Paper

Examples of Objectified Multiple Criteria Ranking in the Selection of Infrastructural Projects

Edward Klimasara and Andrzej P. Wierzbicki

The National Institute of Telecommunications, Warsaw, Poland

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Abstract—The paper addresses the issue of multiple criteria rankings of infrastructural projects (buildings, roads, etc.). Although the amount of literature devoted to this subject is considerable, all methods proposed produce subjective rankings, dependent on a direct or indirect definition of weighting coefficients applicable to subsequent evaluation criteria. Infrastructural projects are usually selected and approved collegially, however, by a group of decision makers with preferences that may potentially differ significantly. Therefore, an objectified ranking, independent from subjectively defined weighting coefficients, is needed for infrastructural projects. Such a ranking is proposed, analyzed and applied by the authors of this paper. This ranking depends originally only on the multiple objective evaluation data, i.e. the values of evaluation criteria related to decision scenarios or alternatives. Such an approach does not render a fully objective ranking, since one of this kind does not exist at all. Even the choice of the ranking method is a subjective decision, but it is objectified to the extent possible. The paper presents several examples of multiple criteria evaluation of infrastructural projects, derived from literature, and compares subjective rankings published in literature with objectified rankings that are independent of weighting coefficients.

Keywords—multiple criteria rankings, objectified multiple criteria ranking, objectified ranking method, subjective rankings.

1. Introduction – Korhonen Paradox

We show, first, that a linear aggregation of criteria values leads essentially to wrong results, thus such methods as the Analytic Hierarchy Process (AHP) [1], [2] should never be applied in serious problems. This results from the Korhonen paradox [3]: a young man considers three candidates for marriage, evaluated based on such criteria as "intelligence"[1] and "sex appeal". The first candidate received 10 points for sex appeal and 0 points for intelligence. The second one is evaluated at 0 points for sex appeal and 10 points for intelligence. The third one is evaluated at 5 points for sex appeal and 4 points for intelligence.

[1]Pekka Korhonen used here the "ability to cook" criterion, but we changed its name to "intelligence", since we do not wish to be accused of sexism.

Actually, any evaluation that is inside the convex cover of two first evaluations can be used. The paradox is that *when applying linear aggregation of criteria, one of the first two points would be selected only – never the third one*. This is illustrated in Fig. 1, where in addition to the linear criteria

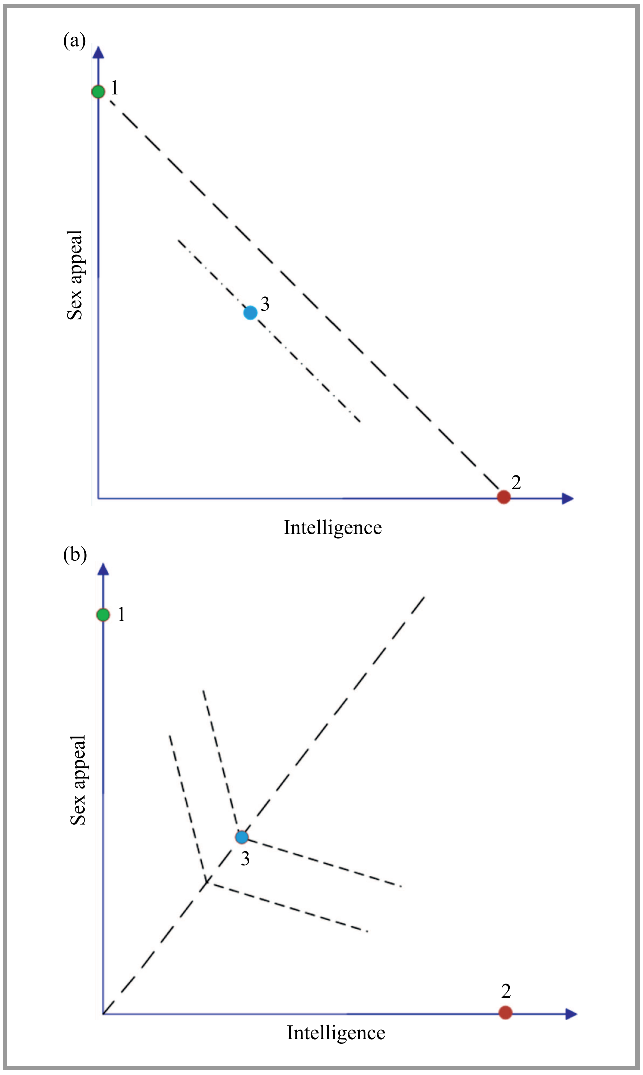

Fig. 1. Graphical illustration of the Korhonen paradox and the manner of overcoming it: (a) linear aggregation of criteria, (b) nonlinear aggregation of criteria.

aggregation method, its nonlinear counterpart is presented as well (as defined in one of following sections).

Pekka Korhonen, the then chairman of the international society of multiple criteria analysis, presented this paradox to show the inadequacy of methods relying on linear aggregation of criteria, in particular the AHP method. But in literature concerned with evaluation of infrastructural projects, no awareness of this difficulty is evident, and the AHP method is widely used.

2. Collegial Selection and Objectified Ranking

Another serious problem is the fact that infrastructural projects are usually evaluated collegially – by groups of decision makers usually representing quite varied and different preferences. Therefore, it is wrong to ask them at the beginning of the evaluation, as required by the AHP method, to define relative importance of subsequent criteria. They much more prefer to be presented a ranking – a list of preferred projects possibly with an objective justification of their selection – that they can later discuss and evaluate.

In fact, the method of objectified ranking was devised precisely because of this particular reason. At a Japanese research institute (actually, a university offering doctoral studies only), a questionnaire concerning diverse aspects of creative work and study organization was filled out by the majority of students, see [4]. The question was which aspects are most important and the dean supervising this event – a specialist in multiple criteria decision making himself – refused to specify any weighting coefficients or aspiration levels, because he wanted to present, to fellow professors, results that were as objective as possible. Therefore, we observed that the data from the questionnaire – the values of criteria related to subsequent issues – suffice to define a nonlinear achievement function that can be used to rank these issues.

Specifically, we assume that we have a decision problem with K criteria, indexed by $k = 1,\ldots,K$ (also denoted by $k \in \mathbf{K}$), and J decision options also referred to as alternatives or variants, indexed by $j = 1,\ldots,J$ or $j = A,B,\ldots,J$ (also denoted by $j \in \mathbf{J} = \{1,\ldots,J\}$). The corresponding criteria values are denoted by q_{kj}. We assume that all are maximized or converted to maximized variables. The maximal values $\max_{j\in J} q_{kj} = q_k^{\mathrm{up}}$ are called upper bounds for criteria and are often equivalent to the components of the so called ideal or utopia point $\mathbf{q}^{\mathrm{uto}} = \mathbf{q}^{\mathrm{up}} = (q_1^{\mathrm{up}},\ldots,q_k^{\mathrm{up}},\ldots,q_K^{\mathrm{up}})$ – except for cases when they were established a priori as a measurement scale. The minimal values $\min_{j\in J} q_{kj} = q_k^{\mathrm{lo}}$ are called lower bounds and, generally, are not equivalent to the components of the so called nadir point $\mathbf{q}^{\mathrm{nad}} \geq \mathbf{q}^{\mathrm{lo}} = (q_1^{\mathrm{lo}},\ldots q_k^{\mathrm{lo}},\ldots q_K^{\mathrm{lo}})$; the nadir point qnad is defined similarly as the lower bound point $\mathbf{q}^{\mathrm{lo}}$, but with minimization restricted to Pareto optimal or efficient or nondominated alternatives. We recall that an alternative $j^* \in \mathbf{J}$ is Pareto optimal (Pareto-nondominated or shortly nondominated, also called efficient), if there is no other alternative $j \in \mathbf{J}$ that dominates j^*, that is, if we denote $\mathbf{q}_j = (q_{1j},\ldots,q_{kj},\ldots q_{Kj})$, there is no $j \in \mathbf{J}$ such that $\mathbf{q}_j \geq \mathbf{q}_{j^*}, \mathbf{q}_j \neq \mathbf{q}_{j^*}$.

In the objectified ranking method, see [5], [6] for more details, reference point approach is used while aspiration and reservation levels a_k and r_k are determined by the following equation. The assumption is made that the corresponding criterion k is maximized. If it is minimized, we just reverse the places of aspiration and reservation levels:

$$\begin{aligned} m_k &= \sum_{j\in\mathbf{J}} \frac{q_{jk}}{J}, \\ r_k &= 0.5(q_k^{\mathrm{lo}} + m_k), \\ a_k &= 0.5(q_k^{\mathrm{up}} + m_k),\ k = 1,\ldots,K. \end{aligned} \quad (1)$$

After determining these reference levels for all criteria, values of partial achievement functions for a given criterion and variant are determined as follows. For maximized criteria:

$$\sigma_{kj}(q_{kj},a_k,r_k) = \begin{cases} \frac{\alpha(q_{kj}-q_k^{\mathrm{lo}})}{r_k-q_k^{\mathrm{lo}}} & \text{for } q_k^{\mathrm{lo}} \leq q_{kj} \leq r_k \\ \alpha + \frac{(\beta-\alpha)(q_{kj}-r_k)}{a_k-r_k} & \text{for } r_k < q_{kj} \leq a_k \\ \beta + \frac{(10-\beta)(q_{kj}-a_k)}{q_k^{\mathrm{up}}-a_k} & \text{for } a_k < q_{kj} \leq q_k^{\mathrm{up}} \end{cases}, \quad (2)$$

where $0 < \alpha < \beta < 10$, α is a parameter denoting the value of the partial achievement function for $q_{kj} = r_k$, and β is a parameter denoting the value of the partial achievement function for $q_{kj} = a_k$. For minimized criteria (where the roles of r_k and a_k are exchanged):

$$\sigma_{kj}(q_{kj},a_k,r_k) = \begin{cases} \beta + \frac{(10-\beta)(a_k-q_{kj})}{a_k-q_k^{\mathrm{lo}}} & \text{for } q_k^{\mathrm{lo}} \leq q_{kj} \leq a_k \\ \alpha + \frac{(\beta-\alpha)(r_k-q_{kj})}{r_k-a_k} & \text{for } a_k < q_{kj} \leq r_k \\ \frac{\alpha(q_k^{\mathrm{up}}-q_{kj})}{q_k^{\mathrm{up}}-a_k} & \text{for } r_k < q_{kj} \leq q_k^{\mathrm{up}} \end{cases}. \quad (3)$$

The overall achievement function for the alternative k, whose values are used to determine objectified ranking lists, is computed on the basis of partial achievement functions, as:

$$\begin{aligned} \sigma(\mathbf{q}_j,\mathbf{a},\mathbf{r}) = &\min_{k\in\mathbf{K}} \sigma_{kj}(q_{kj},a_k,r_k) \\ &+ \frac{\varepsilon}{J}\sum_{k\in\mathbf{K}} \sigma_{kj}(q_{kj},a_k,r_k),\ j = 1,\ldots,J, \end{aligned} \quad (4)$$

where ε is a small parameter (e.g. $\varepsilon = \frac{0.1}{J}$). The ranking obtained on the basis of values $\sigma(\mathbf{q}_j,\mathbf{a},\mathbf{r})$ for consequent variants $j \in \mathbf{J}$ is referred to as objective or objectified, rather, since it is based only on the data of the problem (the values of q_{kj} for $j \in \mathbf{J}$ and $k \in \mathbf{K}$). Such a ranking

Table 1
Data for calculations

Criterion number	Criterion	Variants				
		S	T	Z	U	P
1	PM [m^2]	2826	2920	2689.1	2689.1	3044
2	PZ	3.71	4.07	3.43	3.43	3.78
3	LM	60	78	67	62	78
4	KR [PLN·1000]	7714	8450	7350	7430	8490
5	CR [months]	12	18	14	15	11
6	PU	1	1	0.8	0.4	0.8
7	EE	1	0.6	0.8	1	1
8	DT	0.6	1	0.4	0.8	0.2

can also be subjectified, but in collegial decision making it is always better to start by presenting the group of decision makers with the objectified ranking first, before asking them whether they would also like to take into account the importance of criteria. This is because it happens very seldom that all decision makers agree on the importance of criteria and a specially devised voting procedure is necessary to achieve a consensus in this respect. However, if the group of decision makers agrees to subdivide the criteria into two sets $\mathbf{K}_1 \cup \mathbf{K}_2 = \mathbf{K}$ ($\mathbf{K}_1$ more important, $\mathbf{K}_2$ less important), then by assuming weighting coefficients $\alpha_1 > \alpha_2$ (e.g. $\alpha_1 = 1$, $\alpha_2 = 0.1$) for these two subsets of criteria we can modify Eq. (4), e.g. to the following form:

$$\sigma(\mathbf{q}_j, \mathbf{a}, \mathbf{r}) = \alpha_1 \min_{k \in \mathbf{K}_1} \sigma_{kj}(q_{kj}, a_k, r_k) + \alpha_2 \min_{k \in \mathbf{K}_2} \sigma_{kj}(q_{kj}, a_k, r_k) + \frac{\varepsilon}{J} \sum_{k \in \mathbf{K}} \sigma_{kj}(q_{kj}, a_k, r_k),\ j = 1, \ldots, J. \quad (5)$$

In the following text, we apply the objectified ranking method to several examples of multiple criteria ranking of infrastructural projects found in literature, compare it with subjective ranking presented in literature and with a subjectification of the objectified ranking.

3. Example Case

We use the case published in [7], concerning the investors selection of the best architectural and technological variant of a multi-apartment residential building. The following variants of architectural, technological and material solutions are considered:

- S – four buildings with a single staircase, four storeys and a steel frame,
- T – four buildings with two segments each, built with the use of traditional technology,
- Z – one building of four segments with a monolith reinforced concrete constructure,
- U – one building with four segments and four storeys, traditional technology,
- P – one building with four segments and four storeys, new raised decking technology.

These variants are evaluated according to the following criteria:

- PM – living space (max),
- PZ – utilization of building space (max),
- LM – number of apartments (max),
- KR – full cost of realization (min),
- CR – planned realization time (min),
- PU – urban planning compliance (max),
- EE – esthetics of façade (max),
- DT – availability of technology (max).

The evaluation of criteria for subsequent variants, given in [7], is contained in Table 1 (source: Table 10.75 in [7]). When we apply the objectified ranking method, i.e. Eqs. (1)–(4) with $\alpha = 3$, $\beta = 7$, $\frac{\varepsilon}{J} = 0.1$, we obtain the following values of the overall achievement function, see Table 2.

Table 2
Values of achievement function for Table 1 data

Variants				
1 – S	2 – T	3 – Z	4 – U	5 – P
0.97396	0.93426	0.64526	0.63164	1.02908

Table 3
Data for calculations

Criterion no.	Criterion	Variants		
		1	2	3
Transport				
1	Length of road [km]	3.88	3.82	4.794
2	Number of junctions	1	1	2
Environmental				
3	Interference with "Nature 2000" area [ha]	8.1	2.1	1.9
4	Length of route leading through a forest [km]	2.5	1	2.1
Economic				
5	Construction cost [millions of PLN]	104.76	103.14	129.44
6	Economic net present value [millions of PLN]	32.4	27.5	19.5
Social				
7	Number of houses to demolish	6	18	4
8	Number of people exposed to excessive noise	45	120	20

Thus, the ranking list based on the objectified method is:

$$5-\text{P} \blacktriangleright 1-\text{S} \blacktriangleright 2-\text{T} \blacktriangleright 3-\text{Z} \blacktriangleright 4-\text{U}, \qquad (6)$$

where ► denotes *is better than*. In [7], five different subjective ranking methods are used, each resulting in a variant of the ranking list ([7], Table 10.90):

AHP/ANP add.: 5 – P ► 2 – T ► 1 – S ► 3 – Z ► 4 – U
AHP/ANP mult.: 5 – P ► 1 – S ► 2 – T ► 3 – Z ► 4 – U
DEMATEL: 5 – P ► 1 – S ► 2 – T ► 3 – Z ► 4 – U
MUZ: 5 – P ► 2 – T ► 1 – S ► 3 – Z ► 4 – U
TW: 5 – P ► 1 – S ► 3 – Z ► 2 – T ► 4 – U

We note that the rankings obtained by all methods - both objectified and subjective – are similar, and the objectified method renders the same results as multiplicative AHP/ANP and DEMATEL [8]. However, it is not a particular ranking list that is the advantage of the objectified method, but the fact that it is not necessary to agree collegially on the relative importance of subsequent criteria.

4. Road Infrastructure

This example follows the data from [9]. The choice concerns the best variant of the selection of a route of a road. The data for calculations are given in Table 3 (source: Table 2 in [9]).
Maximized criterion is 6 – economic net present value. Minimized criteria are 1 – length of road, 2 – number of junctions, 3 – collision with "Nature 2000" area, 4 – length of route through forest, 5 – construction cost, 7 – number of houses to demolish, 8 – number of people exposed to excessive noise. When applying the method of objectified ranking as above, we obtain the following values of the overall achievement function shown in Table 4.
This example follows the data from [9]. The choice concerns the best variant of a path along which a road is to be constructed. The data for calculations are given in Table 3 (source: Table 2 in [9]).
The maximized criterion is 6 – economic net present value. Minimized criteria are 1 – length of road, 2 – number of junctions, 3 – interference with "Nature 2000" sites, 4 – length of route leading through a forest, 5 – construction cost, 7 – number of houses to demolish, 8 – number of people exposed to excessive noise. When applying the objectified ranking method, as presented above, we obtain the following values of the overall achievement function shown in Table 4.
Thus, the resulting ranking is V2 ► V1 ► V3. In the paper [9] six subjective ranking methods and five preference scenarios are considered, resulting in 30 different rankings, in which V2 was ranked first 16 times, while V1 only 5 times, and V3 9 times. Therefore, objectified ranking renders results that are not inconsistent with subjective rankings, but all that is done in a much simpler way and without the necessity to collegially agree on the scenario of preferences.

Table 4
Values of achievement function for the data in Table 3

Variants		
1	2	3
1.74425	1.84128	1.11481

Table 5
Data for calculations

No.	Criterion	Variants							
		1	2	3	4	5	6	7	8
		Ferro-concrete	Teriva	Cerambet	Ackerman	Muro-therm	Ytong	Filigran	Strop Smart
1	Cost [PLN]	1943.20	1123.80	1566.10	1528.80	1485.30	2105.20	1249.40	1346.80
2	Time [w-h]	34.50	14.20	20.10	27.30	14.90	1.80	4.80	2.50
3	Thermal insulation [U]	11.33	2.70	2.22	4.00	1.02	0.53	11.33	5.88
4	Acoustic insulation	5.00	4.00	4.00	4.00	3.00	2.00	5.00	5.00
5	Fire integrity	5.00	3.00	3.00	3.00	2.00	4.00	3.00	3.00
6	Simplicity of execution	1.00	3.00	3.00	2.00	3.00	5.00	4.00	5.00
7	Comfort of usage	4.00	3.00	5.00	5.00	3.00	2.00	4.00	4.00

Table 6
Values of the achievement function for Table 5 data

Variants							
1	2	3	4	5	6	7	8
0.45787	3.44978	2.78297	1.23442	0.286690	0.333333	4.669905	4.649105

5. Type of Ceiling Choice Case

This example is based on data given in [10] and concerns the selection of the best technology for constructing a ceiling. The data for calculations are presented in Table 5 (source Table 1 in [10]:

Minimized are criteria 1 – cost, 2 – time of construction. Maximized are all other criteria: 3 – thermal insulation, 4 – acoustic insulation, 5 – fire integrity, 6 – simplicity of execution, 7 – comfort of usage. The values of the overall achievement function calculated according to Eqs. (1)–(4) are given in Table 6.

Thus, the objectified ranking in this case is: V7 ► V8 ► V2 ► V3 ► V4 ► V1 ► V6 ► V5. In paper [10], calculations using ideal point method resulted in a slightly different ranking: V8 ► V7 ► V2 ► V5 ► V3 ► V4 ► V6 ► V1. Variants V7 and V8 are ranked best in both methods, although their placing is reversed.

6. Choosing Best Logistics Center Variant Case

This example is related to the choice of the best variant of a building for a logistics center, or actually any industrial building located in a big city. The data given in [11], [12] express the knowledge of experts in this field by evaluating numerous criteria with the use of values from the range of $<0, 1>$ and by applying weighting coefficients to these criteria. We summarize this data in Table 7 (source: [11], [12]).

Criteria in group A were minimized, in groups B, C, D, E they were maximized. While using the entropy method [11], [13] and the ideal point method [12], [14], the following two rankings were obtained from the data presented in Table 7.

Ideal point method: V2 ► V1 ► V3 ► V4 ► V5.

Entropy method: V2 ► V5 ► V1 ► V3 ► V4.

The objectified method results in the overall achievement values presented in Table 8.

Thus, the resulting ranking is:

Objectified method: V2 ► V3 ► V4 ► V5 ► V1.

While the best variant in all three methods is V2, the remaining ones are ordered differently. The question is whether this is the effect of taking into account the weighting coefficients in the first two methods. Knowing that the criteria from groups D, E are less important, we can apply Eq. (5) with $\mathbf{K}_1 = (A, B, C)$, $\mathbf{K}_2 = (D, E)$, $\alpha_1 = 1$, $\alpha_2 = 0.1$,

Table 7
Evaluation of five logistics center variants

Type and name of criterion	Weight	Evaluation of five variants				
Basic criteria	**0.89**	**V1**	**V2**	**V3**	**V4**	**V5**
A. Technology of construction	**0.31**	**0.92**	**0.83**	**0.81**	**0.89**	**0.80**
Time of construction	0.10	0.77	0.92	1.00	0.81	0.95
Cost of construction	0.10	1.00	0.80	0.70	0.90	0.70
Durability	0.03	1.00	0.75	1.00	1.00	1.00
Technological complexity	0.07	1.00	0.80	0.60	1.00	0.60
Ecological value	0.01	0.80	0.60	1.00	0.60	1.00
B. Adaptability of construction	**0.36**	**0.80**	**0.87**	**0.68**	**0.62**	**0.85**
Height utilized	0.12	1.00	0.80	0.80	1.00	0.80
Space between structural elements	0.18	1.00	1.00	0.50	0.50	0.90
Technology and construction of curtain walls	0.06	0.40	0.80	1.00	0.20	0.80
C. Functionality and utility value	**0.22**	**1.00**	**1.00**	**1.00**	**1.00**	**0.90**
Degree of fulfilment of qualitive requirements	0.11	1.00	1.00	1.00	1.00	0.80
Degree of fulfilment of safety requirements	0.06	1.00	1.00	1.00	1.00	1.00
Possibility of repeated usage	0.05	1.00	1.00	1.00	1.00	0.80
Additional criteria	0.11	**V1**	**V2**	**V3**	**V4**	**V5**
D. Placement of structure	**0.07**	**0.83**	**0.86**	**0.93**	**0.94**	**0.79**
Proximity of city railway lines	0.04	0.80	0.80	1.00	1.00	0.75
Proximity of trams and buses	0.01	1.00	1.00	1.00	1.00	0.80
Proximity of a throughway	0.01	0.60	0.80	1,00	0.60	0.80
Proximity of another industrial site	0.01	1.00	1.00	0.50	1.00	0.80
E. Standard of veneer	**0.04**	**0.79**	**0.90**	**0.94**	**0.95**	**0.83**
External walls	0.01	0.75	1.00	0.75	1.00	0.80
Internal walls	0.01	0.80	0.80	1.00	0.80	1.00
Administrative rooms	0.01	0.80	0.80	1.00	1.00	0.60
Social rooms	0.01	0.80	1.00	1.00	1.00	1.00

which leads to the following modification of Table 8. It is given as Table 9.

Table 8
Values of the achievement function for Table 7 data

Variants				
1	2	3	4	5
0.33912	5.34933	3.29121	0.61894	0.42953

Table 9
Values of the achievement function according to Eq. (5) for Table 7 data

Variants				
1	2	3	4	5
0.33512	7.6816	3.87428	1.25894	0.38257

The resulting ranking is the same as one without weights:

Objectified method with weights: V2 ► V3 ► V4 ► V5 ► V1.

We conclude that the objectified ranking is quite robust and is not strongly influenced by criteria with small weighting coefficients.

7. Summary and Conclusions

This paper presented a comparison between the objectified ranking method and diverse subjective ranking methods used in various infrastructural applications. While the results achieved (rankings) are very similar, the objectified method is simpler and does not require the specification of weighting coefficients. Therefore, we can conclude as follows:

- The objectified ranking method renders good results when compared with other methods, while it is simpler in application and, most importantly, does not require any collegial agreement on weighting coefficients or on the importance of specific criteria.
- If the weighting coefficients are known, they might be used in a subjectified variant of the objectified method. However, the presence of many criteria of lesser importance does not necessarily impact the outcome ranking.
- Each method has its advantages and disadvantages, but subjective methods used in infrastructural problems are usually more complicated than the objectified ranking method. They also utilize weighting coefficients and often assume a linear combination of criteria, which can lead to erroneous results.

The ranking of potential solutions is not always decisive when selecting the variant of the investment project to be followed, but other factors beyond the merits, such as political factors, are taken into account as well. As a result, financial resources, often originating from state budget, may be wasted.

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Edward Klimasara received his M.Sc. from the Faculty of Mathematics and Mechanics, University of Warsaw, in 1977. Since 1984 he has been employed at the National Institute of Telecommunications in Warsaw, currently as the main specialist at the Department of Advanced Information Technology. He is an author and co-author of publications in the field of computer science and telecommunications. His professional interests include knowledge management, multi-criteria optimization, Big Data, application of information techniques in telecommunications, medicine, transport, administration and education.

https://orcid.org/0000-0002-9761-0088
E-mail: E.Klimasara@itl.waw.pl
National Institute of Telecommunications
Szachowa 1
04-894 Warsaw, Poland

Andrzej Piotr Wierzbicki received his M.Sc. in telecommunications and control engineering in 1960, his Ph.D. in nonlinear dynamics in control in 1964, and his D.Sc. in optimization and decision science in 1968. He worked as the Dean of the Faculty of Electronics, Warsaw University of Technology (WUT), Poland (1975–1978); the Chairman of Systems and Decision Sciences Program of the International Institute for Applied Systems Analysis in Laxenburg n. Vienna, Austria (1979–1984). He was elected a member of the State Committee for Scientific Research of the Republic of Poland and the Chairman of its Applied Research Committee (1991–1994). He was the Director General of the National Institute of Telecommunications in Warsaw (1996–2004). He worked as a research Professor at the Japan Advanced Institute of Science and Technology (JAIST), Nomi, Ishikawa, Japan (2004–2007). Beside teaching and lecturing for over 45 years and promoting over 100 master's theses and 20 doctoral dissertations at WUT, he also lectured at doctoral studies at many Polish and international universities. Professor Wierzbicki is an author of over 200 publications, including 14 books, over 80 articles in scientific journals, over 100 conference papers; He is the author of 3 industrially applied patents. His current interests include vector optimization, multiple criteria and game theory approaches, negotiation and decision support, information society and knowledge civilization, rational evolutionary theory of intuition, theories of knowledge creation and management.

https://orcid.org/0000-0001-5817-3906
E-mail: A.Wierzbicki@itl.waw.pl
National Institute of Telecommunications
Szachowa 1
04-894 Warsaw, Poland