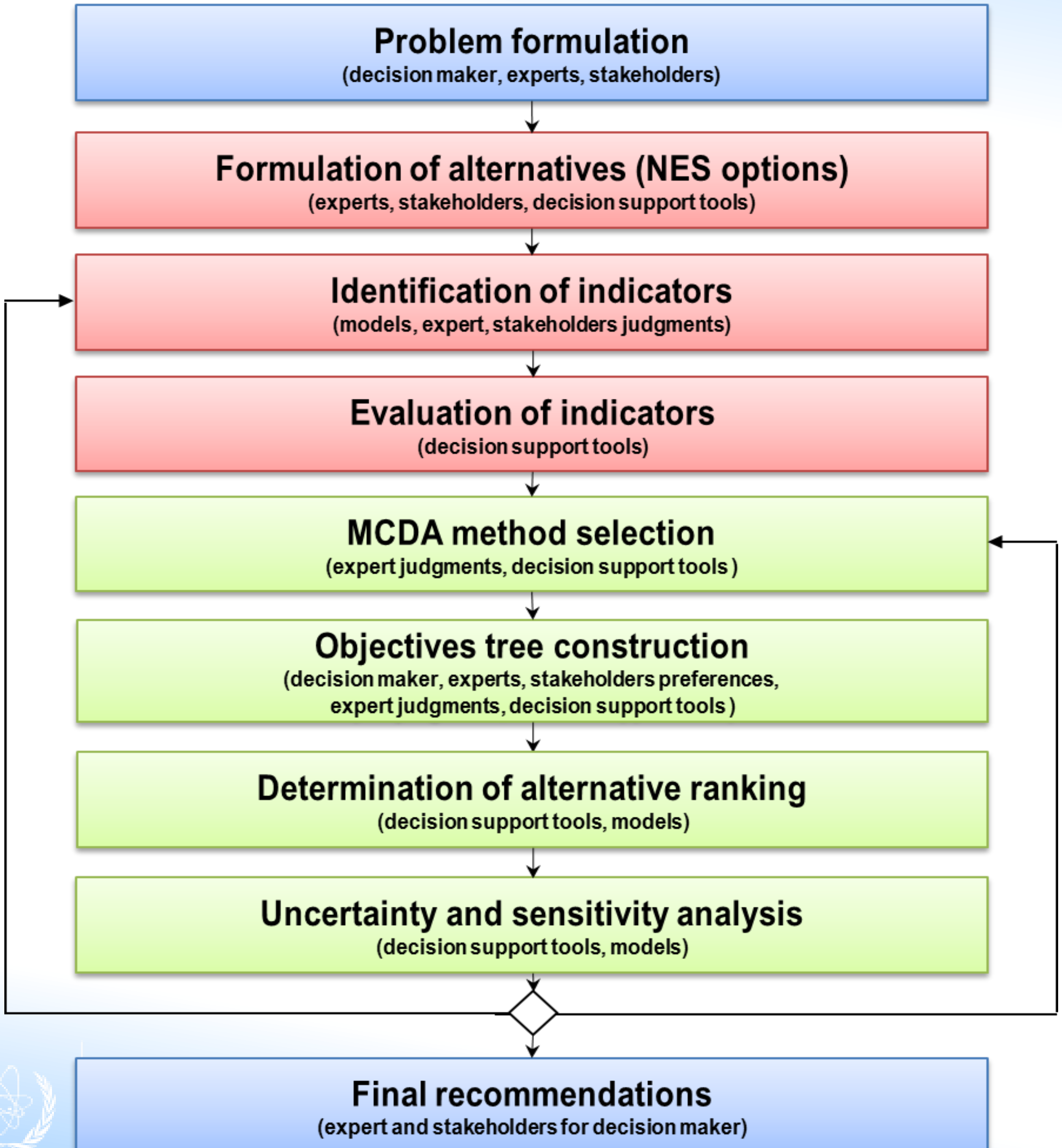
Most commonly used MCDM methods

- A large number of MCDA techniques have been developed to deal with different kinds of problems. At the same time, each technique has pros and cons and can be more or less useful, depending on the situation.
- There are various MODM methods for solving the multi-objective optimization problem: *a priori* methods; *a posteriori* methods; adaptive methods; methods based on the preliminary construction of the Pareto (efficient, non-dominated) set approximation.

MODM methods	MCDA methods
No preference methods	***Elementary methods***
▪ Global criteria	▪ Simple additive weighting
▪ Goal programming	▪ Kepner-Tregoe method
A priori methods	***Value-based methods***
▪ Criteria constraints method	▪ MAVT
▪ The achievement scalarizing function	▪ MAUT
▪ The weighted sum	▪ AHP
A posteriori methods	***Outranking methods***
▪ ADBASE	▪ ELECTRE
▪ Normal constraint method	▪ PROMETHEE
▪ Directed search domain	▪ QUALIFLEX
Adaptive and interactive methods	***Reference point based methods***
▪ Genetic algorithms (NSGA-II, MOCHC, etc.)	▪ TOPSIS
▪ Feasible and reasonable goals methods	▪ VIKOR
▪ Parameter space investigation (PSI) method	▪ BIPOLAR

Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis



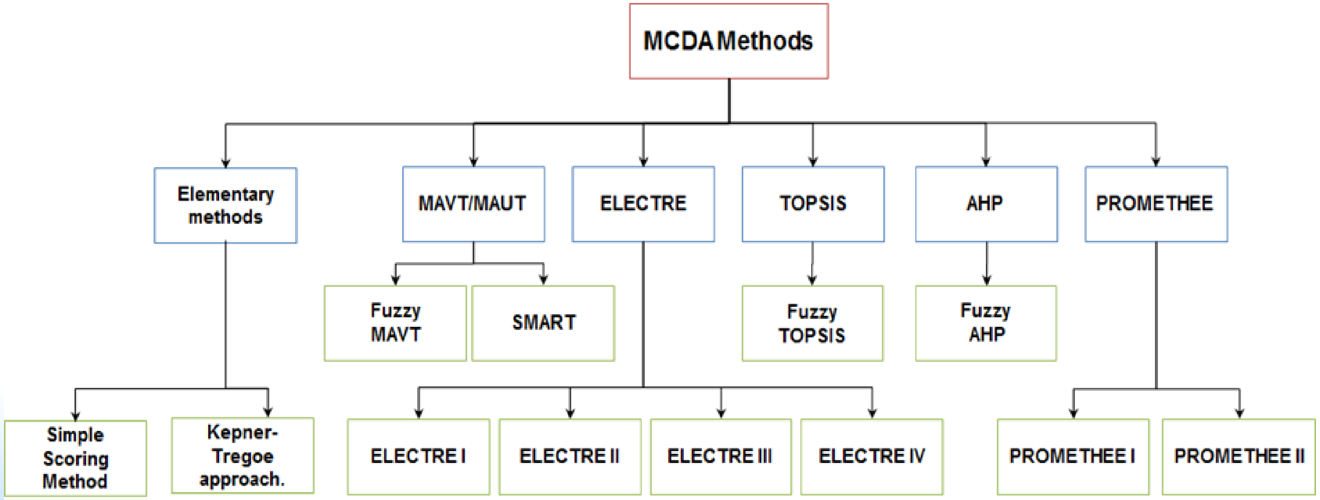
- The problem should be formulated and structured.
- All parties interested in the analysis should develop a common attitude to the problem, its interpretation and understanding.
- This includes elaborating sets of alternatives, criteria, various constraints, uncertainties, etc.; and identifying goals and preferences as well as factors and possible solutions providing a list of key points for further discussion and analysis.

- The phase implies construction of a model and using of it.
- The basic characteristic of a multi-criteria decision analysis is the formalization of all preferences involved in the analysis.
- Based on these preferences, decisions could be made by comparison of refined and elaborated sets of alternatives in a systematic and transparent manner.

- Based on the evaluations performed and results obtained, including results of sensitivity and uncertainty analysis, a certain decision on the more preferable solution could be made.
- Otherwise it is needed to turn back to one of the previous multi-criteria decision analysis stages.

MCDA methods

- A large number of multi-criteria techniques have been developed to deal with different kinds of problems.
- Each technique has pros and cons and can be more or less useful depending on the situation. Few approaches have been proposed to guide the selection of a technique adapted to a given situation.
- Experience in previous applications shows that both simple scoring models and more sophisticated MCDA methods may be used for multi-criteria comparison of nuclear energy systems, both technology and scenario based.
- The final choice of the most appropriate method for a particular problem should be made on the basis of the problem context analysis and the initial information quality provided by subject matter experts.



Types of criteria and relevant MCDA methods

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The set of criteria should meet certain requirements: completeness, informativeness, non-redundancy, independence, decomposability.

Different types of criteria may be used: qualitative, quantitative (binary, discrete, continuous etc.)

Criteria evaluated on natural scale

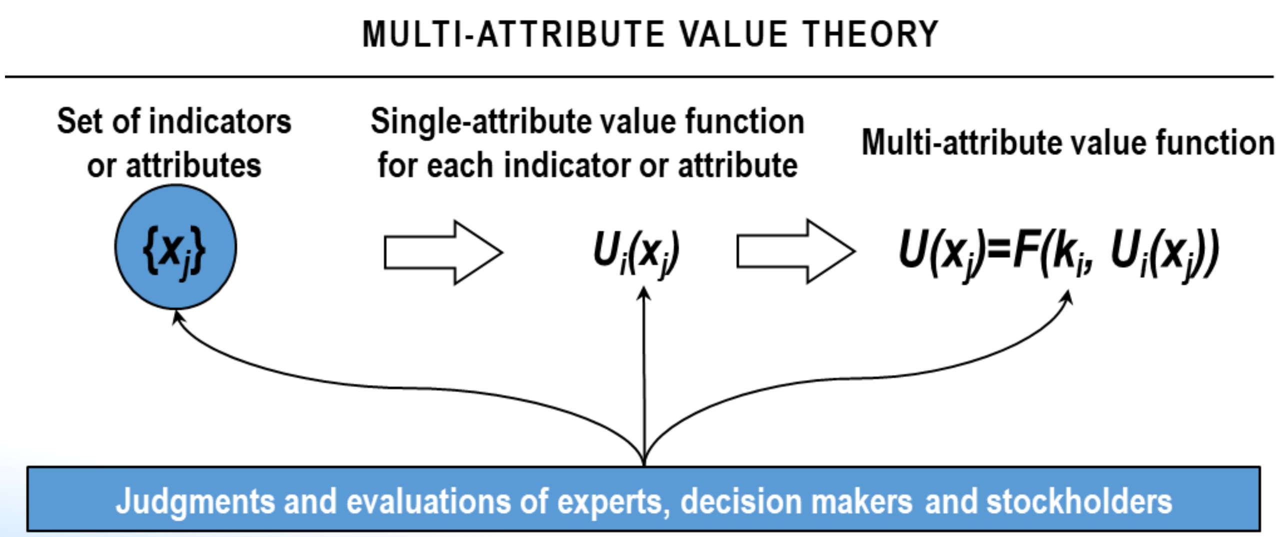
- MAVT (Multi-Attribute Value Theory, aggregation)
- MAUT (Multi-Attribute Utility Theory, uncertain criterion values)
- TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution, distance to ideal point)
- PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations, pairwise comparison based on preference functions)
- etc.

Criteria evaluated by scores

- SAW (simple additive weighting)
- SMART (simple multi-attribute rating technique)
- K-T (Kepner-Tregoe) decision analysis
- AHP (Analytic Hierarchy Process, pairwise comparison)
- etc.

Multi-Attribute Value/Utility Theory

- MAVT/MAUT are quantitative comparison methods used to combine different measures of costs, risks and benefits along with expert and decision-maker preferences into an overall score.
- MAUT extends MAVT in using probabilities and expectations to deal with uncertainties.
- The foundation of MAVT/MAUT is the use of value/utility functions. These functions transform diverse criteria to one common, dimensionless scale or score (0 to 1) known as the value function (MAVT) or utility function (MAUT).



k_i and k are weighting factors

Multi-attribute value/utility function

The general form of the multi-attribute utility/value function is:

$$u(x) = \sum_{i=1}^{n} k_i u_i(x_i) + k \sum_{\substack{i=1 \\ j \rangle i}}^{n} k_i k_j u_i(x_i) u_j(x_j) + k^2 \sum_{\substack{i=1 \\ j \rangle i \\ l \rangle j}}^{n} k_i k_j k_l u_i(x_i) u_j(x_j) u_l(x_l) + \ldots + k^{n-1} k_1 k_2 \ldots k_n u_1(x_1) u_2(x_2) \ldots u_n(x_n)$$

$$1 + k = \prod_{i=1}^{n} (1 + k k_i)$$

k_i and k are weighting factors

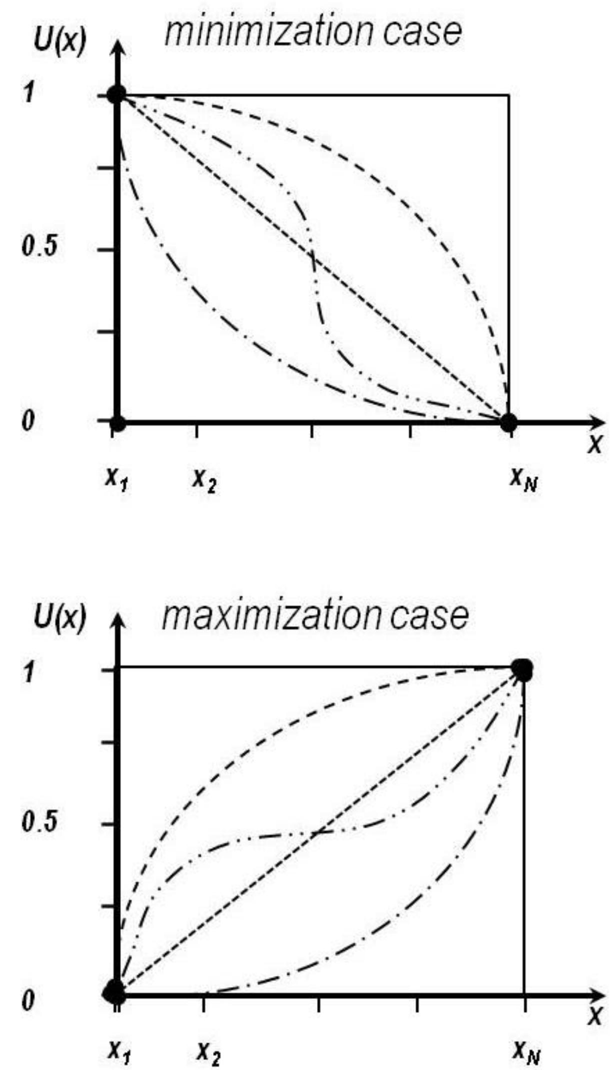
TYPES OF INTERACTION REPRESENTED BY RELATIONSHIPS BETWEEN k_i, k

k value	Σk_i	Type of interaction
negative	>1.0	compensatory
positive	<1.0	complementary
0	1.0	additive
∞	0	multiplicative

- **In the case of compensation**, the low performance of one indicator can be compensated by the high performance of other indicators. This refers to a situation when decision-makers are satisfied with the following judgment: *"If just one of the indicators takes its worst level, then it is acceptable."*
- **In the case of complementation**, the good performance of one indicator is less important than the balanced performance across all indicators. This refers to a situation when decision-makers are satisfied with the following judgment: *"If just one of these indicators is at its worst level, then the whole system performance is unacceptable."*

Value/utility functions

- Value function (in MAVT) and utility function (in MAUT) transforms the value of criterion evaluated in ‘natural’ scale to the scores scales [0; 1] in accordance with experts’ and decision-maker’s judgments. These scores are used in further calculations.
- Value/utility functions are used, when quantitative information is known about each alternative. Every criterion has such function created for it. Utility functions can take into account relation to the risks and, in principle, may differ from value functions.
- The criteria are weighted according to importance. To identify the preferred alternative, for each alternative criterions are multiplied by corresponding weights and summarized, resulting in overall score. In this, the weights used may reflect the experts’ and decision-maker’s preferences alike.
- The overall scores indicate the ranking for the alternatives. The preferred alternative will have the highest total score.

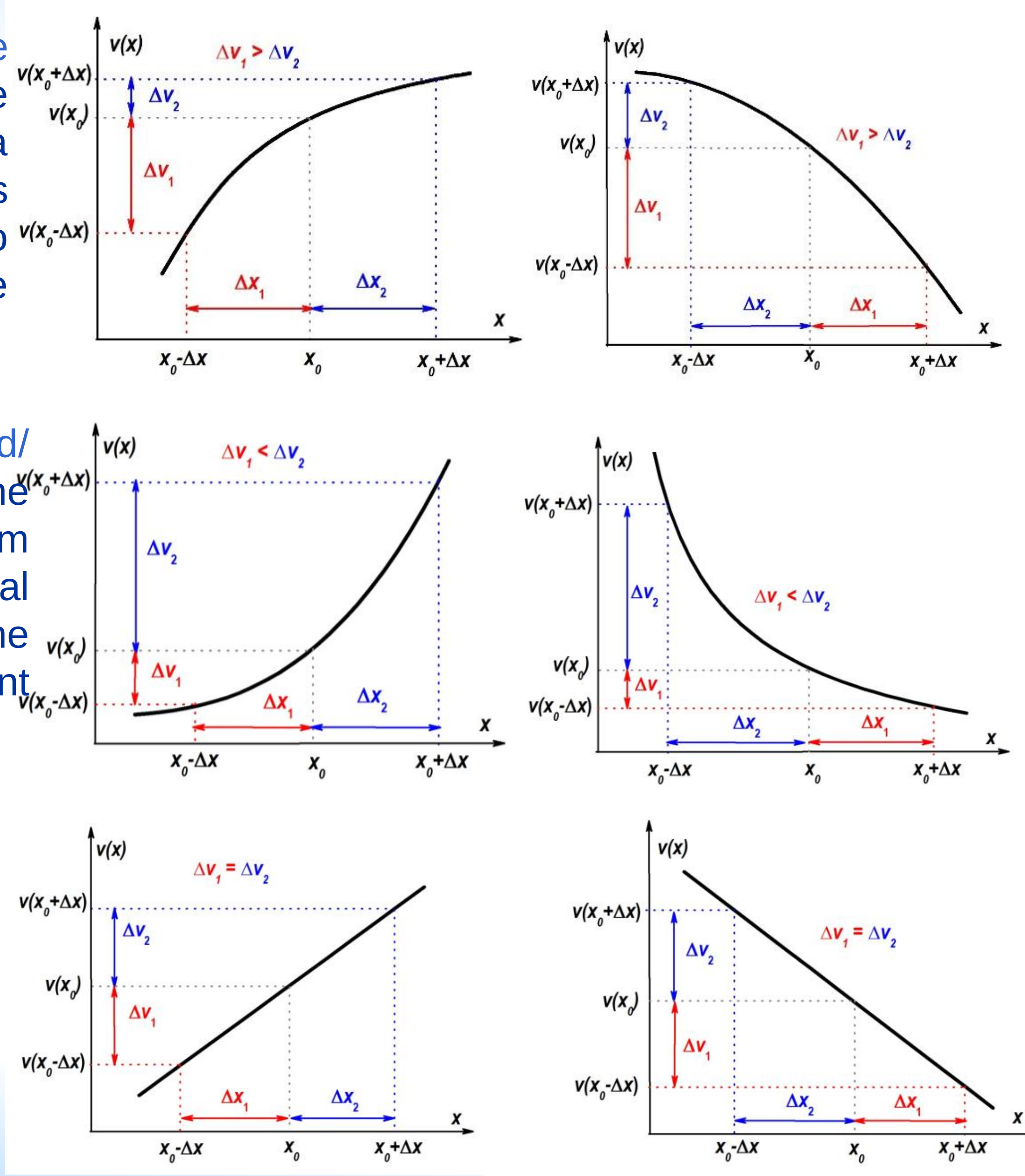


Value/utility function types

Risk aversion (convex upward/concave downward function) – for risk-averse persons, emotional distress due to a decrease in the performance indicator's value is stronger than satisfaction due to an analogous increase in the performance indicator's value.

Risk proneness (convex downward/ concave upward function) – for a risk-prone decision-maker, psychological benefits from the possibility of acquiring additional performance indicator Δx units surpass the distress due to a potential loss of equivalent additional performance indicator units.

Risk neutrality (linear function) – for risk-neutral persons, the value function is a straight line assuming an equal attitude both to gains and losses.



Examples

<table>
<tr><th>Type</th><th>Increasing value functions</th><th>Decreasing value functions</th></tr>
<tr><td rowspan="2">Linear</td><td>$$V(x)=\frac{x-x^{\min}}{x^{\max}-x^{\min}}$$</td><td>$$V(x)=\frac{x^{\max}-x}{x^{\max}-x^{\min}}$$</td></tr>
<tr><td colspan="2">Additional parameter determination is not required. x^{min} and x^{max} are the minimal and maximal domain values of a single-attribute value function (end points of the value function).</td></tr>
<tr><td rowspan="2">Polynomial</td><td>$$V(x)=\left(\frac{x-x^{\min}}{x^{\max}-x^{\min}}\right)^{a}$$</td><td>$$V(x)=\left(\frac{x^{\max}-x}{x^{\max}-x^{\min}}\right)^{a}$$</td></tr>
<tr><td colspan="2">for any a >0; if a>1 – convex downward (concave upward) function; if 0<a<1 – convex upward (concave downward) function; symmetric reflection if a → 1/a</td></tr>
<tr><td rowspan="2">Exponential</td><td>$$V(x)=\frac{1-\exp\left(a\cdot\frac{x-x^{\min}}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$$</td><td>$$V(x)=\frac{1-\exp\left(a\cdot\frac{x^{\max}-x}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$$</td></tr>
<tr><td colspan="2">for any a≠0; if a>0 – convex downward (concave upward) function; if a<0 – convex upward (concave downward) function; symmetric reflection if a → – a</td></tr>
<tr><td rowspan="2">Logarithmic</td><td>$$V(x)=\frac{\ln\left(a\cdot\frac{x-x^{\min}}{x^{\max}-x^{\min}}+1\right)}{\ln(a+1)}$$</td><td>$$V(x)=\frac{\ln\left(a\cdot\frac{x^{\max}-x}{x^{\max}-x^{\min}}+1\right)}{\ln(a+1)}$$</td></tr>
<tr><td colspan="2">for any a≠0; if a>0 – convex downward (concave upward) function; if a<0 – convex upward (concave downward) function; symmetric reflection if a → – a</td></tr>
<tr><td rowspan="2">Piecewise</td><td>$$V(x)=\sum_{i=1}^{N}\Delta V_i\cdot\Theta(x-x_i),$$ Θ – Heaviside step function, $$\Delta V_i>0,\ \sum_{i=1}^{N}\Delta V_i=1$$</td><td>$$V(x)=1-\sum_{i=1}^{N}\Delta V_i\cdot\Theta(x-x_i),$$ Θ – Heaviside step function, $$\Delta V_i>0,\ \sum_{i=1}^{N}\Delta V_i=1$$</td></tr>
<tr><td colspan="2">It is necessary to determine additional parameters in an amount equal to the number of steps into which the value function domain is divided</td></tr>
</table>

Weighting methods

- The presentation of preferences among different criteria (weights identification) is the most sensitive issue in the formal application of MCDA methods that requires accurateness and reasonableness.
- Weighting allows taking into account the relative importance of the criteria. The weights in different aggregation rules have different interpretations and implications. Weights can be identified in several ways.

Methods	Evaluation algorithms	Illustrations
Direct Method	Expert has to directly specify the weights for all indicators.	$(w_1, w_2, ..., w_N), \sum_{i=1}^{N} w_i = 1$
Ranking Method	In ranking weighting expert has to specify the ranks for criteria. The most important criterion must have the rank 1.	$(r_1, r_2, ..., r_N)$, where $r_i \in [1, N] \rightarrow$ $(w_1, w_2, ..., w_N), \sum_{i=1}^{N} w_i = 1$
Rating Method	Expert has to define rating points for every indicator. To the most important indicator 100 points rating is to be assigned and all other importance points are then related to the most important one.	$(r_1, r_2, ..., r_N)$, where $r_i \in [1, 100] \rightarrow$ $(w_1, w_2, ..., w_N), \sum_{i=1}^{N} w_i = 1$
Pairwise Comparisons	Pairwise comparison is used as weighting technique in the AHP method.	$\begin{pmatrix} 1 & a_{ij} & ... \\ 1/a_{ij} & 1 & ... \\ ... & ... & 1 \end{pmatrix}, a_{ij} \in [1, 3, 5, 7, 9] \rightarrow \begin{pmatrix} \lambda_1 \\ ... \\ \lambda_N \end{pmatrix} \rightarrow$ $(w_1, w_2, ..., w_N), \sum_{i=1}^{N} w_i = 1$ $(w_1, w_2, ..., w_N), \sum_{i=1}^{N} w_i = 1 \rightarrow$
Swing Method	The method allows taking into account swings of criteria scales along with corresponding relative importance.	$(w_1^*, w_2^*, ..., w_N^*), \sum_{i=1}^{N} w_i^* = 1$

Sensitivity and uncertainty analysis

- Sensitivity and uncertainty analyses are useful to evaluate the **impact of experts' and decision-makers' preferences on the alternative ranking** to make sure they select the best alternative to meet their preferences. Such analyses are used to increase **clarity of the alternative selection**.
- The purpose of a sensitivity/uncertainty analysis is **to validate the alternative evaluation and alternatives' rankings** by demonstrating that small changes in the alternative scores against the indicators or weights do not change the alternatives' ranking.

INPRO/KIND approach to comparative evaluation of NES/ scenario options

IAEA NUCLEAR ENERGY SERIES - NG-T-3.20

APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS METHODS TO COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEM OPTIONS

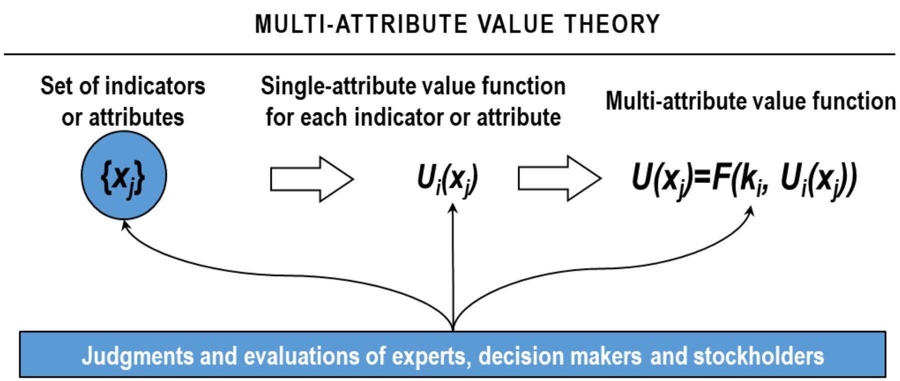
FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT ON KEY INDICATORS FOR INNOVATIVE NUCLEAR ENERGY SYSTEMS (KIND)

Please note: This is a final draft version of IAEA-Nuclear Energy Series NG-T-3.20 made available as an advance copy for reference at the 2nd Consultants Meeting of the INPRO Donors Group, 17– 8 June 2019. However, this version may contain errors and is not an official publication of the IAEA. The official publication is currently scheduled for online publication in September 2019.

Multi-attribute value theory (MAVT)

MAVT represents quantitative comparison methods used to combine different measures of costs, risks and benefits along with expert and decision-maker preferences into high-level aggregated performance index.

- The foundation of MAVT is the use of value functions.
- These functions transform diverse criteria to one common, dimensionless scale or score (0 to 1) known as the single-attribute value function.
- Single-attribute value functions are combined into the multi-attribute value function.

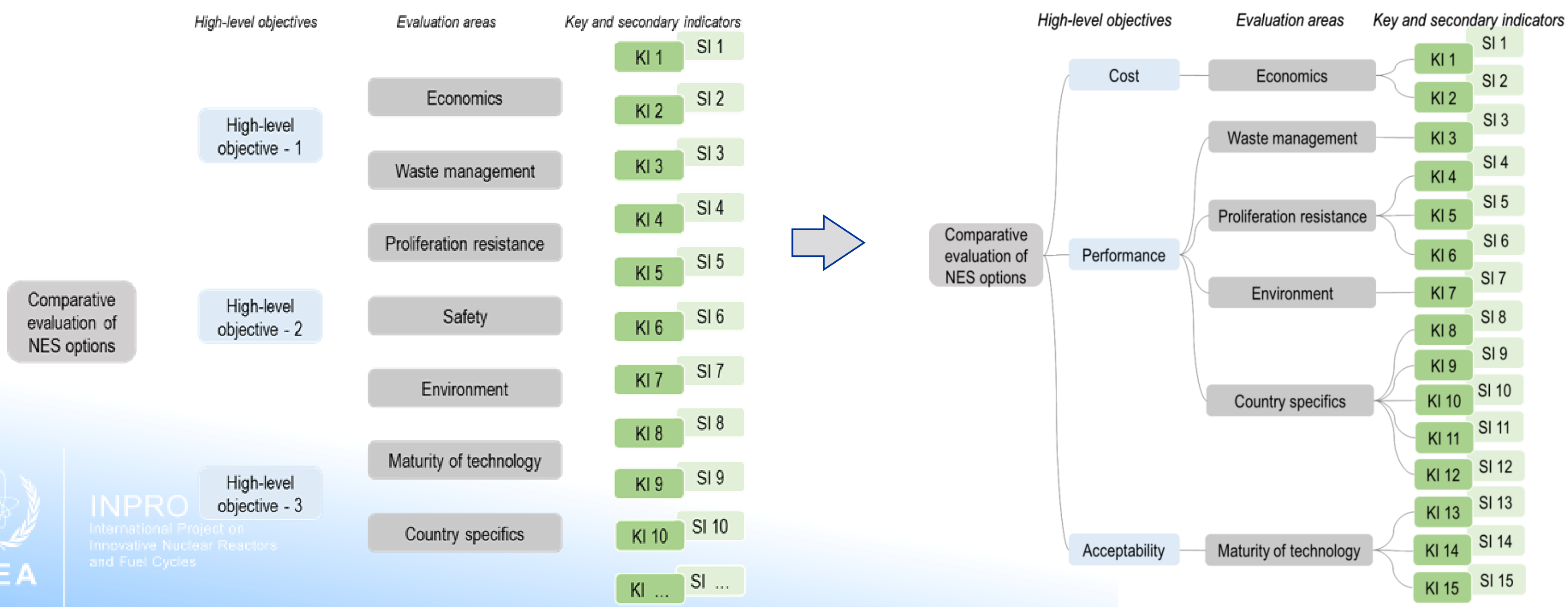


The type of multi-attribute value function widely applied in different studies:

$$u(x) = \sum_{i=1}^{n} k_i u_i(x_i) \qquad \sum_{i=1}^{n} k_i = 1$$

Objectives tree

- The objectives tree structure is selected taking into account the considerations of expertise organization simplification with respect to weighting factors assessment and ranking results interpretation.
- High-level evaluation might be simplified by focusing on a smaller number of the major objectives. It is practically reasonable to consider two or three objectives at the higher level.
- Aggregation of indicators in a limited number of groups allows a more understandable and meaningful interpretation of the NES ranking results and simplification of the procedure of weighting factors preparation.



Single-attribute value functions

Linear and exponential functions are used in KIND-ET:

- For the risk neutrality case, a linear form of a value function should be used.
- When value functions are to reflect risk attitudes, it is recommended to use exponential functions.

Type	Decreasing value functions	Increasing value functions
Linear	$V(x) = \dfrac{x^{max} - x}{x^{max} - x^{min}}$	$V(x) = \dfrac{x - x^{min}}{x^{max} - x^{min}}$
	Attitude to risk: risk neutral trend	
Exponential	$V(x) = \dfrac{1 - \exp\left(a \cdot \dfrac{x^{max} - x}{x^{max} - x^{min}}\right)}{1 - \exp(a)}$	$V(x) = \dfrac{1 - \exp\left(a \cdot \dfrac{x - x^{min}}{x^{max} - x^{min}}\right)}{1 - \exp(a)}$
	Attitude to risk: if a>0 – risk proneness trend (convex downward (concave upward) function) if a<0 – risk aversion trend (convex upward (concave downward) function)	
x^{max} and x^{min} are the minimal and maximal domain values of a single-attribute value function, which are reasonable to select as close to each other as reasonably possible to improve MAVT resolution		

Exponent power ***a*** is the ***risk proneness level***

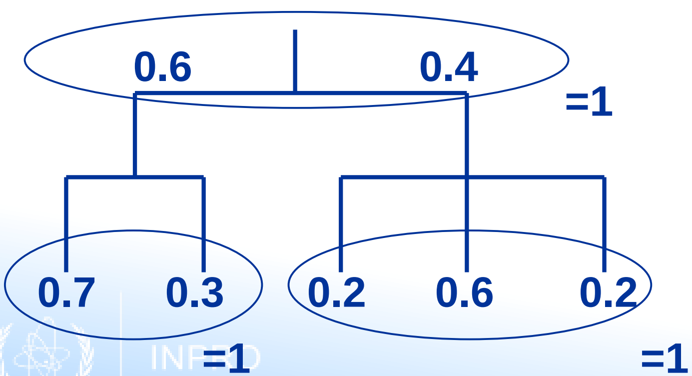
Weighting factors, weighting method

- When using MCDA methods, it is necessary to specify weights which reflect experts' preferences related to the KIs' relative importance/significance
- Weighting of indicators or areas is the responsibility of each Member State or other user and could be used to reflect the anticipated scale of national nuclear power deployment in a country as well as other considerations

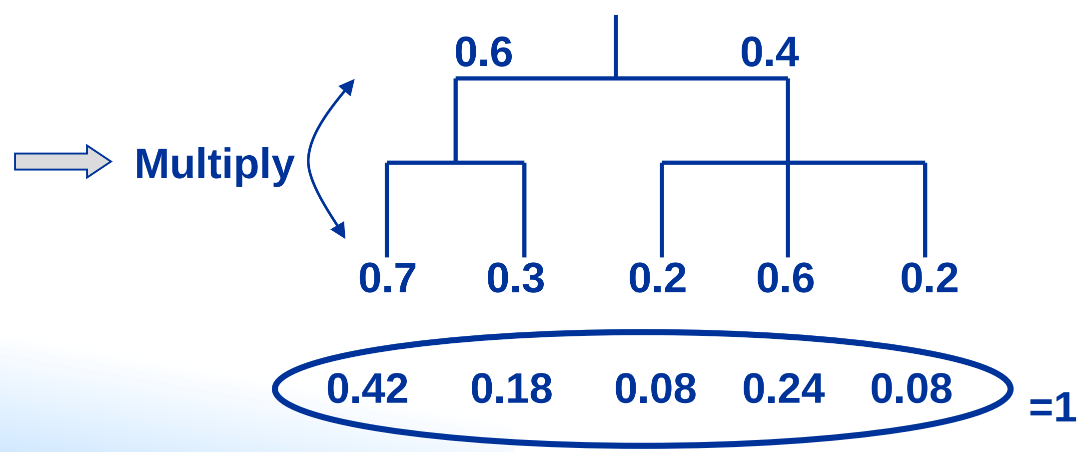
Weighting methods	Algorithm	Illustrations
Direct Method and Hierarchical Weighting	An expert has to specify the weights for each hierarchical level and multiply them downward to get the final lower level weights.	$\left(w_1, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1$

Hierarchical weighting assumes

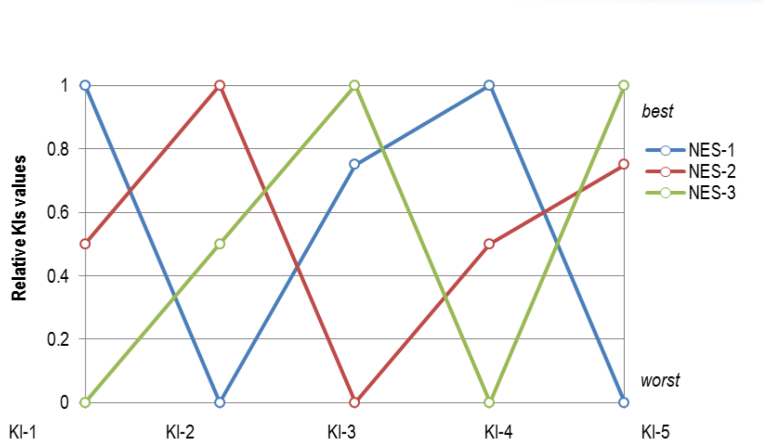
weights are defined for each hierarchical level...



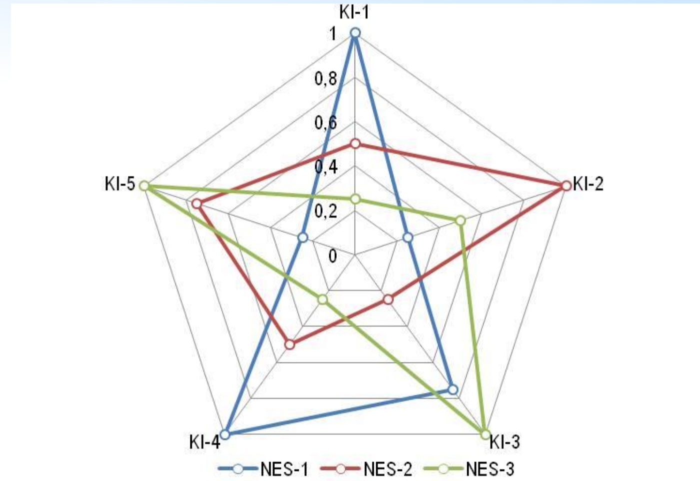
and multiplied down to get the final lower level weights.



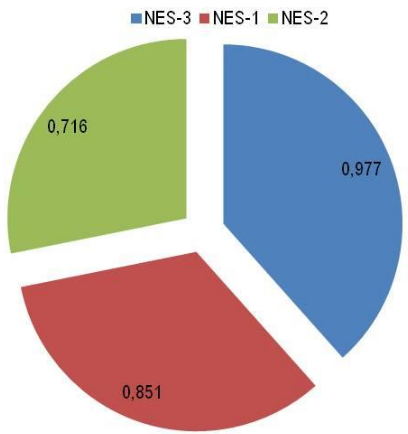
Ranking results



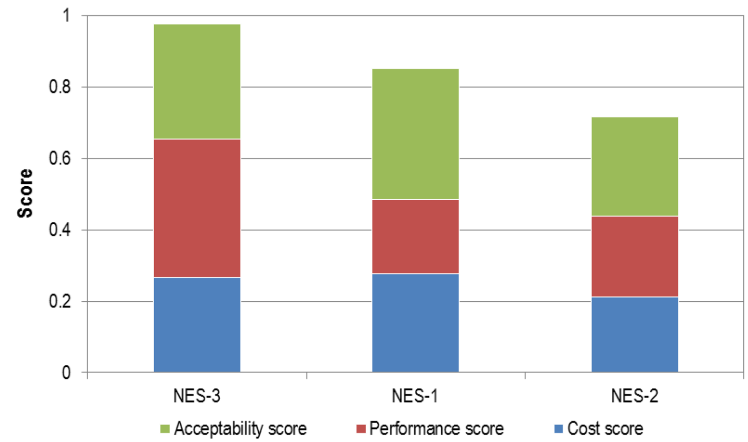
Value path



Radar chart



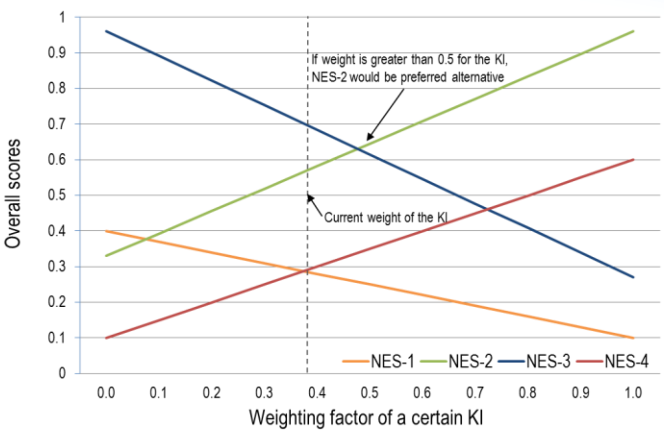
Pie chart



Bar chart

Sensitivity and uncertainty analysis

KIND-ET provides only basic necessary functionalities to perform a multi-criteria evaluation and sensitivity analysis. Users can apply KIND-ET extensions for an advanced uncertainty/sensitivity analysis in regard to weights, key indicators and single-attribute value functions.



Weights uncertainty/sensitivity analysis

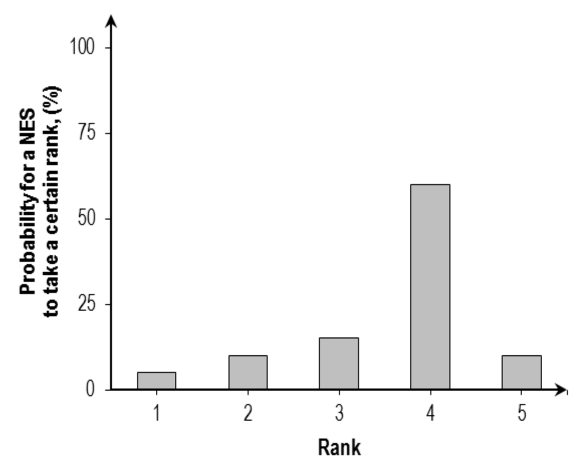
- Direct approach (KIND-ET)
- Linear weights approach (KIND-ET)
- Sampling-based uncertainty analysis (Overall Score Spread Builder, Ranks Mapping Tool)

S.-a. value function uncertainty/sensitivity analysis

- Direct approach (KIND-ET)
- Parametric sensitivity analysis (KIND-ET)
- Error analysis based uncertainty analysis (Uncertainty Propagator)

Key indicator uncertainty/sensitivity analysis

- Direct approach (KIND-ET)
- Error analysis based uncertainty analysis (Uncertainty Propagator)



Robustness analysis

- Benchmarking against other MCDA methods (AHP, TOPSIS, PROMETHEE, etc.)

KIND-ET - supporting tool for the INPRO/KIND approach

- **KIND-ET (KIND-Evaluation Tool)** is a MAVT based Excel-template developed for the NES multi-criteria comparative evaluation in accordance with the approach and recommendations elaborated in the KIND collaborative project.
- The following extensions expand the KIND-ET capability to perform advanced sensitivity/uncertainty analysis with respect to weights, key indicators and single-attribute value functions:
  - **Domination Identifier** – an analytical tool for identification of non-dominated and dominated options among the set of considered feasible options;
  - **Overall Score Spread Builder** – an express tool for evaluation of overall score spreads of an option caused by uncertainties in weighting factors and the objectives tree structure;
  - **Ranks Mapping Tool** – a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights.
  - **Uncertainty Propagator** – an instrument based on the traditional error analysis framework for evaluation of uncertainties in options' overall scores due to uncertainties in single-attribute value functions' forms and key indicators.
- These instruments are provided as separate Excel-based tools in separate files and may be used by experts independently or in any combinations to deepen the analysis/expertise and enhance the quality of presented results.

INPRO/KIND approach applications - Trial case studies

Comparative evaluation of hypothetical NESs

This case study was performed to demonstrate the procedure to perform a comparative evaluation of NESs and interpret the results

I. Comparative evaluation of 5 hypothetical NESs – testing the KIND approach and demonstrating the relevant comparative evaluation procedure

Assumptions: 3-level objectives tree, 15 KI and 15 SI, linear decreasing value functions

II. Comparative evaluation of 2 hypothetical NESs – demonstration of the specifics using different scoring scales and domains of a single-attribute value function

Assumptions: 3-level objectives tree, 19 KI, linear increasing value functions

Five NESs: performance table

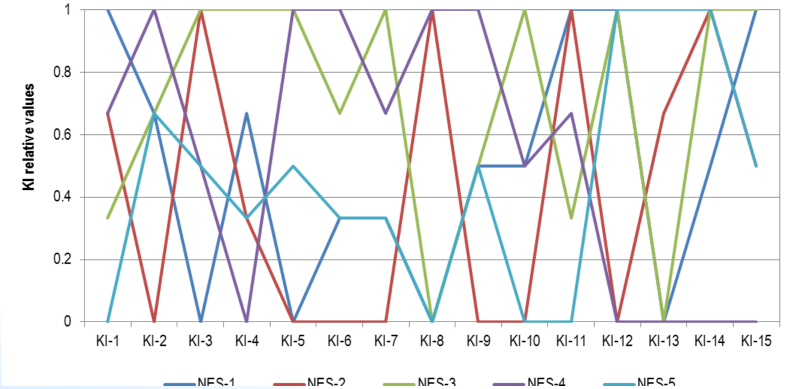
An indicator value with **score 1 is the best value**; an indicator value with **score 5 is the worst one**

Performance tables were formed randomly

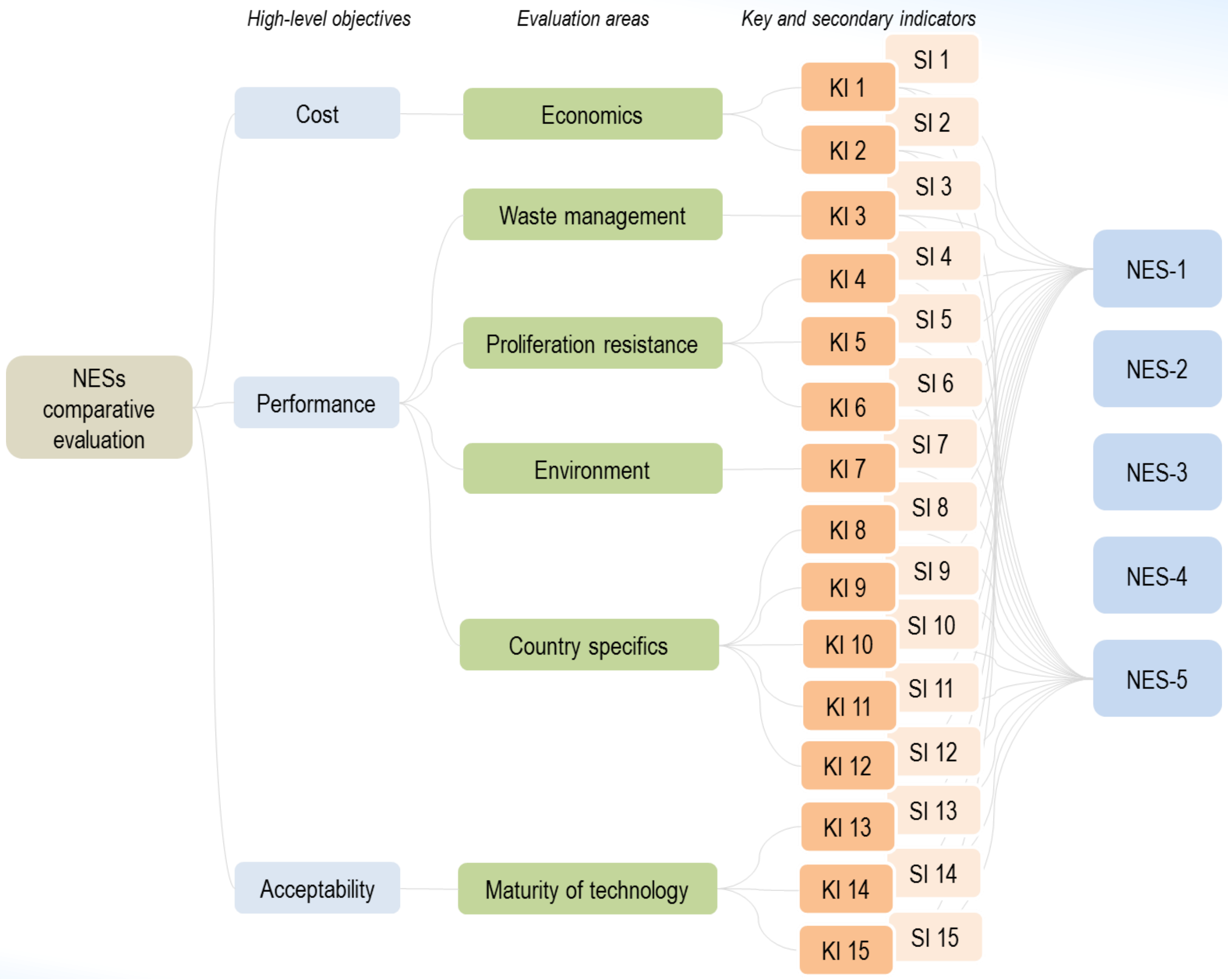
Model parameters were selected in line with the recommendations of the KIND project:

- 15 KIs were used
- The target was to minimize all KIs
- Linear decreasing functions defined on local domains were used as single-attribute value functions for the base case

KIs	#	NES-1	NES-2	NES-3	NES-4	NES-5
E.1	1	1	2	3	2	4
E.2	2	2	4	2	1	2
WM.1	3	5	1	1	3	3
PR.1	4	2	3	1	4	3
PR.2	5	5	5	3	3	4
PR.3	6	4	5	3	2	4
ENV.1	7	3	4	1	2	3
S.1	8	4	3	4	3	4
S.2	9	3	4	3	2	3
S.3	10	3	4	2	3	4
S.4	11	2	2	4	3	5
S.5	12	2	4	2	4	2
M.1	13	4	2	4	4	1
M.2	14	4	3	3	5	3
M.3	15	3	4	3	5	4



Five NESs: objectives tree



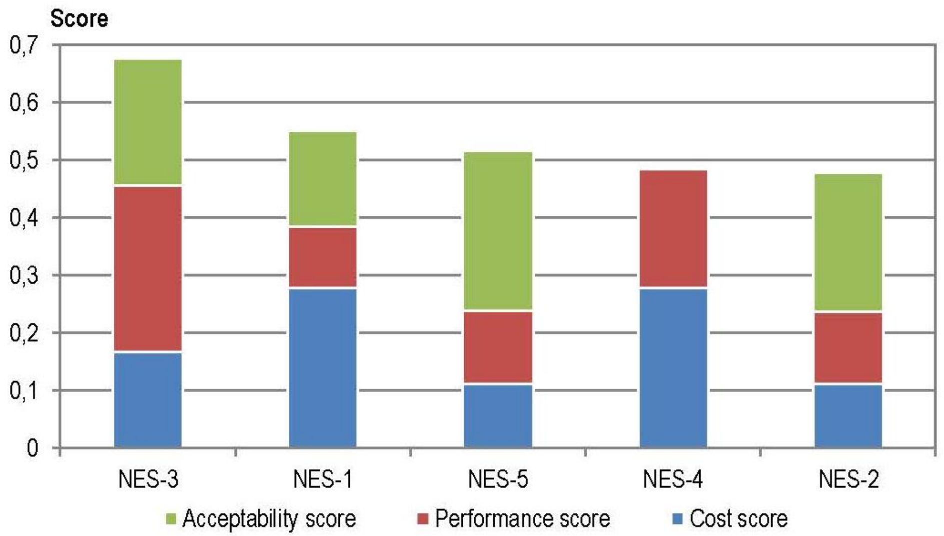
KIs	weights
E.1	0.167
E.2	0.167
WM.1	0.083
PR.1	0.028
PR.2	0.028
PR.3	0.028
ENV.1	0.083
S.1	0.017
S.2	0.017
S.3	0.017
S.4	0.017
S.5	0.017
M.1	0.111
M.2	0.111
M.3	0.111

Five NESs: ranking results

Overall score	NES-1	NES-2	NES-3	NES-4	NES-5
Multi-attribute value function	0.550	0.478	0.677	0.483	0.516

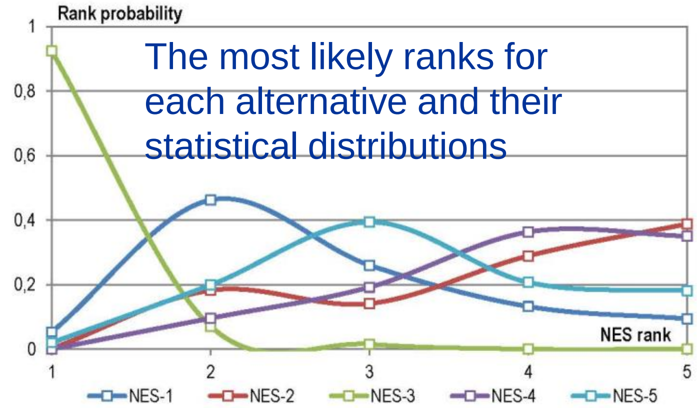
High-level objectives scores	NES-1	NES-2	NES-3	NES-4	NES-5
Cost	0.278	0.111	0.167	0.278	0.111
Performance	0.106	0.126	0.288	0.206	0.127
Acceptability	0.167	0.241	0.222	0.000	0.278

Areas' scores	NES-1	NES-2	NES-3	NES-4	NES-5
Economics	0.278	0.111	0.167	0.278	0.111
Waste management	0.000	0.083	0.083	0.042	0.042
Proliferation resistance	0.028	0.009	0.074	0.056	0.032
Environment	0.028	0.000	0.083	0.056	0.028
Country specifics	0.050	0.033	0.047	0.053	0.025
Maturity of technology	0.167	0.241	0.222	0.000	0.278



Five NESs: sensitivity analysis

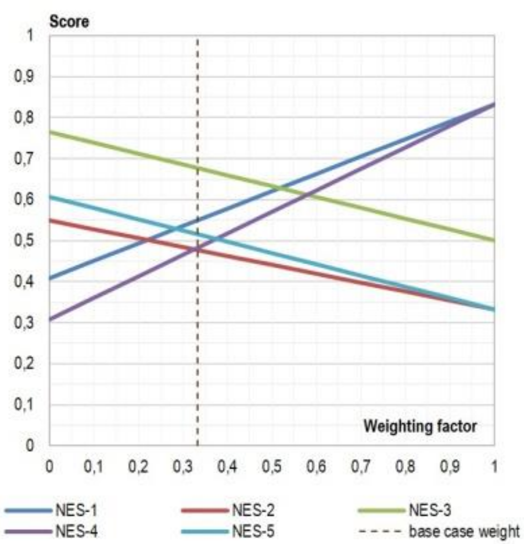
Impact of single-attribute value function shape on ranking



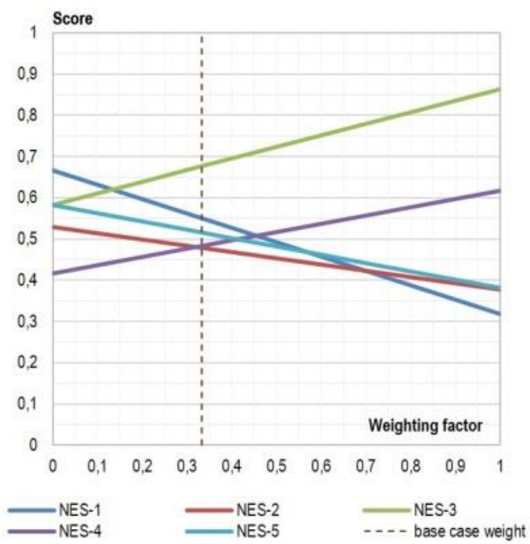
- To demonstrate sensitivity of the ranking results to the form of single-attribute value functions, a special statistical analysis was carried out using randomly chosen generation of single-attribute value functions and building a statistical ranks distribution of each considered alternative.

Linear weights approach to weights sensitivity analysis

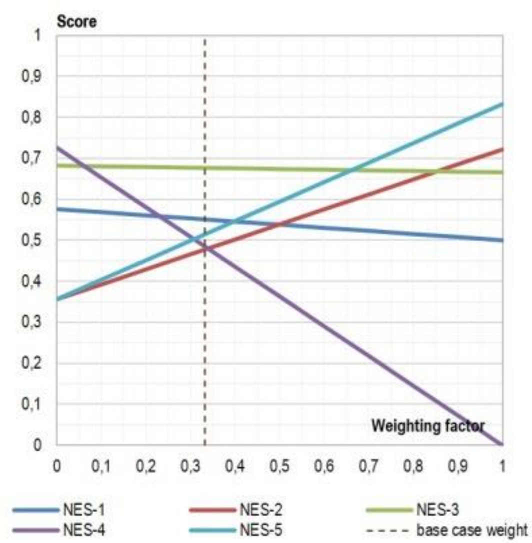
‘Cost’ weight



‘Performance’ weight

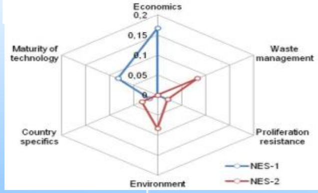


‘Acceptability’ weight



Two NESs: performance table

High-level objectives	Area	KI abbr,	Qualitative evaluation		2-point scoring scale		10-point scoring scale	
			NES-1	NES-2	NES-1	NES-2	NES-1	NES-2
Cost	Economics	E.1	x		1	0	9	1
		E.2	~	~	0	0	6	5
Performance	Waste management	WM.1		x	0	1	2	9
		WM.2		x	0	1	1	10
		WM.3		x	0	1	2	10
	Proliferation resistance	PR.1	x		1	0	10	2
		PR.2		x	0	1	1	10
		PR.3	~	~	0	0	2	3
		PR.4	~	~	0	0	4	3
	Environment	ENV.1		x	0	1	1	9
	Country specifics	CS.1	~	~	0	0	8	7
		CS.2	~	~	0	0	7	6
		CS.3	x		1	0	10	1
		CS.4		x	0	1	1	10
		CS.5		x	0	1	2	9
Acceptability	Maturity of technology	M.1	~	~	0	0	6	5
		M.2	~	~	0	0	0	0
		M.3	~	~	0	0	2	3
		M.4	x		1	0	9	2

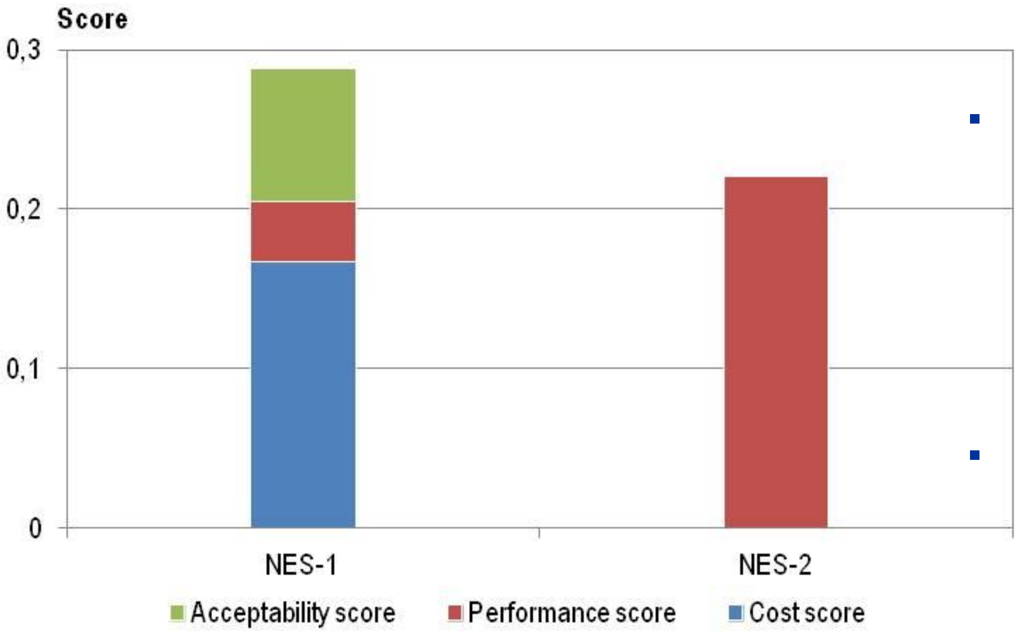


x – a pointer for the NES which provides the best performance on a corresponding KI
~ – a pointer of a KI on which both NESs have comparable performance

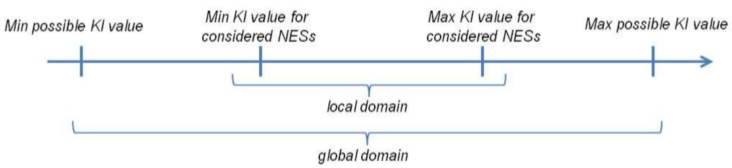
Two NESs: ranking results

NES options	Overall scores			
	2-point scoring scale		10-point scoring scale	
	Local domains	Global domains	Local domains	Global domains
NES-1	0.288	0.288	0.592	0.440
NES-2	0.221	0.221	0.325	0.368
Δ (NES-1 — NES-2)	0.067	0.067	0.267	0.072

Ranking results for 2-point scoring scale



- When two NESs are compared with local domains, the ranking results are not sensitive to the form of single-attribute value functions
- The same is true for global domains of single-attribute value functions within a 2-point scoring scale

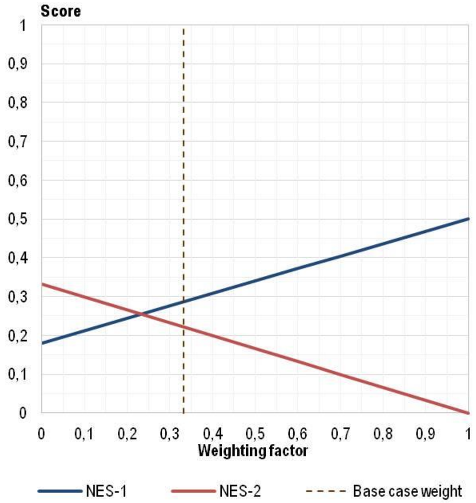


- If global domains and a 10-point scoring scale are used, the probability that the first alternative would have the first and second ranks would be equal to 77% and 23%, respectively

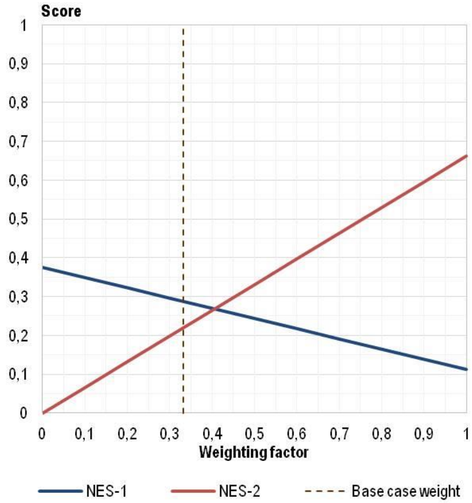
Two NESs: sensitivity analysis

Linear weights approach to weights sensitivity analysis

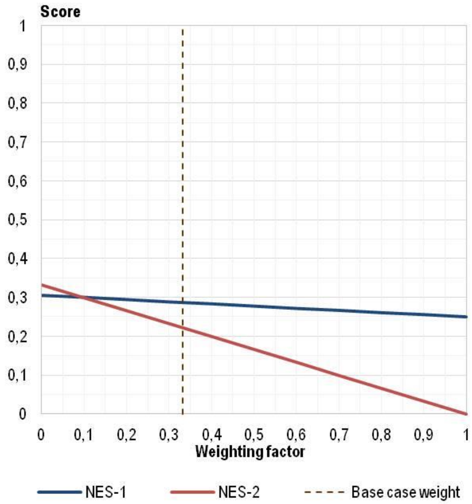
‘Cost’ weight



‘Performance’ weight



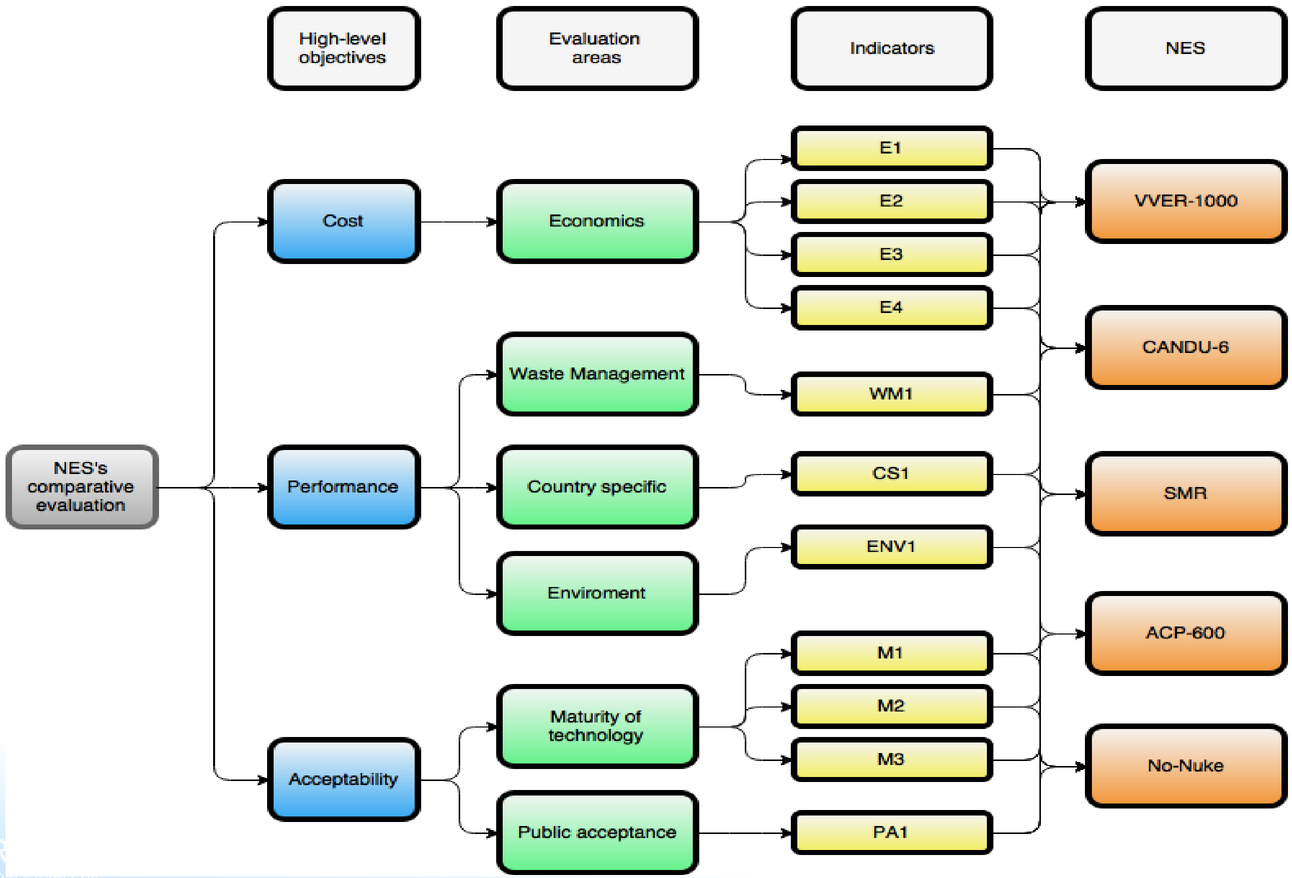
‘Acceptability’ weight



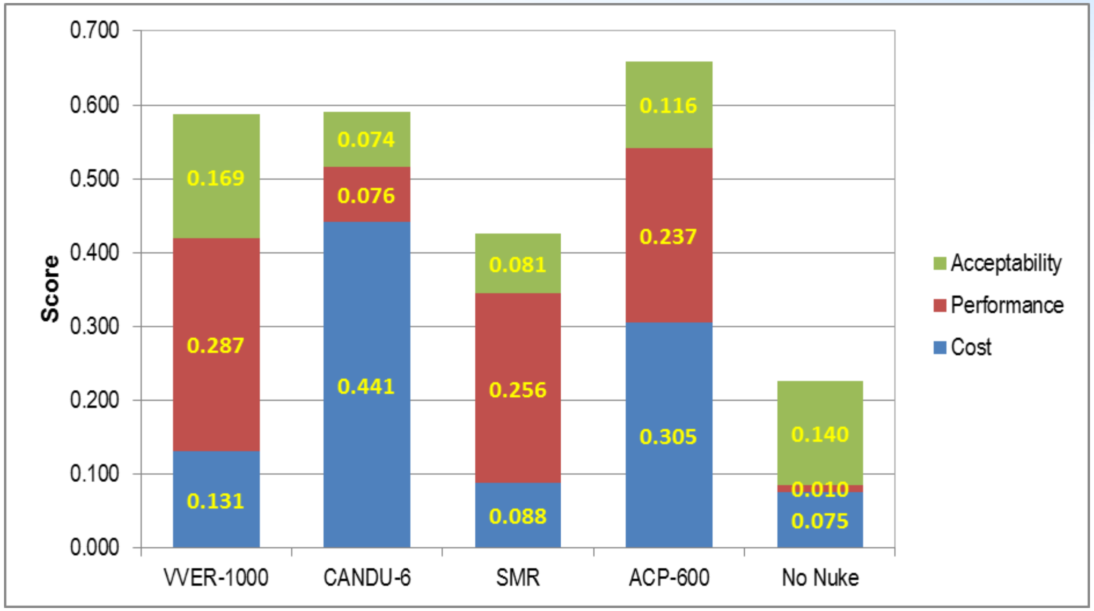
Case study from Armenia (1)

The overall objective was to select the most attractive nuclear option for Armenia. Nuclear (with WWER-1000, CANDU-6, SMR of 360 MW(e) and ACP-600) and thermal generation expansion plans have been evaluated in this study.

The structure of the objectives tree in the Armenian case study



Case study from Armenia (2)



‘Cost’ : 0.5
‘Performance’: 0.3
‘Acceptability’: 0.2

The most attractive alternative for implementation in Armenia is the medium sized reactor ACP-600 with an overall score of 0.658. The differences in alternatives CANDU-6 and WWER-1000 can be considered as indistinguishable according to the scores of multi-attribute value functions; these options take the second and third places, respectively. The worst case for energy system development is No Nuke scenario, which has significantly low ranking value (0.225).

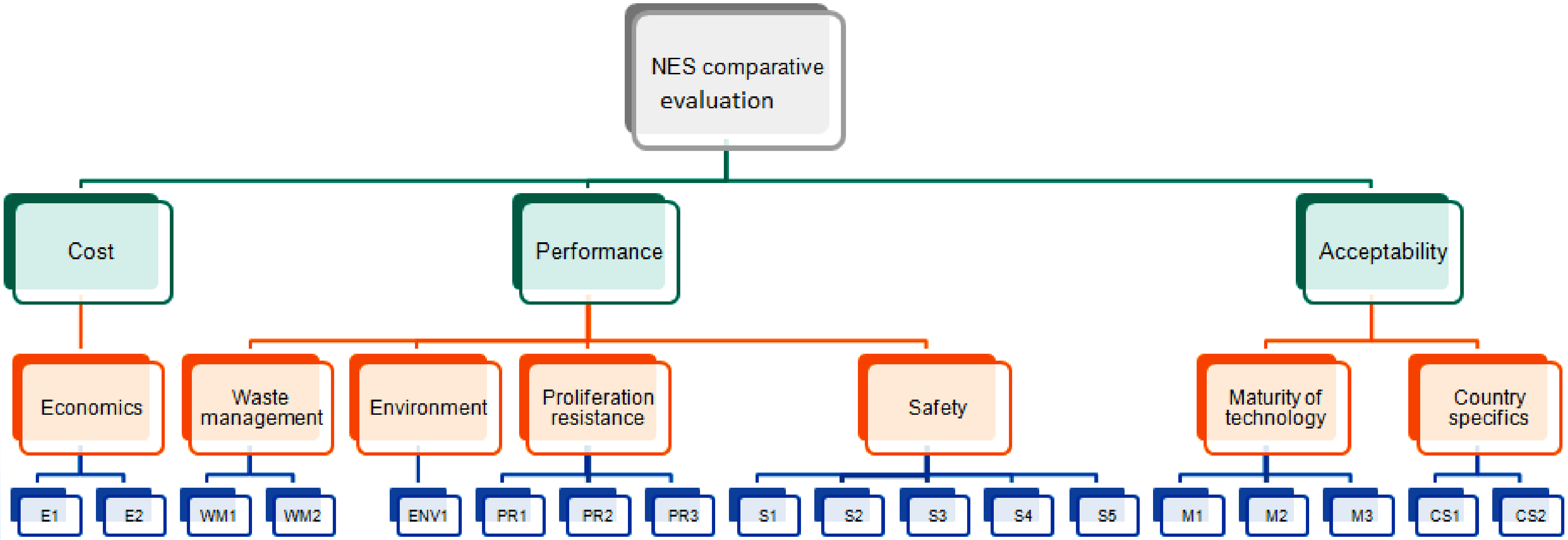
For ranking results interpretation, it is necessary to decompose multi-attribute value functions into individual components in accordance with the specified structure of objectives tree. CANDU-6 has the best rank for Cost (0.441) followed by ACP-600 (0.305). At the same time, CANDU-6 has the lowest rank of Performance and Acceptability in nuclear options, whereas WWER-1000 takes the best rank.

Case study from Romania (1)

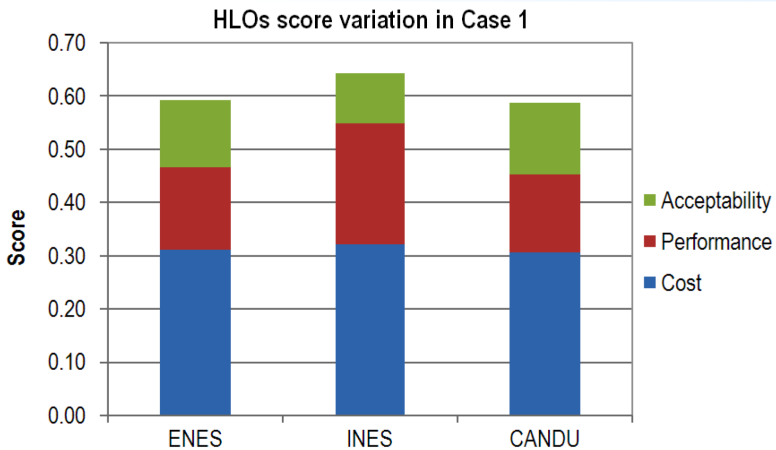
The study performed by the expert team from Romania addressed the following specific objectives:

- To evaluate ENES (HWR) and INES (LFR) together with the already existing/operating NES technology (CANDU 6), based on specific key indicators (key indicators developed under the framework of the KIND project) and taking into consideration the country specifics;
- To examine the robustness of the obtained results by performing sensitivity analysis.

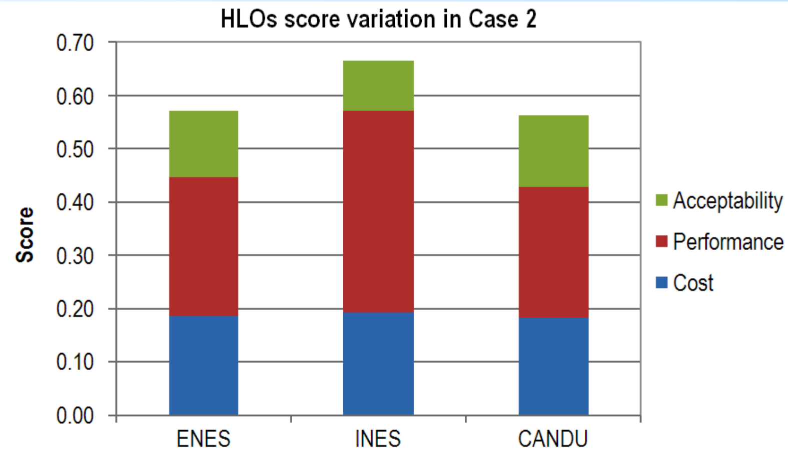
The structure of the objectives tree in the case study from Romania



Case study from Romania (2)



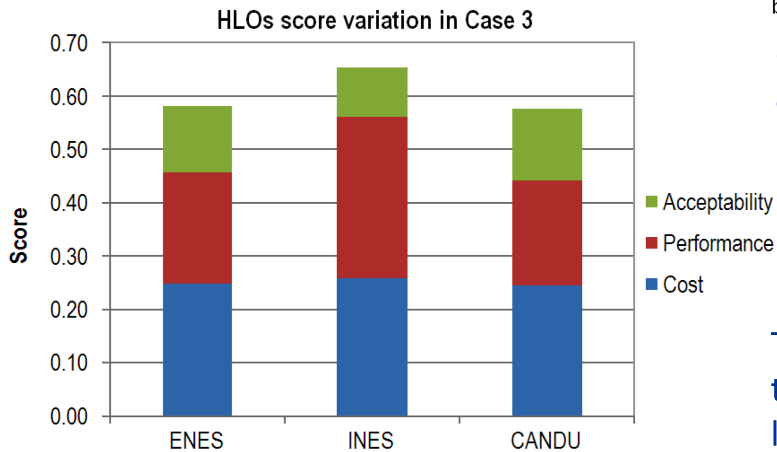
a)



b)

Case1 — ratings for HLOs: cost 50%, performance 30%, acceptability 20%

Case2 – ratings for HLOs: cost 30%, performance 50%, acceptability 20%



c)

Innovative NES technology appears to be more attractive than the evolutionary NES technology.

The CANDU NES technology has the lowest overall scores

Case3 – ratings for HLOs: cost 40%, performance 40%, acceptability 20%

Parameter	CANDU	ENES	INES
Reactor type	HWR	HWR	LFR
Fuel type	Natural UO_2	Slightly enriched UO_2	MOX

Case study from Thailand (1)

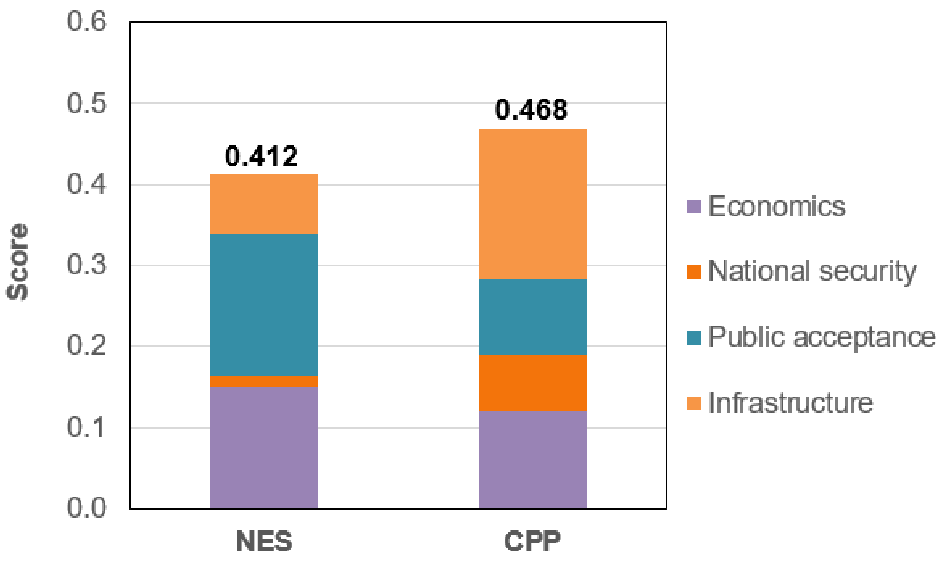
The objective of the study was to apply a set of KIs (tailored to address the needs of newcomer countries) for comparative evaluation of NES and a non-nuclear energy system (non-NES). The KI set enveloped the four areas: economics, national security, public acceptance and infrastructure.

The structure of the objectives tree in the Thailand case study

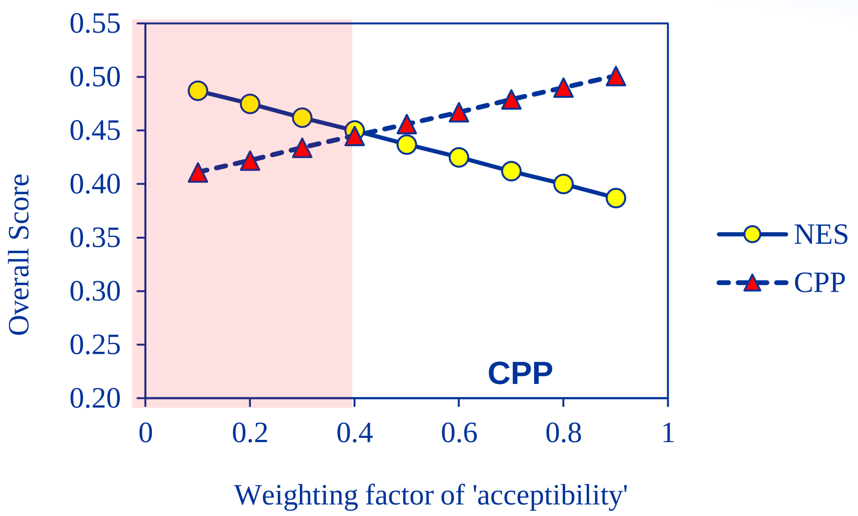
Area title	Key indicator
Economics	Levelized unit electricity cost (LUEC)
	Cash flow
National security	Degree of dependence on supplier(s)
Public acceptance	Survey of public acceptance
	External cost
	Risk of accident
Infrastructure	Status of legal framework
	Status of State organizations
	Availability of infrastructure to support owner/operator
	Government policy
	Availability of human resources

Case study from Thailand (2): ranking results

Structure of area scores for NES and CPP for Option 1



Results of sensitivity analysis



For a case when NES is less attractive than coal power plant (CPP) the ratio of the HLO weighting factors ‘Economics’ to ‘Acceptability’ was 0.3/0.7

The sensitivity analysis was performed by varying the ratio of the high-level objective weighing factors while fixing the weighting factors of the evaluation areas and the indicators

IAEA
International Atomic Energy Agency

Thank you!

IAEA
INPRO
International Project on
Innovative Nuclear Reactors
and Fuel Cycles

IAEA
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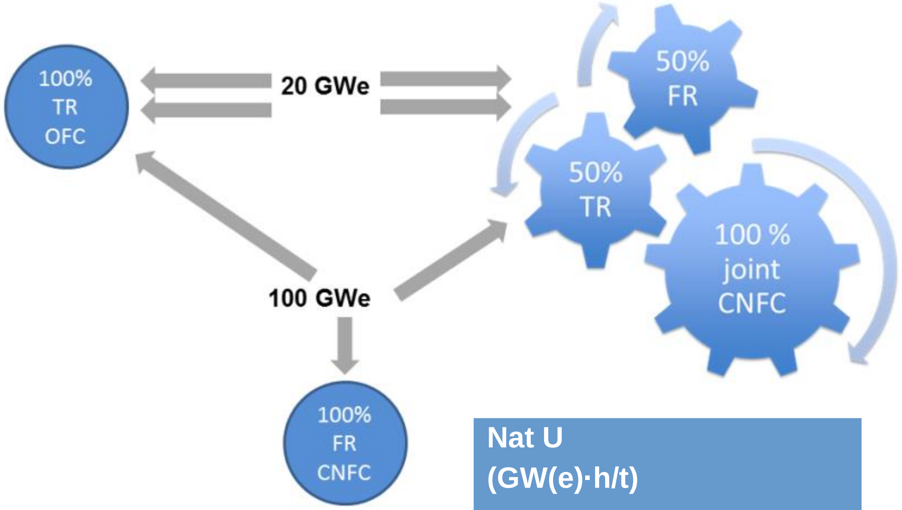
Back-up viewgraphs

Case studies from Russia (1)

Two case studies have been performed by Russian experts under the KIND project on comparison of NESs based thermal and fast reactors with closed nuclear fuel cycle.

The following types of reactors were considered in the case study:
Thermal reactor (TR) technologies TR1, TR2 and TR3 have the same technical features regarding natural uranium consumption and spent fuel generation, but different levelized unit fuel cost in the fuel cycle back end.

There are two types of fast reactor (FR) technologies under consideration in the current study. The first fast reactor FR1 is considered as near term deployable reactor. As this technology is new, LUEC is higher than for TR. The fast reactor FR2 is a conceptual project with improved safety by design and more attractive LUEC. FR1 consumes MOX-fuel; FR2, depending on the system under consideration, consumes MOX or enriched uranium fuel.



Nat U (GW(e)·h/t)

LUEC (US $/MW(e)·h)

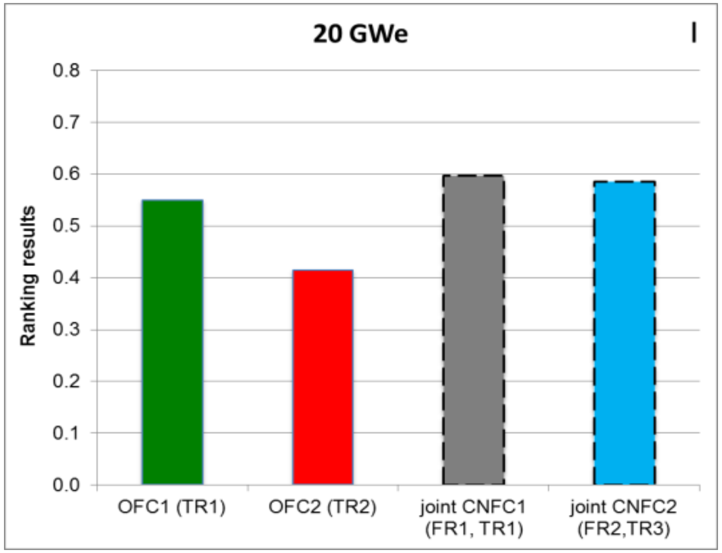
Wastes (t/TW(e)·h)

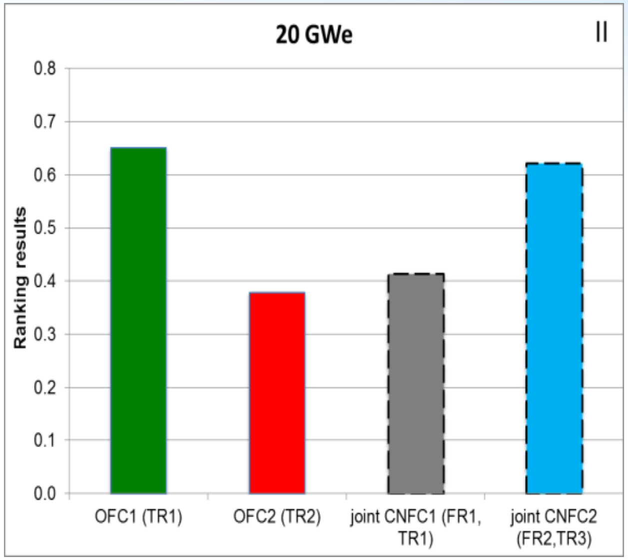
TtMature (years)

R&D refund (billion US $)

Case studies from Russia: ranking results

Ranking results for different weighting options





KI Final weight	1 Nat. U	2 LUEC	3 Wastes	4 TtMature	5 R&D refund
Option I	0.15	0.25	0.3	0.25	0.05
Option II	0.15	0.5	0.2	0.1	0.05

Option I focuses on ‘Wastes’ key indicator. In this case, the potential of OFC1(TR1) will be lower than that of the joint CNFC1 (FR1, TR1). This result indicates that an acceptable solution to the problem can be found in the fuel cycle back end in case of cooperation among the technology holder and the technology user countries. Option II allows to postpone decisions regarding the final stages of the NFC, such as long term interim storage of SNF. An open NFC 1 based on thermal reactors TR1 (OFC1(TR1)) acquires the highest score/potential with the value 0.65. This is an option where the best cost makes the best alternative.

Conclusion

- The INPRO collaborative project “Key indicators for innovative nuclear energy systems” (KIND) has developed an approach for comparative evaluation of NES/ scenario options.
- The approach is based on the application of a set of selected key indicators, reflecting upon certain subject areas of the INPRO methodology, and a selected verified judgment aggregation/ uncertainty analysis methods.
- The developed approach is recommended for establishing a productive dialogue between energy-option proponents and decision makers regarding sustainable nuclear energy options.
- The KIND-ET excel-tool is based on the MAVT method and adapted for performing the comparative evaluation of NES options in accordance with the KIND approach and recommendations. KIND-ET extensions make it possible to expand the KIND-ET capability to assist experts facing difficulties with evaluations of weighting factors.
- KIND-ET and its extensions can help identify merits and demerits of the NES options being compared at the technological and scenario levels under different circumstances/perspectives and evaluate their overall ranks taking into account NESs' performance, along with experts' and decision makers' judgments and preferences.