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Inter-Criteria Dependencies-Based Decision Support in the Sustainable wind Energy Management

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Abstract: Decision problems related to the wind energy require considering many, often interrelated and dependent on each other, criteria. To solve such problems, decision systems based on Multi-Criteria Decision Analysis (MCDA) methods are usually used. Unfortunately, most methods assume independence between the criteria, therefore, their application in decision problems related to the wind energy is debatable. This paper presents the use of the Analytic Network Process (ANP) method to solve a decision problem consisting in selecting the location and design of a wind farm. The use of the ANP method allows capturing the complexity of the decision problem by taking into consideration dependencies between criteria. As part of the verification of the solution, the results of the ANP method were compared with those of the Analytic Hierarchy Process (AHP) method, which uses only hierarchical dependencies between criteria. The conducted verification showed that the inter-criteria dependencies may have a significant influence on the obtained solution. On the basis of the conducted sensitivity analysis and the research into robustness of the rankings to the rank reversal phenomenon, it has been found out that the ranking obtained with the use of the ANP is characterized by a higher quality than by means of the AHP.

Keywords: Multi-Criteria Decision Analysis; sustainable wind energy management; sensitivity analysis; rank reversal; Analytic Network Process; Analytic Hierarchy Process

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1. Introduction

One of the biggest challenges of today's energy management is adapting it to the demands of low carbon economy characterized by, most of all, the use of renewable energy sources (RES) [1]. The fact can be confirmed in the Polish energy policy, for which major priorities are, among other things: energy efficiency improvement, reduction of pollutions from the energy sector, development of renewable energy and an increase in the use of RES [2,3]. The Polish energy policy in this area is coherent with the policy of the European Union (EU), which assumes that there will be at least a 20% reduction of greenhouse gas emissions by 2020 compared to the 1990 levels and it requires increasing a share of renewable energy in gross final energy consumption to about 20% in 2020 from its member states [4]. In a broader perspective, i.e. by 2030, at least 40% reduction of greenhouse gas emissions is assumed in relation to 1990 and the share of renewable energy in total energy consumption is 32%. The minimum contribution of Member States to the new framework for 2030 should be the achievement of the national targets for 2020 [5]. It should be noted that the objectives set for 2020 have a chance to be met at the level of the European Union (without dividing them into individual Member States). According to the Eurostat data, in 2016 the share of renewable energy in energy consumption in the whole EU amounted to 17% [6]. In turn, the emission of greenhouse gases was reduced in the period 1990-2016 by 22.4% [7]. Nevertheless, the analysis of the quoted sources [6,7] indicates that some Member States have little chance of achieving the targets set for 2020.

The Polish Energy Law Act defines renewable energy as biogas, biomass, geothermal, river fall, sea wave and tidal, solar, and wind energy [8]. Among the above-mentioned RES, the great potential for energy production, both in Poland and in the EU, have wind farms [2,4]. It is because onshore wind farms are characterized by the low capital investment and levelised cost of electricity as well as one of the shortest construction period of all RES power stations [9–11]. The comparison of the most popular RES technologies [12] with regard to costs, construction time, lifetime and installed capacity in Poland and in the EU [9–11,13] are presented in Table 1.

Table 1. Comparison of basic RES technologies with regard to necessary investment and installed capacity.

Energy Source	Capital Investment 2017 (2016 USD/kW)	Levelised Cost of Electricity 2017—World (2016 USD/kWh)	Levelised Cost of Electricity 2017—Europe (2016 USD/kWh)	Construction Time (Year)	Life-Time (Year)	Installed Capacity in Poland—2017 (MW)	Installed Capacity in EU—2017 (MW)
Onshore Wind	1 477	0.06	0.08	1	25	5 798	152 751
Offshore Wind	4 239	0.14	0.15	2	25	-	15 835
Hydropower	1 535	0.05	0.12	3	30	969	130 411
Bioenergy	2 668	0.07	0.07	2	20	1 075	36 341
Geothermal	2 959	0.07	0.08	2	25	-	846
Solar Photovoltaic	1 388	0.1	0.13	0	25	268	106 546
Concentrating Solar Power	5 564	0.22	-	2	25	-	2 308

As for the considerably greater installed power of wind farms with reference to other RES in Poland, apart from lower capital investment, the installed power results from the enormous potential of the wind in Poland. It is assumed that the Polish potential of wind is bigger than in countries, such as Denmark and Sweden, in which an important part of the energy is obtained from the wind. The potential is equal to that of Germany, which is the "world's wind giant" [8]. It is forecasted that by 2020 the installed RES capacity in Poland will amount to circa 10,000 MW, of which about 50% will be wind energy [2]. Therefore, Poland is expected to experience a dynamic increase in wind farm construction investment.

The most important decision problems whose solutions will lead to a successful realization of a wind farm project are selection of a location [14] and selection of a project design [15]. Decision problems concerning wind energy, and similarly other decision issues related to RES management, are multi-criteria decision making problems that require consideration of many contradictory and mutually correlated criteria comprising economic, environmental, social as well as technological and spatial issues [14–20]. Single-criterion decision making methods are not able to deal with such decision problems correctly [21]. In solving such problems, Multi-Criteria Decision Analysis (MCDA) methods can be applied since they are able to deal with multiple and conflicting criteria [22]. However, most MCDA methods assume independence between criteria [23], therefore, it is difficult to apply the methods to complex decision problems in which there are mutual dependencies between criteria [24]. Issues related to RES and sustainable management [24,25], especially problems dealing with wind energy [15], are this kind of decision problems.

The aim of this article is to select a project design and the location of an onshore wind farm in Poland. The selection should be based on a decision model which takes into account dependencies between criteria. The methodological contribution of this article consists in the comparison of the solution obtained using inter-criteria dependencies (based on the ANP approach) with the solution of the decision model which do not take into consideration interdependencies between criteria (based on the AHP approach). This will allow assessing the impact of taking into account the dependencies between criteria on the obtained results. Additionally, an analysis of intrinsic characteristics of the MCDA methods, and thus a formal selection of the MCDA method applied to the decision problem can also be treated as an important contribution. Section 2 contains the analysis of the literature on MCDA methods related to the decision problems in the wind energy field. Section 3 discusses the applicability of MCDA methods in decision problems in the field of wind energy. Additionally in Section 3, the proposed methodology was presented. In Section 4, the approach was applied to the decision problem consisting in selecting the location and design of a wind farm in Poland. Section 5 deals with a summary of research results. Also, further research directions are pointed out.

2. Literature Review

The MCDA methods are often used for solving decision problems related to RES, such as, among other things, the selection of a location for an RES-based power plant, selecting an energy production technology, evaluation of the influence of a renewable energy power station on the environment, an analysis of different scenarios of RES development, optimization of the energy production, etc. [17,26]. The most popular MCDA methods used for solving decision problems in the field of RES are first of all: the AHP and ANP, MAVT, MAUT, TOPSIS, PROMETHEE, ELECTRE [18] as well as fuzzy methods [27]. Also, hybrids were employed, which are a combination of various MCDA methods [26]. Applications of the MCDA methods in the field of RES are presented in the papers [17–19,22,26,27]. In the context of decision support, in the literature, the most often mentioned type of renewable energy is wind energy [18]. Publications concerning decision support in wind energy include, most of all, the construction of decision models and the construction of DSS (Decision Support System) and GIS (Geographical Information System) systems.

An example of constructing a decision model for selecting a wind farm location is [28]. In this paper, evaluation criteria and their weights, presented in a decision model for the sake of selecting a wind farm location, were determined. On the other hand, in [29] a decision model was constructed in order to select a location of an onshore wind farm. The problem of constructing a decision model for selecting an onshore wind farm location is also dealt with in [30], a hybrid farm in [31,32], and an offshore wind farm in [14]. GIS decision systems were proposed, among other things in [33–38]. These systems evaluate the potential of onshore areas with regard to situating wind farms on the areas. Similarly, in [39] a GIS, which allowed evaluating a location of hybrid power stations based on wind and solar energies, were presented. In [40] and [41], a GIS-based DSS systems considering potential onshore wind farm locations were discussed. The problem of constructing a DSS for selecting an offshore wind location was attempted in [42,43]. Decision models dealing with a location selection and the design of a wind farm related to the selection are presented in [44–46]. Similarly, in [47], the location and design of a hybrid power plant were selected. As far as decision problems closely related to the project design of a wind farm are concerned, such an issue was discussed in [15,48]. To the wind farm design are also related technical aspects of wind turbines [16,49,50] as well as, in a broader context, risk assessment [51]. On the other hand, in [52], a decision model used for evaluating the influence of a wind farm on the environment in a given location was presented. Table 2 includes a list of publications dealing with the issue of decision support in the area of wind energy on the basis of MCDA methods.

The analysis of Table 2 indicates that in decision problems concerning wind energy, the AHP method is often used, both in its crisp and fuzzy versions. It is employed to determine the weight of criteria and preference aggregation. A generalization of the AHP, namely the ANP, and different variants of the ELECTRE method are rarely used. Sporadically, other MCDA methods, such as TOPSIS, PROMETHEE, Weighted Overlay, WLC, OWA, DEMATEL, Conjunctive Method, are used. Other MCDA methods are employed in individual cases. It should be noted that in order to solve decision problems related to wind energy, decision models characterized by various complexities are used. The number of criteria ranges from 5 to as many as 35. These criteria are often related to each other and dependent on one another. For example, in the publication [15], the following criteria were used: generating cost, generating profit, and payback period. As it can be easily found out the payback period results from, among other things, the calculation of costs and profits.

Table 2. The use of MCDA in decision support concerning wind energy.

Type of Solution	No. of Criteria	MCDA Approach	Reference
DM	15	Fuzzy DEMATEL (CD); ANP (CW)	[28]
DM	7	Fuzzy AHP (CW); Fuzzy VIKOR (PA)	[29]
DM	5	AHP	[30]
DM	20 *	AHP	[31]
DM	11 *	ELECTRE II	[32]
DM	22	Fuzzy ELECTRE III	[14]
GIS	7	AHP (CW); OWA (PA)	[33]
GIS	6	AHP (CW); WLC (PA)	[34]
GIS	10	LM; ELECTRE TRI	[35]
GIS	10	Fuzzy AHP (CW); Fuzzy TOPSIS (PA)	[36]
GIS	5	AHP (CW); WO (PA)	[37]
GIS	13	CM (EA); AHP (CW); ELECTRE III, ELECTRE TRI, SMAA-TRI (PA)	[38]
GIS	10 *	OWA	[39]
DSS, GIS	14	CM (EA); WO (PA)	[40]
DSS, GIS	8	AHP (CW); WLC (PA)	[41]
DSS	31	Fuzzy DEMATEL (CD); Fuzzy ANP (CW); Fuzzy ELECTRE (PA)	[42]
DSS	10	AHP (CW); PROMETHEE II (PA)	[43]
DM	29	AHP	[44]
DM	9	C-K-Y-L (with indifference threshold)	[45]
DM	10	AHP; PROMETHEE II	[46]
DM	27 *	Fuzzy AHP	[47]
DM	11	NAIADE I	[48]
DM	35	FCI (sub-criteria PA); GIFOGA (criteria PA)	[15]
DM	14	Fuzzy ANP	[16]
DM	9	IFE (CW); Fuzzy TOPSIS (PA)	[49]
DM	11	AHP	[50]
DM	9	Fuzzy ANP	[51]
DM	14	AHP	[52]

Abbreviations: *—wind energy criteria; **Type of solution**: DM—Decision model; DSS—Decision Support System; GIS—Geographical Information System; **MCDA approach (method)**: AHP—Analytic Hierarchy Process; ANP—Analytic Network Process; C-K-Y-L—Condorcet–Kemeny–Young–Levenglick method; CM—Conjunctive Method; DEMATEL—DEcision MAking Trial and Evaluation Laboratory; ELECTRE—ELimination Et Choix Traduisant la REalité; FCI—Fuzzy Choquet Integral; GIFOGA—Generalized Intuitionistic Fuzzy Ordered Geometric Averaging; IFE—Intuitionistic Fuzzy Entropy; LM—Lexicographic Method; NAIADE—Novel Approach to Imprecise Assessment and Decision Environments; OWA—Ordered Weighted Averaging; PROMETHEE—Preference Ranking Organization METHod for Enrichment Evaluation; SMAA—Stochastic Multi-objective Acceptability Analysis; TOPSIS—Technique for Order of Preference by Similarity to Ideal Solution; VIKOR—VIšekriterijumsko KOmpromisno Rangiranje; WLC—Weighted Linear Combination; WO—Weighted Overlay; TRI—Triage; **MCDA approach (application)**: CD—criteria dependencies defining; CW—criteria weighting; EA—elimination of areas; PA—preference aggregation.

Because of inter-criteria dependencies and other elements of specificity of decision problems in the field of RES, an important issue is the selection of a proper MCDA method which can be used in decision problems in the area of wind energy. This is important because solutions to a decision problem may vary depending on the method used [53]. Differences between methods result primarily from: the different way in which weights are taken into account in the decision problem, differences in calculation procedures and the application of additional parameters of the decision problem by the different methods [54].

3. Methodological Background

3.1. Choosing an MCDA Method for Decision Problems in the RES Field

As it was pointed out in [55], appropriateness of an MCDA method to the specificity of a decision problem is essential for its selection. This means that there is no universal method that can be applied to all decision problems [56]. Therefore, determining the specificity of a decision problem is a significant step when selecting an MCDA method, and after this step, to a given problem a method should be selected which complies with specific characteristics.

On the basis of reference sources [24,57–59], in which the issue of an MCDA method selection for decision problems in the fields of RES and sustainability was considered, the following characteristics determining the specificity of decision problems were taken into consideration:

- the issues of a decision which was being considered [58],
- applied preference relations and a way of organizing alternatives [58,59],
- a compensation degree of criteria [24,57–59],
- discrimination power of criteria [57,59],
- a type of applied information [24,57–59],
- applying weights of criteria [24,57–59],
- support for many decision-makers [24,58,59],
- using dependencies between criteria [24,59].

MCDA methods are designed for solving different reference problematics. One can distinguish the following problematics [60]: choice ($P.\alpha$)—aids the decision-maker in choosing a subset that is as small as possible so that a single alternative can eventually be chosen from the subset; sorting ($P.\beta$)—aids the decision-maker by assigning each alternative to a category, where the categories are defined beforehand as a function of certain norms; ranking ($P.\gamma$)—aids the decision-maker by building an order of alternatives, that is obtained by placing alternatives into equivalence classes that are completely or partially ordered according to preferences; description ($P.\delta$)—aids the decision-maker by developing a description of alternatives and their consequences.

In MCDA methods, an order between decision alternatives a and b is expressed by means of relations describing preference situations. Depending on an MCDA method, one can list the following relations: indifference ($a\ I\ b$)—which means that alternatives are equal, strict preference ($a\ P\ b$)—which means that there is a strong advantage of an alternative a over b, weak preference ($a\ Q\ b$)—which means that there is a weak advantage of an alternative a over b, outranking ($a\ S\ b$)—which includes an indifference relation, a weak one and a strict preference relation, incomparability ($a\ R\ b$)—which means that none of the remaining relations takes place [60]. The incomparability relation is related to a way of organizing alternatives in the ranking problematics. That is, when an MCDA method does not take into consideration the incomparability relation, the method usually allows obtaining a total order, i.e., full comparability of all alternatives in the ranking. Otherwise, a partial order is achieved, what means that there may be alternatives which cannot be compared to other ones in the obtained ranking [61].

An important characteristic of multi-criteria methods in the context of sustainability and RES problems is the degree of compensation of the criteria. In the literature [56], there are three basic degrees of compensation: (1) full compensation—meaning that the low values of some criteria can be fully compensated for by the high values of other criteria, (2) no compensation—meaning that the low values of some criteria cannot be compensated for in any way by other criteria, (3) partial compensation—being the intermediate step between full and no compensation. In many methods, absolute compensation is excluded by using a veto threshold (v) as well as an incomparability relation, which is usually related to it. It is important to note that the concept of strong sustainability is reflected by a low degree of compensation and also weak sustainability corresponds to a high degree of criteria compensation [59].

The discriminating power of the criteria refers to how preference relations are established. Absolute discriminating power means that even a minimal advantage of an alternative a over b with regard to a given criterion c results in a strict preference ($a\ P\ b$) relation. On the other hand, applying non-absolute discriminating power results in a situation where indifference ($a\ I\ b$) or weak preference ($a\ Q\ b$) relations take place. Non-absolute discriminating power usually requires using indifference (q) and preference (p) thresholds [60] in an MCDA method.

Both action performance and criterion weights can be expressed on different scales, depending on the nature of the data. Qualitative and quantitative scales are the most common, while Roy [62] indicates that they can be identified with ordinal and cardinal scales respectively. A data nature refers to whether they are certain or uncertain [63]. Certain data (deterministic) have a crisp form, whereas uncertain data (non-deterministic) can be expressed in a fuzzy form [63] or by defining a proper value of indifference or preference thresholds [24,57]. The information type refers to the performance of decision alternatives and weights of criteria. An MCDA method may: not use weights of criteria, accept weights expressed on an ordinal scale or operate on weights presented on a cardinal scale [24]. In addition, some methods offer the possibility of aggregating information from many decision-makers or reflecting different priorities or scenarios.

Most MCDA methods assume independence between criteria what is not a realistic assumption in many real-world problems [23]. These methods cannot be easily applied to more difficult decision problems [24], because omitting existing dependencies between criteria does not allow the problem to be correctly reflected in a decision model what results in obtaining wrong solutions [64].

Table 3 depicts the basic characteristics of the MCDA methods. Table 3 takes into account only method families whose applicability is confirmed by the analysis of reference literature presented in Section 2. Table 3 particularly presents MCDA methods which were used at least twice in decision problems related to wind energy. Consequently, methods which had been incidentally used in this area were eliminated from further analysis. In addition, Table 3 also includes the latest MCDA methods used in sustainability and wind energy issues: BWM (Best Worst Method), COMET (Characteristic Objects Method), NEAT F-PROMETHEE (New Easy Approach To Fuzzy PROMETHEE), PROSA (PROMETHEE for Sustainability Analysis).

In papers dealing with a selection of an MCDA method suitable for applying in RES and sustainability fields, recommendations of characteristics, which such a method should meet, were defined. The characteristics are presented in Table 4.

On the basis of Table 4, it can be stated that the selected method should generate a full ranking of alternatives (total order without incomparability). The MCDA method solving decision problems related to wind energy management should be characterised by non-absolute discriminating power of the criteria, i.e., it should apply q and p thresholds. Additionally, it should apply at most partial compensation of criteria. The method should be able to capture quantitative and qualitative information since in RES problems there are the two types of information [59]. What is more, it is recommended that the method takes into consideration uncertainty of information, makes it possible to support group decisions and allows capturing hierarchical and horizontal dependencies between criteria. When analysing Table 4, one ought to notice that in decision problems dealing with wind energy, no MCDA methods meeting the above-mentioned requirements are usually used. The PROMETHEE II and ANP methods meet the most of the listed characteristics. The PROMETHEE II method does not allow using other than hierarchical dependencies between criteria, whereas the ANP does not make it possible to define indifference and preference thresholds what results in absolute discriminating power of the criteria. Both methods meet seven recommended characteristics. An advantage of the ANP over PROMETHEE is the ability of presenting mutual inter-criteria dependencies in a decision model, thus, such a model could, to a greater extend, present the complexity of a decision problem in the field of RES and sustainability [25].

Table 3. Characteristics of MCDA methods applied in the field of wind energy.

MCDA Method	Reference Problematic	Preference Modelling		Degree of Compensation	Criterion Function		Information Type		Type of Weights	Group Decision Making	Dependencies between Criteria	Reference
		Preference Relations	Order of Alternatives		Discriminating Power of the Criteria	Thresholds	Type of Information	Information Features				
AHP	γ	I, P	TO	PC	AB	n	QL, QN	D, N	C	SG	HD	[65]
ANP	γ	I, P	TO	PC	AB	n	QL, QN	D, N	C	SG	HD, ID	[66]
ELECTRE I	α	S, R	SU	PC	AB	n [1]	QL, QN	D	C	NG	IN	[67]
ELECTRE IS	α	S, R	SU	PC	NA	q, p, v	QL, QN	D, N	C	NG	IN	[67]
ELECTRE II	γ	S, R	PO	PC	AB	v [2]	QL, QN	D	C	NG	IN	[67]
ELECTRE III	γ	S, R	PO	PC	NA	q, p, v	QL, QN	D, N	C	NG	IN	[67]
ELECTRE IV	γ	S, R	PO	PC	NA	q, p, v	QL, QN	D, N	NW	NG	IN	[67]
ELECTRE TRI	β	S, R	PO	PC	NA	q, p, v	QL, QN	D, N	C	NG	IN	[67]
TOPSIS	γ	I, P	TO	FC	AB	n	QN	D	C	SG	IN	[68]
PROMETHEE I	γ	I, P, R	PO	PC	NA	q, p, o [3]	QL, QN	D, N	C	SG [4]	HD [8]	[69]
PROMETHEE II	γ	I, P	TO	PC	NA	q, p, o [3]	QL, QN	D, N	C	SG [4]	HD [8]	[69]
Conjunctive Method	α	I, P	FI	NC	AB	n	QL, QN	D	NW	NG	IN	[68]
WLC [5]	γ	I, P	TO	FC	AB	n	QN	D	C	NG	IN	[70]
Weighted Overlay	γ	I, P	TO	FC	AB	n	QN	D	C	NG	IN	[71]
OWA	γ	I, P	TO	FC, PC, NC [6]	AB	n	QN	D, N	C	SG	IN	[72]
DEMATEL	γ	I, P	PO, TO [7]	FC	AB	n	QL	D, N	NW	SG	ID	[73]
BWM	γ	I, P	TO	PC	AB	n	QL, QN	D, N	C	NG	IN	[74]
COMET	γ	I, P	TO	FC	AB	n	QL, QN	D, N	NW	SG	IN	[75]
NEAT F-PROMETHEE I	γ	I, P, R	PO	PC	NA	q, p, o [3]	QL, QN	D, N	C	NG	IN	[76]
NEAT F-PROMETHEE II	γ	I, P	TO	PC	NA	q, p, o [3]	QL, QN	D, N	C	NG	IN	[76]
PROSA	γ	I, P	TO	PC	NA	q, p, o [3]	QL, QN	D, N	C	NG	HD	[77]

Abbreviations: [1]—ELECTRE Iv applies a veto (v) threshold; [2]—two veto thresholds; [3]—depending on the applied preference function; [4]—supported by applying PROMETHEE GDSS method; [5]—also known as Simple Additive Weighting; [6]—depending on an applied OWA operator; [7]—depending on implementation; [8]—3-level hierarchy is applied in Visual PROMETHEE software; **Reference problematic**: α—choice; β—sorting; γ—ranking; **Preference modelling**: I—indifference; Q—weak preference; P—strict preference; S—outranking; R—incomparability; TO—total order; PO—partial order; SU—subset; FI—filtration; **Degree of compensation**: FC—full compensation; PC—partial compensation; NC—non-compensation; **Criterion function**: AB—absolute; NA—non-absolute; q—indifference; p—preference; v—veto; n—none; o—other; **Information type**: QL—qualitative; QN—quantitative; D—deterministic; N—non-deterministic; **Type of weights**: NW—not applicable; O—ordinal; C—cardinal weights; **Group decision making**: NG—not supported; SG—supported; **Dependencies between criteria**: IN—independence; HD—hierarchical dependencies; ID—interdependencies.

Table 4. Recommendations of characteristics of an MCDA method suitable for applying in RES and sustainability problems.

Reference Problematic (Ch. 1)	Preference Modelling (Ch.2)		Degree of Compensation (Ch. 3)	Criterion Function (Ch. 4)		Type of Information (Ch. 5)		Type of Weights (Ch. 6)	Group Decision Making (Ch. 7)	Dependencies between Criteria (Ch. 8)	References
	Preference Relations	Order of Alternatives		Discriminating Power of the Criteria	Thresholds	Kind of Information	Information Features				
γ	I, P	TO	PC	NA	q, p	QL, QN	-	C	SG	-	[58]
-	I, P	TO	PC	NA	q, p	QL, QN	D, N	NW, O, C	SG	HD	[59]
-	-	-	NC, PC	NA	q, p	QL, QN	D, N	NW, O, C	-	-	[57]
-	-	-	NC	-	-	QL, QN	D, N	C	SG	HD, ID	[24]
γ	I, P	TO	NC ∨ PC	NA	q, p	QL, QN	D, N	NW, O, C	SG	HD, ID	Sum of characteristics

What is more, it should be noted that the ANP is a generalization of the AHP in which a problem of a network structure, as opposed to a hierarchical one, is considered [78]. In other words, the AHP and ANP methods are based on the same calculation apparatus. However, the AHP does not allow modelling other than hierarchical dependencies between criteria [79]. Therefore, solving a decision problem by means of the AHP and ANP methods will allow examining the influence of applying inter-criteria dependencies on an obtained solution, thus the influence of computational algorithms used in individual MCDA methods will be eliminated. Such a comparison is vital since the AHP method is often used in decision problems concerning wind farms. As a consequence, the author of this paper made a decision to use the ANP method as an engine of a proposed solution.

The AHP and ANP methods are based on utility theory. Both methods can be presented in three steps of the calculation procedure:

1. identifying the decision problem and preparing a problem model in the form of a hierarchical structure (AHP) or a network structure (ANP),
2. carrying out pairwise comparisons (alternatives and criteria),
3. achieving a solution with the use of supermatrix [80].

In the hierarchical structure, the decision problem is modelled in the form of objective, criteria, sub-criteria and alternatives. Therefore, only hierarchical relationships are used in it. In the network model, apart from hierarchical dependencies, inner and outer dependencies between criteria/sub-criteria and feedbacks are also modelled [81], i.e., dependencies directed contrary to the classical hierarchy. These differences allow creating more complex decision models using the ANP method. An overview of the network decision model is shown in Figure 1.

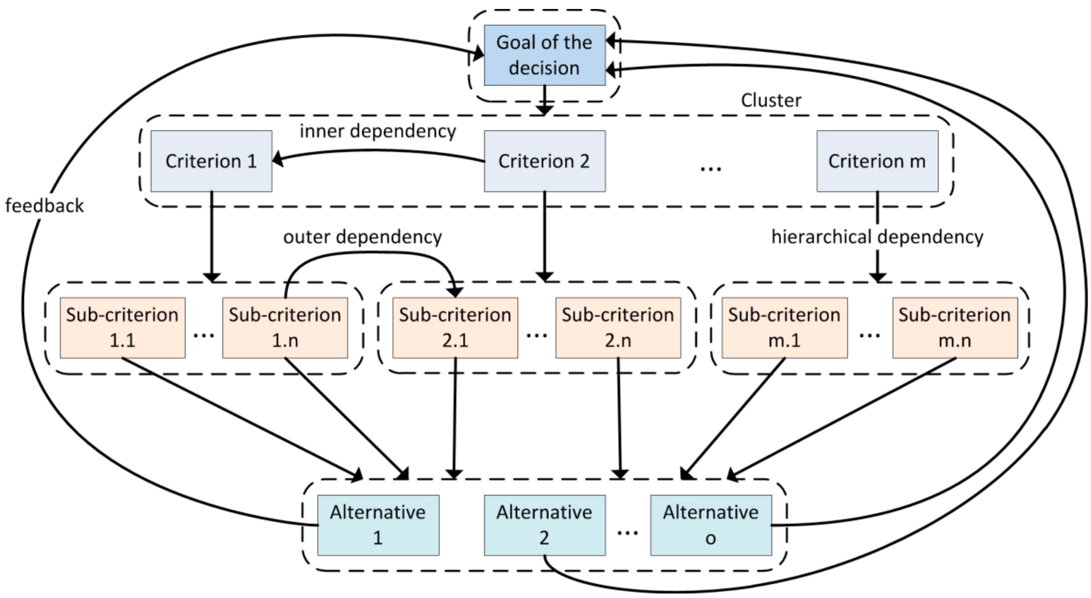


Figure 1. Network structure in the ANP method.

To compare the alternatives or criteria in both methods, pairwise comparison matrices are used. Any such matrix M ought to be positive and reciprocal, according to the formula (1):

$$m_{ji} = \frac{1}{m_{ij}} \tag{1}$$

The main diagonal of the matrix contains unit values. For each matrix M, the preference vector $W = [w_1, \ldots, w_n]$ is calculated, which determines the weights of the criteria considered or the assessment of alternatives. Saaty recommends calculating the vector W using the eigenvector method [82], but other methods of determining the vector W, e.g., column sums, power method, simple geometric mean, are often used in the literature in order to simplify the calculation procedure [80]. The eigenvector method consists in solving Equation (2):

$$MW = \lambda_{max} W \tag{2}$$

where λ_{max} is the highest eigenvalue of the M matrix. It should be emphasized that in the M matrix only minor inconsistencies are allowed, which arise due to incomplete transitory preferences [81]. Moreover, if the data in the matrix are represented on their natural scales, then the M matrix is always consistent.

Both methods allow obtaining a solution to a decision problem with the use of supermatrix [83]. At the beginning, the interfactorial dominance supermatrix [84] is defined, which indicates relations between elements of the decision-making model. In the next step, the unweighted supermatrix is defined, in which eigenvectors W are placed in individual pairwise comparison matrices. A weighted supermatrix is obtained on the basis of the unweighted supermatrix by normalizing column sums to a unit value (stochastic supermatrix). In the last step, the limit supermatrix is reached using the formula (3):

$$LSM = \lim_{k \to \infty} \frac{1}{N} \sum_{k=1}^{N} WSM^k \tag{3}$$

where WSM stands for a weighted supermatrix. A limit supermatrix represents global priorities to solve a decision problem (weighting of criteria, global values of alternatives) [66].

3.2. Proposed Methodology

The used research procedure, whose goal is to select a project design and the location of an onshore wind farm, was based on a decision process model defined by Roy [60]. Therefore, the verification model had the following stages:

1. determining a goal of the decision and alternatives;
2. developing criteria;
3. modelling preferences;
4. investigating and developing the recommendation.

Stages 2–4 were carried out separately for the AHP and ANP methods.

In Stage 2 for the ANP, sub-criteria used for solving a decision problem were defined and dependencies between them were determined. These dependencies were presented in a network ANP decision model, whereas for the AHP, a hierarchical decision model, which was similar to the network model, but did not take into consideration dependencies between criteria, was constructed.

In Stage 3, initial weights of criteria and sub-criteria were attributed. It should be stressed that in the conducted research, each of the criteria was attributed the same weight. Analogically, sub-criteria within one criterion were also considered equally important. After performing the ANP procedure, the influence of the network model on sub-criteria weights, which were finally obtained, was examined and the weights were compared to the initial importance. Additionally, for the network model, the influence of a cluster containing decision alternatives on the obtained sub-criteria weights was examined. It was carried out by determining sub-criteria weights on the basis of a complete model containing the goal of the decision, criteria, sub-criteria and decision alternative clusters, and by determining sub-criteria weights on the basis of a model from which a decision alternative cluster was deleted.

Stage 4 consisted in determining a ranking of alternatives with the use of the ANP and AHP and comparing obtained rankings. The rankings were determined by means of comparing alternatives in pairwise comparison matrices. Usually, in pairwise comparison matrices, Satty's fundamental scale (a qualitative scale [1,2,...,9]) is used. However, the ANP and AHP methods also allow presenting data on their natural scale [85]. In the case of this paper, performances of alternatives for individual criteria are presented on natural scales. The comparison of rankings was carried out with the use of a sensitivity analysis as well as research into the susceptibility of rankings to the rank reversal phenomenon. In this way, the influence of dependencies between sub-criteria on the obtained solution was examined. It should be noted that comparing the results of the operation of the ANP with any other method, different from the AHP, would not enable such research. It results from the fact that the ANP and AHP methods are based on the same computational apparatus, but they differ in that the ANP takes into consideration dependencies between criteria. However, other methods employ different computational algorithms and, therefore, differences in obtained results could be caused by the very differences and not by inter-criteria dependencies. The research procedure is depicted in Figure 2.

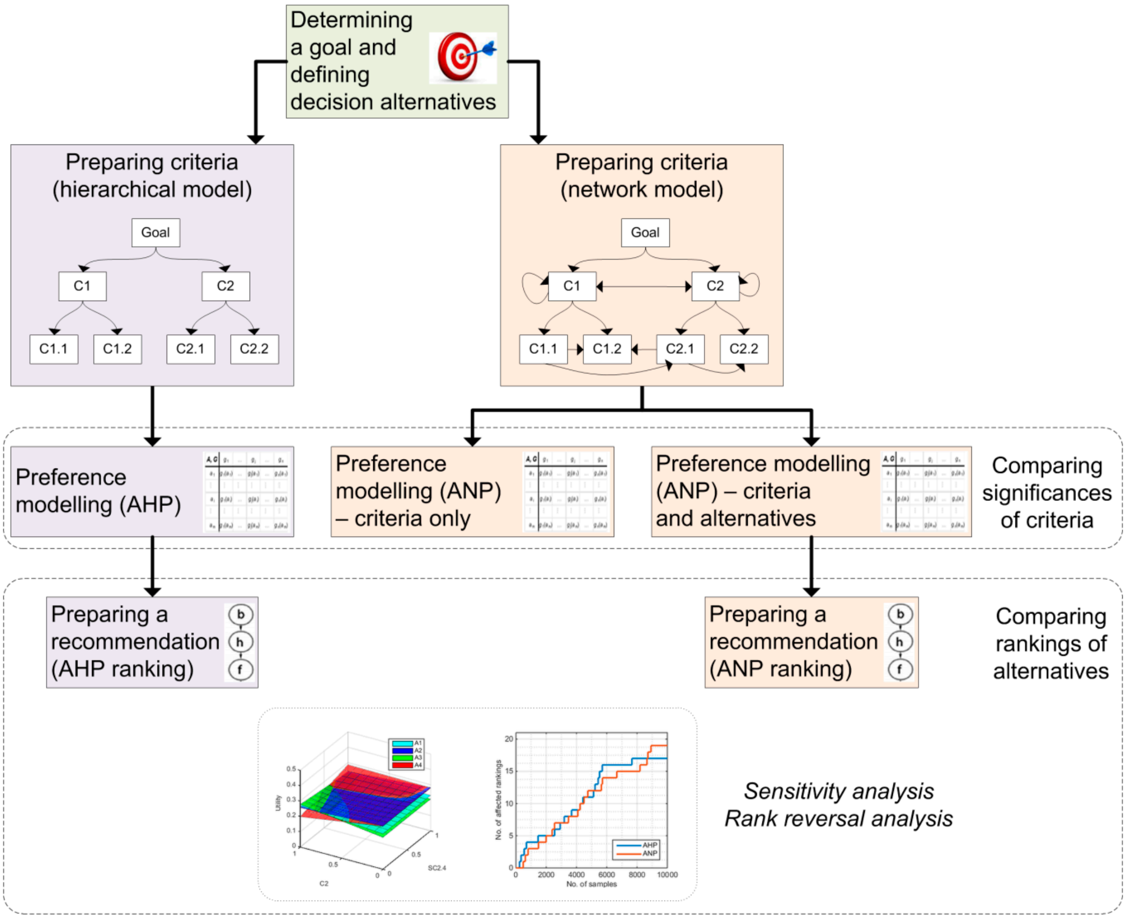


Figure 2. Research procedure

4. Results

4.1. Determining a Goal of the Decision and Developing Criteria

The goal of the decision was the selection of a location for an onshore wind farm in Poland related to its specific design. Four decision alternatives were considered, which had different values of individual sub-criteria.

Another step was to select criteria and sub-criteria against which decision alternatives would be evaluated. On the basis of the literature analysis presented in Section 2, a set of criteria and sub-criteria for evaluating locations and designs of onshore wind farms, presented in Table 5, was prepared. Technical, economic, spatial, social and environmental criteria were singled out. For each criterion, detailed sub-criteria taken from the literature were attributed. Here, a certain level of sub-criterion generalization was accepted in order to avoid many sub-criteria having the same or similar meaning which could occur in the set. For instance, in the paper [48], an "energy production capacity" criterion was used, whereas in [43], "energy production", in [51], "power production", and in [15] and [31], "annual on-grid energy" were applied. All the criteria in this work were generalized as "annual energy production", since, in fact, they refer to it.

Table 5. Criteria and sub-criteria for evaluating locations and designs of onshore wind farms.

Criteria	Sub-Criteria		Reference
C1—Technical	C1.1	Annual mean wind speed (at the height of 100 m)	[14,15,28,31,33–37,40,42,44,46,47,52]
	C1.2	Output power of wind turbine	[15,16,29,44,47,50]
	C1.3	Power transmission grid voltage	[46,52]
C2—Economic	C2.1	Annual energy production	[15,31,38,43,44,46–48,50,51]
	C2.2	Investment cost	[14–16,29–32,43,46–48,50]
	C2.3	Annual operation and maintenance costs	[14–16,29,30,32,46–48,50]
	C2.4	Annual profit	[14,15,31,41,42,46,49]
	C2.5	Payback period	[14,15,31,43]
C3—Social	C3.1	Social acceptability	[29,31,32,42,43,46,48]
	C3.2	Employment	[14,15,49]
C4—Spatial	C4.1	Distance to main roads	[28,33–40,46]
	C4.2	Distance to power transmission grid	[14,31,32,35,36,38–40,42,43,46]
C5—Environmental	C5.1	Distance to protected areas (i.e., Nature 2000)	[34,38–41,43,46]

Table 6 contains a full characteristic of alternatives, with regard to the criteria.

Table 6. Criteria and sub-criteria for evaluating locations and designs of onshore wind farms

Criteria	Sub-Criteria		Alternatives			
			A1	A2	A3	A4
C1—Technical	C1.1	Annual mean wind speed (at the height of 100 m) (m/s)	6.75	7.12	6.95	6.04
	C1.2	Output power of wind turbine (MW)	0.53	0.58	0.57	0.38
	C1.3	Power transmission grid voltage (kV)	220	400	220	220
C2—Economic	C2.1	Annual energy production (MWh)	106 784	86 374	104 857	46 603
	C2.2	Investment cost (mln PLN)	455.40	336.60	415.80	277.20
	C2.3	Annual operation and maintenance costs (mln PLN)	8.86	7.17	8.70	3.87
	C2.4	Annual profit (mln PLN)	27.98	22.63	27.47	12.21
	C2.5	Payback period (years)	16.3	14.9	15.1	22.7
C3—Social	C3.1	Social acceptability (%)	59	24	61	26
	C3.2	Employment (number)	1062	606	831	533
C4—Spatial	C4.1	Distance to main roads (km)	6	10	7	3
	C4.2	Distance to power transmission grid (km)	2	3	60	2
C5—Environmental	C5.1	Distance to protected areas (binary)	1	9	1	9

What needs explaining are the values of alternatives for sub-criterion C5.4—a distance to protected areas. Because there is no possibility of attributing the "0" value to a criterion in the ANP and AHP, binary values reflected on Saaty's fundamental scale [66] was used here. When a location was situated outside, protected areas it got a "9", otherwise it was given a "1".

Another step was to determine dependencies between sub-criteria. The dependencies were formulated on the basis of the literature analysis. The dependencies between sub-criteria are presented in Table 7. In cells of Table 7, literature sources, from which information was taken about individual dependencies, were marked. The direction of dependency is defined from rows to columns, e.g., the sub-criterion C1.1 has influence on the C1.2.

Table 7. Dependencies between sub-criteria based on the literature sources

	C1.2	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1
C1.1	[38,41]						
C1.2		[38,41]					
C2.1				[86]	[86]		
C2.2				[48]		[87]	
C2.3					[52]		
C2.4						[87]	
C3.2							[14,28]
C4.1			[38]	[38]			
C4.2					[38]		

For the considered decision problem were constructed two network models considering dependencies between sub-criteria and a hierarchical model which does not consider dependencies of this type. One of the network models, which can be determined as complete, contained the considered decision alternatives. The second network model included only the aim of the decision, criteria and sub-criteria. Therefore, the evaluation of decision alternatives was not possible in the second model and it was constructed only for the sake of obtaining the weight of criteria and sub-criteria for comparison. The complete decision model containing decision alternatives and considering dependencies between sub-criteria is presented in Figure 3.

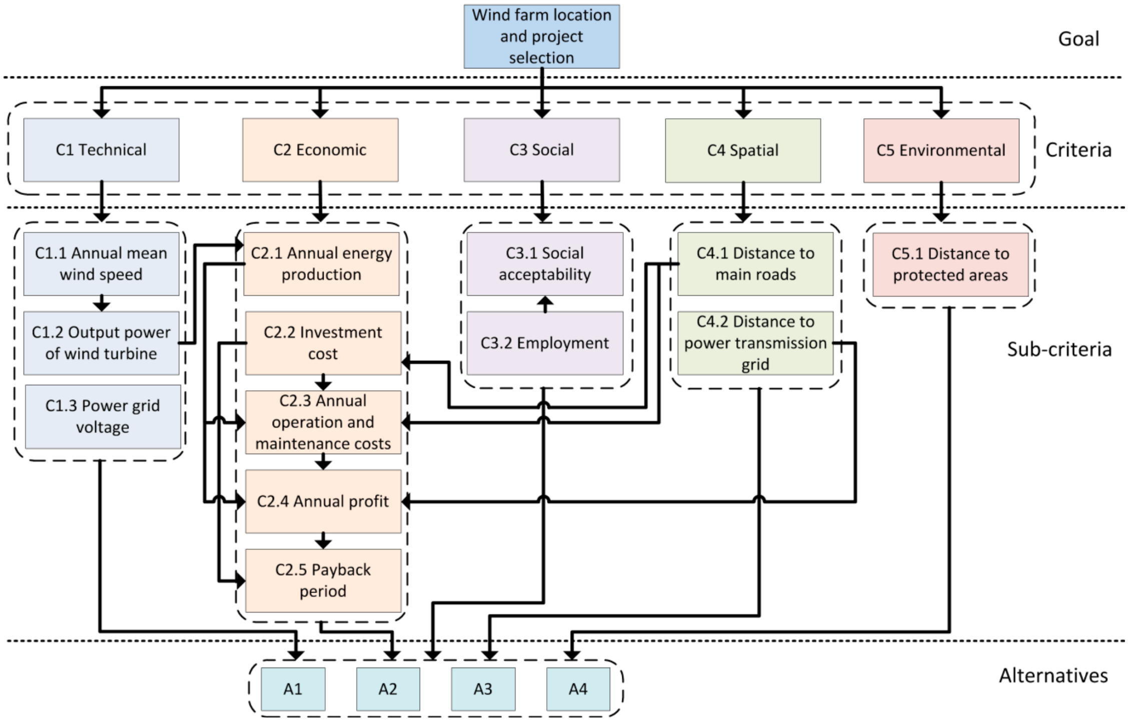


Figure 3. Decision model with alternatives and dependencies between sub-criteria

4.2. Modelling Preferences

The criteria and sub-criteria were attributed initial weights and preference directions presented in Table 8. Also, Table 8 contains sub-criteria weights obtained as a result of conducting the ANP computational procedures for network models with and without presented decision alternatives. It should be stressed that the AHP method, unlike the ANP, in the whole computational procedure uses criteria and sub-criteria weights defined at the beginning and it does not set their new values.

The analysis of Table 8 points out that the final weight of criteria (sub-criteria) changes significantly with reference to predefined values, as a result of applying the ANP calculation procedure. In general, the weight of a sub-criterion which other sub-criteria influence is increasing. Consequently, the weight of another sub-criteria in a given cluster is decreasing. Moreover, taking into consideration the cluster of alternatives in the decision model influences the result of sub-criteria weights. This effect can be seen in the case of an interdependent pair of sub-criteria C3.1 and C.3.2. The effect of weight changes takes also place in the case of sub-criteria which are not mutually dependent on each other, what can be illustrated by a criterion C1.3.

Table 8. Weights of criteria

Criteria	Predefined Weight	Sub-Criteria	Preference Direction	Weight—Predefined and AHP	Weight—ANP without Alternatives	Weight—ANP with Alternatives
C1	0.2	C1.1	max	0.333	0.25	0.286
		C1.2	max	0.333	0.5	0.428
		C1.3	max	0.333	0.25	0.286
C2	0.2	C2.1	max	0.2	0.118	0.16
		C2.2	min	0.2	0.061	0.116
		C2.3	min	0.2	0.151	0.185
		C2.4	max	0.2	0.306	0.293
		C2.5	min	0.2	0.364	0.246
C3	0.2	C3.1	max	0.5	0.667	0.6
		C3.2	max	0.5	0.333	0.4
C4	0.2	C4.1	min	0.5	0.5	0.5
		C4.2	min	0.5	0.5	0.5
C5	0.2	C5.1	max	1	1	1

4.3. Investigating and Developing the Recommendation

4.3.1. Preference Aggregation

The last stage was to determine the utilities and ranking of alternatives as well as the analysis of the utilities and ranking. The rankings obtained for the AHP and ANP methods are shown in Table 9.

Table 9. Utility and rank of alternatives.

Alternative		A1	A2	A3	A4
Utility	AHP	0.237	0.275	0.195	0.293
	ANP	0.235	0.279	0.218	0.268
Rank	AHP	3	2	4	1
	ANP	3	1	4	2

When analysing Table 9, one can notice that the AHP and ANP rankings are different from one another with regard to the obtained values of alternative utilities. The differences result from, most of all, different weights of sub-criteria obtained by means of the AHP and ANP methods. The presentation of dependencies between sub-criteria also influences the obtained differences. The dependencies influence the form of a weighted supermatrix used in the AHP and ANP methods. Unweighted, weighted and limit supermatrices obtained for the AHP and ANP methods are shown in Appendix A. The most significant differences with regard to utilities can be noticed in the case of alternatives A3 and A4, since they amount to 0.023 and 0.025 respectively. The differences seem to be insignificant, however, they can influence their positions in the ranking. It is shown in the case of alternatives A2 and A4, for which a slight change in the utilities obtained by means of the ANP method with reference to the utilities determined by the AHP influenced the exchange of their positions in the rankings.

As for the comparison of qualities of rankings obtained with the AHP and ANP methods, it is not possible in a mathematical sense [88]. It results from the fact that MCDA methods, such as the AHP and ANP, are used in problems in which individual decision alternatives are Pareto-optimal solutions [89]. Also, in the decision problem which is being examined, all considered alternatives belong to Pareto-front solutions (they are Pareto-optimal solutions). However, Pareto-optimal solutions are not comparable in a mathematical programming sense. This means that one cannot formally decide which alternative is better than another one [90]. That's why, in the present paper, the comparison of the results obtained with the use of the AHP and ANP methods was conducted on the basis of a sensitivity analysis [91] and the examination of occurrence of the rank reversal phenomenon [92,93].

4.3.2. Sensitivity Analysis

The sensitivity analysis carried out by the author of the present paper is more precise than the analysis proposed by the author of the AHP and ANP methods, i.e. Saaty. Saaty finds out that because of the complexity of a network or hierarchical structure, the sensitivity analysis of precise numerical values is difficult to carry out, that's why he suggests using an abstract value P (perturbation) based on linear optimization and describing a trend of changes [66] (Chapter 15). However, in the sensitivity analysis presented in this paper, the precise numerical value of a weight of criteria and sub-criteria were obtained. A dedicated solution to a decision problem is obtained for these weights. Hence, such stability intervals based on the numerical value of weights were also determined.

In the presented model of a decision problem, there are two levels of a hierarchy of criteria. This fact has been used in the present author's sensitivity analysis. As a result, in this case, the sensitivity analysis is an issue consisting of three dimensions which are: possible weights of a criterion (e.g., C1) and a sub-criterion (e.g., C1.1) belonging to it as well as utilities of alternatives. It results from the fact that the real weight of a sub-criterion is the product of the weight of a criterion and a sub-criterion. For instance, for weights depicted in Table 8, the real predefined weight of sub-criteria C1.1, C1.2 and C1.3 amount to 0.0666. However, for a weight C1 = 0.1 and a weight C1.1 = 0.666, the real weight amounts to 0.0666, whereas for C1.2 and C1.3 the real weight C1.1 amounts to 0.01665. In consequence, for the two cases, where the real weight is C1.1 = 0.0666, the result will be different utility values of individual alternatives of individual values.

The sensitivity analysis was carried out on the basis of implementation of the AHP and ANP methods in the MATLAB software. Plane graphs presenting utility values of individual alternatives in the function of the weight of the criterion C1 and sub-criterion C1.1 are shown in Figure 4a (for the AHP method) and 4b (for the ANP method). Other graphs are depicted in Supplementary Materials.

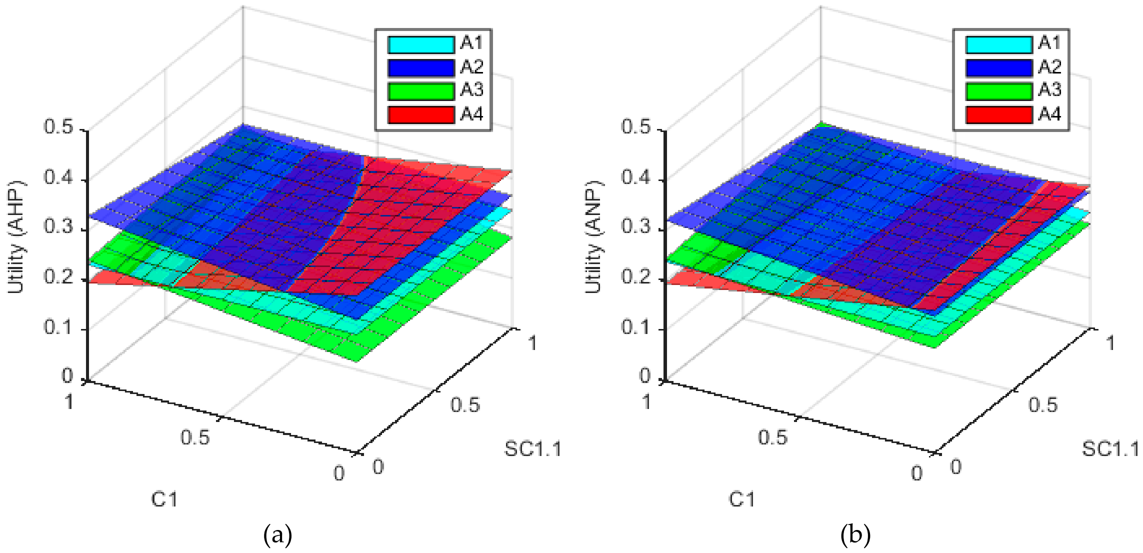


Figure 4. Utility of alternatives determined by means of: (**a**) the AHP method; (**b**) the ANP method; depending on the weight of the criterion C1 and sub-criterion C1.1.

Table 10 presents selected intervals of stability of the AHP and ANP solutions. Stability intervals for criteria were determined on the assumption that all sub-criteria contained in a given criterion have equal predefined weights. On the other hand, stability intervals for sub-criteria were determined on the assumption that superior criteria weights are equal. As a result of the sensitivity analysis it was found out that, assuming an equal weights of criteria, only changes to weights of sub-criteria presented in Table 10 can influence the ranking of alternatives.

Table 10. Stability intervals of rankings

AHP					ANP				
Criterion/ Sub-Criterion	**Stability Interval (Weight)**			**Nominal Weight**	**Criterion/ Sub-Criterion**	**Stability Interval (Weight)**			**Nominal Weight**
	Min	**Max**	**Range**			**Min**	**Max**	**Range**	
C1	0	0.32	0.32	0.2	C1	0.11	0.52	0.41	0.2
C2	0	0.63	0.63	0.2	C2	0	0.57	0.57	0.2
C3	0	0.33	0.33	0.2	C3	0	0.31	0.31	0.2
C4	0.13	0.4	0.27	0.2	C4	0.02	0.29	0.27	0.2
C5	0.11	1	0.89	0.2	C5	0.13	0.99	0.86	0.2
C2.2	0	0.95	0.95	0.2	C2.3	0	0.97	0.97	0.2
C2.6	0	0.95	0.95	0.2	C2.4	0	0.72	0.72	0.2
C4.1	0.01	1	0.99	0.5	C4.1	0	0.85	0.85	0.5
C4.2	0	0.99	0.99	0.5	C4.2	0.15	1	0.85	0.5

When analysing Table 10, it can be noticed that the ranking obtained with the AHP method is almost as stable as the solution generated by means of the ANP method. In both cases, the ranges of stability intervals, with relation to a predefined weight of criteria and sub-criteria (see Table 8), is wide enough to acknowledge the rankings obtained by means of both AHP and ANP as stable rankings.

4.3.3. Rank Reversal Phenomenon Analysis

The analysis of ranking robustness to the rank reversal phenomenon was based on the implementation of the AHP and ANP methods in the MATLAB software. The analysis was conducted by constructing an alternative A5 which was examined along with alternatives A1–A4. A ranking, which was obtained in this way, of five alternatives, was compared with the reference ranking presented in Table 9. If the sequence of alternatives A1–A4 was changed with relations to the reference ranking, the rank reversal phenomenon was considered to have taken place. The alternative A5 was constructed on the basis of random data in two ways, that is both (1) taking into consideration dependencies between sub-criteria and (2) without taking into account the above-mentioned dependencies.

In the case of constructing the alternative A5, in which inter-criteria dependencies were taken into account, only the values of independent sub-criteria were random, i.e. C1.1, C1.3, C3.2, C4.1, C4.2, C5.1. On the basis of the values of independent criteria, the values of the remaining sub-criteria were determined. The value interval of the sub-criterion C1.1 was determined on the basis of the annual average wind speed in Poland [94]. The value of C1.2 as a dependent sub-criterion was determined on the basis of the formula for the wind power energy for a generic turbine: $P = (1/2)dACv^3$, where d is the air density (equal to 1.225 kg/m3), A is the rotor's blades swept area (equal to 6362m2), Cp is the power coefficient (equal to 0.45), and v representing the wind speed [95]. The values of individual parameters of the formula were taken from the specification of one wind turbine [96]. Three permissible values of C1.3 result from the fact that the voltages of the national power grid of higher voltages used in Poland amount to 110kV, 220kV, and 400kV [97]. The value of C2.1 (annual energy production) was calculated as the product of the number of wind turbines (N), energy generated by a single turbine (C1.2) and the number of hours in a year (8760) [41]. Determining the value of C2.2 (investment cost) was based on the fact that the value of capital investment for an onshore wind farm in Poland amounts to 6.6 million PLN/MW [98]. Approximate costs of constructing a service road to the wind farm were added to the amount (1 million PLN/km). The calculations of C2.3 (operation and maintenance costs) take into consideration the fact that the operation costs of a wind farm in Poland amounts to 83 PLN per one MWh of the energy generated by the wind farm [98]. To the operation costs, the costs, estimated at 10.000 PLN/km, related to the transport and delivery of service elements were also added. To put it simply, a yearly profit (C2.4) from selling the energy can be determined as the difference between incomes from the energy sales and operational costs incurred to generate the energy sold. Incomes are above all influenced by a current energy price. However, new law defining so-called RES auctions has been recently introduced in Poland. The reference price, for an RES auction, of the onshore wind energy generated in a wind farm of combined power greater than 1MW in 2016 amounts to 385PLN/MWh [99].

The reference price in the bidding can be lowered to some extent, therefore, in the prepared simulation, the price of 345 PLN/MWh was taken. Moreover, it was assumed that the profit is reduced by the maintenance cost of the connection to the grid, estimated at 10.000 PLN/km. The payback period (C2.5) was calculated as a ratio of the investment costs to annual profits. Social acceptability (C3.1) is a random value increased by an employment factor amounting to 1% per 100 potential work places related to the construction and maintenance of a power plant. The number of potential work places (C3.2) was determined with the use of a conversion factor, according to which 1MW generates ca. 15.4 work places [98]. The distance to main roads (C4.1) and the distance to the power transmission grid (C4.2) were determined as random values within the range of 1–15 km, whereas for a criterion C5.1 (distance to protected areas) the value of yes or no was drawn. In addition, for some independent sub-criteria, deviation in the range of up to 15% of the calculated value was admitted.

The construction of the alternative A5 without taking into consideration dependencies between sub-criteria consisted in drawing the value of every sub-criterion C1.1–C5.1 from determined ranges of values. The ranges for the sub-criteria were calculated on the basis of minimal and maximal values which could be obtained with the use of the dependencies described above. The way of determining sub-criterion values for the alternative A5 is presented in detail in Table 11.

Table 11. The way of generating the alternative A5 which does not take into consideration and considers dependencies between sub-criteria.

Sub-Criterion	No Dependencies between Sub-Criteria	Implementation of Dependencies between Sub-Criteria
C1.1	*Random <5, 7.5> (m/s)*	*Random <5, 7.5> (m/s)*
C1.2	*Random <0.22, 0.74> (MW)*	$\left(\frac{1}{2} * 1.225 * 6362 * 0.45 * C1.1^3\right)/1000000$ *(MW)*
C1.3	*Random {110; 220; 400} (kV)*	*Random {110; 220; 400} (kV)*
C2.1	*Random <16321, 186311> (MWh)*	$(N * C1.2 * 8760)$ *+/- 15% (MWh)*
C2.2	*Random <169.2, 586.5> (mln PLN)*	$(P * 6.6 + C4.1)$ *+/- 15% (mln PLN)*
C2.3	*Random <1.16, 17.96> (mln PLN)*	$\left(\frac{C2.1*83}{1000000} + 0.01 * C4.1\right)$ *+/- 15% (mln PLN0*
C2.4	*Random <4.66, 73.91> (mln PLN)*	$\left(\frac{C2.1*345-C2.3}{1000000} - 0.01 * C4.2\right)$ *+/- 15% (mln PLN)*
C2.5	*Random <7.9, 36.3> (years)*	C2.2/C2.4 *(years)*
C3.1	*Random <19, 93> (%)*	*Random <15, 80>* $+0.01 * C3.2$ *(%)*
C3.2	*Random <393, 1328> (number)*	$P * 15.4$ *+/- 15% (number)*
C4.1	*Random <1, 15> (km)*	*Random <1, 15> (km)*
C4.2	*Random <1, 15> (km)*	*Random <1, 15> (km)*
C5.1	*Random {1; 9} (binary)*	*Random {1; 9} (binary)*
N	-	*Random <10, 25> (number)*
P	-	$N * 3$ *(MW)*

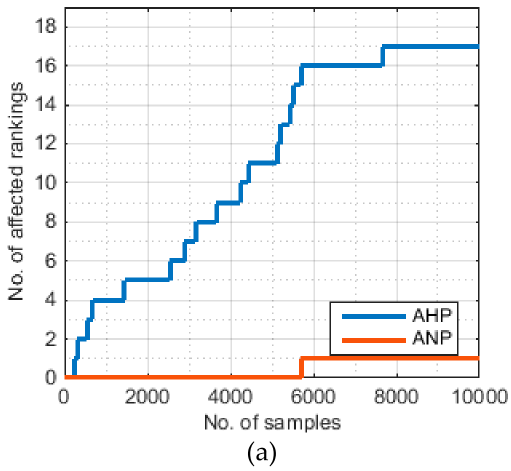
Abbreviations: N—number of turbines; P—installed power.

The results of examining the robustness of the rankings to the rank reversal phenomenon are shown in Table 12. It should be noted that the generator of random numbers before each test was reset, what guarantees the repeatability of results.

Table 12. The occurrence of the rank reversal phenomenon in examined rankings depending on the way of generating the alternative A5.

Dependencies between Sub-Criteria of the Alternative A5	The Number of Samples of the Alternative A5	AHP Ranking		ANP Ranking	
		The Number of Changed Rankings	The Number of Changes in Rankings	The Number of Changed Rankings	The Number of Changes in Rankings
Independent	1000 samples	4	7	0	0
	10,000 samples	17	32	1	2
Dependent	1000 samples	10	19	0	0
	10,000 samples	66	127	1	2

Figure 5a,b present the number of changed rankings depending on the number of samples of the alternative A5.



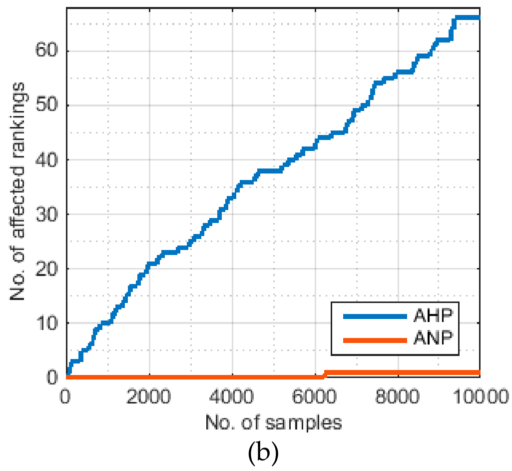


Figure 5. The number of changed rankings for the alternative A5 generated: (**a**) without considering dependencies between sub-criteria; (**b**) when taking into account dependencies between sub-criteria

The analysis of research results points out that when the alternative A5 was constructed without or with the implementation of dependencies between criteria, the ANP ranking had much higher robustness to the rank reversal. It might be assumed that the higher robustness resulted from the fact that the ANP method, unlike the AHP, took real dependencies between sub-criteria into consideration. The robustness of the rankings to the rank reversal phenomenon is especially important in decision problems in which new alternatives may appear for consideration. Decision problems related to the selection of wind farm location are this kind of problems.

It should be pointed out that conclusions drawn from the sensitivity analysis as well as the research into the rank reversal phenomenon occurrence refer only to the comparison of ranking shown in Table 9 and obtained by means of the AHP and ANP methods. Without further research, the results cannot be generalized and related to the quality of other solutions obtained by means of the indicated MCDA methods. However, on the basis of the conducted research in should be noted that the application of the ANP method in the decision problems concerning wind farm location and design makes it possible to obtain a solution with a higher value than by means of the AHP. Furthermore, after analysing the literature [23,25,64,100,101], one can find out that taking into consideration real dependencies between criteria in the decision model makes the model precisely reflect the real decision problem and allows obtaining a more reliable solution.

5. Discussion

The application analysis, presented in Section 2, of the MCDA methods in decision problems in the field of wind energy points out that in order to solve these problems the MCDA methods are used, although usually they do not take into consideration dependencies between criteria or they allow considering only hierarchical dependencies (criteria – sub-criteria). It takes place even though many authors notice that in such decision problems, methods which allow modelling dependencies between criteria ought to be used [15,24,25]. The ANP is a method of this kind. Due to this fact, the decision model, prepared for the problem of the selection of the location and design of a wind farm was based on the ANP method. Therefore, it takes into consideration complex dependencies between decision-making criteria. However, the ANP method does not meet all expectations with regard to the MCDA methods used in the RES issues [24,57–59], since it does not allow applying indifference and preference thresholds, therefore, the ANP is characterized by absolute discriminating power of the criteria. It indicates the need for further development of the MCDA methods and requires working out a method combining the features of the ANP (dependencies between criteria) and outranking methods (indifference and preference thresholds) such as PROSA (PROMETHEE for Sustainability Analysis) [77] and NEAT F-PROMETHEE (New Easy Approach To Fuzzy PROMETHEE) [76].

As part of the verification of the obtained solution, it has been demonstrated that taking into consideration dependencies between criteria in the decision model can influence the obtained recommendation of the decision. It was obtained by comparing solutions gained for the network ANP model and the hierarchical AHP model. A significant observation refers to the differences between sub-criteria weights (see Section 4.2). The weights were obtained by means of the ANP method with the considered cluster of alternatives or without it. The differences, in the author's opinion, question the publications in which the ANP method is only used to obtain the weight of criteria and sub-criteria, e.g., [28].

On the basis of the conducted sensitivity analysis and the research into the robustness of the rankings to the rank reversal phenomenon, it has been found out that the ranking obtained with the use of the ANP method is characterized by higher quality. Moreover, on the basis of the literature one can state that the solution obtained with the ANP method is more reliable owing to the fact that it considers inter-criteria dependencies [102]. However, it is obvious that the network model (ANP) allows reflecting the decision problem more precisely than the hierarchical model (AHP).

As regards the policy recommendations that can be defined on the basis of the study carried out, a number of issues need to be identified here, mainly related to the analysis of potential decision-making alternatives (see Table 6). First of all, it should be noted that in many areas of Poland a power grid with relatively low voltages is available (220kV). This grid should be systematically developed to operate at 400 kV and 750 kV voltages, which will improve the robustness of transmission lines against voltage and power fluctuations generated in the grid by high-capacity wind turbines. As regards the economics of this type of investment, it should be noted that the availability of the road network makes it possible to reduce investment costs and operating costs to a certain extent. Therefore, onshore wind farms should be located close to the main roads. However, in Poland, areas with good wind conditions are usually poorly covered with the road network. Therefore, in addition to the development of the power grid, the development of the road network is also important. Another issue is the relatively low public acceptance of wind energy investments. This is due to the fact that a few years ago in Poland wind energy was developed without taking into account social costs. Wind farms were built very close to human settlements, which resulted in a continuous decrease in public acceptance of this type of investment. Meanwhile, the development of wind energy should be carried out with respect for the inhabitants of the areas in the vicinity of which wind power plants are being built. This development should take into account not only economic and environmental but also social issues. Therefore, this development should be sustainable in economic, environmental and social terms.

Among the limitations of the study presented, it should be pointed out that the comparison of the AHP and ANP methods was carried out in a single case study. Therefore, conclusions drawn from the sensitivity analysis as well as the research into the rank reversal phenomenon occurrence only refer the decision problem presented in this study. Without further research, the results cannot be generalized and related to the quality of other solutions obtained by means of the indicated MCDA methods. However, on the basis of the conducted research it should be noted that the application of the ANP method in the decision problems concerning wind farm location and design makes it possible to obtain a solution with a higher value than by means of the AHP. Furthermore, after analysing the literature [23,25,64,100,101], one can find out that taking into consideration real dependencies between criteria in the decision model makes the model precisely reflect the real decision problem and allows obtaining a more reliable solution. Another constraint linked to the decision problem itself is that the decision-maker, when considering a similar decision problem, may formulate other criteria, the inclusion of which may, of course, be given a different ranking of alternatives. Finally, it should be noted that this is an ex-ante study so that the values of the alternatives in terms of evaluation criteria are uncertain and may change to some extent [103].

6. Conclusions

When summing up the studies carried out, it is important to note their methodological and practical contribution to management science, and in particular to the decision analysis. One should mention here:

- formal selection of the MCDA method for decision problems in the field of RES and sustainability, based on the analysis of intrinsic characteristics of individual methods,
- consideration of different locations and projects for the construction of onshore wind farms,
- comparison of rankings obtained using the AHP (without dependencies between criteria) and ANP (with inter-criteria dependencies) methods in order to assess the impact of such dependencies on the solution obtained,
- study of the quality of the solutions obtained through a sensitivity analysis and rank reversal phenomenon analysis.

Obviously, the prepared solution should be continuously developed. A natural direction of further work is to extend the decision model with other criteria and sub-criteria of evaluating onshore wind farms as well as to include other RES decision problems in the metamodel. Furthermore, an interesting issue would be presenting the decision model in the form of an ontology, what would make it possible to infer new knowledge from the model [104]. It would also be a natural development of the functionality of the model in the direction of an ontological knowledge base.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/4/749/s1, Figure S1–12: Utility of alternatives determined by means of: (a) the AHP method; (b) the ANP method; depending on the weight of the criterion Cx and sub-criterion Cx.y.

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Appendix A Unweighted, Weighted and Limit Supermatrices

Table A1. AHP unweighted and weighted supermatrix

	A1	A2	A3	A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1	C3.2	C4.1	C4.2	C5.1	C1	C2	C3	C4	C5	Goal
A1	0	0	0	0	0.251	0.257	0.208	0.310	0.196	0.180	0.310	0.257	0.347	0.350	0.224	0.370	0.05	0	0	0	0	0	0
A2	0	0	0	0	0.265	0.282	0.377	0.251	0.266	0.223	0.251	0.281	0.141	0.200	0.135	0.247	0.45	0	0	0	0	0	0
A3	0	0	0	0	0.259	0.277	0.208	0.304	0.215	0.184	0.304	0.277	0.359	0.274	0.192	0.012	0.05	0	0	0	0	0	0
A4	0	0	0	0	0.225	0.184	0.208	0.135	0.323	0.413	0.135	0.185	0.153	0.176	0.449	0.370	0.45	0	0	0	0	0	0
C1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C2.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
C3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
C4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
Goa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A2. ANP unweighted supermatrix

	A1	A2	A3	A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1	C3.2	C4.1	C4.2	C5.1	C1	C2	C3	C4	C5	Goal
A1	0	0	0	0	0.251	0.257	0.208	0.310	0.196	0.180	0.310	0.257	0.347	0.350	0.224	0.370	0.05	0	0	0	0	0	0
A2	0	0	0	0	0.265	0.282	0.377	0.251	0.266	0.223	0.251	0.281	0.141	0.200	0.135	0.247	0.45	0	0	0	0	0	0
A3	0	0	0	0	0.259	0.277	0.208	0.304	0.215	0.184	0.304	0.277	0.359	0.274	0.192	0.012	0.05	0	0	0	0	0	0
A4	0	0	0	0	0.225	0.184	0.208	0.135	0.323	0.413	0.135	0.185	0.153	0.176	0.449	0.370	0.45	0	0	0	0	0	0
C1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C2.1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0.2	0	0	0	0
C2.3	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0.5	0	0	0	0.2	0	0	0	0
C2.4	0	0	0	0	0	0	0	0.5	0	1	0	0	0	0	0	1	0	0	0.2	0	0	0	0
C2.5	0	0	0	0	0	0	0	0	0.5	0	1	0	0	0	0	0	0	0	0.2	0	0	0	0
C3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.5	0	0	0
C3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
C4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
Goa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A3. ANP weighted supermatrix

	A1	A2	A3	A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1	C3.2	C4.1	C4.2	C5.1	C1	C2	C3	C4	C5	Goal
A1	0	0	0	0	0.126	0.129	0.208	0.155	0.098	0.090	0.155	0.257	0.347	0.175	0.112	0.185	0.05	0	0	0	0	0	0
A2	0	0	0	0	0.133	0.141	0.377	0.125	0.133	0.111	0.125	0.281	0.141	0.100	0.067	0.123	0.45	0	0	0	0	0	0
A3	0	0	0	0	0.129	0.138	0.208	0.152	0.108	0.092	0.152	0.277	0.359	0.137	0.096	0.006	0.05	0	0	0	0	0	0
A4	0	0	0	0	0.112	0.092	0.208	0.068	0.161	0.206	0.068	0.185	0.153	0.088	0.224	0.185	0.45	0	0	0	0	0	0
C1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.2	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0	0
C2.1	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
C2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0.2	0	0	0	0
C2.3	0	0	0	0	0	0	0	0.25	0.25	0	0	0	0	0	0.25	0	0	0	0.2	0	0	0	0
C2.4	0	0	0	0	0	0	0	0.25	0	0.5	0	0	0	0	0	0.5	0	0	0.2	0	0	0	0
C2.5	0	0	0	0	0	0	0	0	0.25	0	0.5	0	0	0	0	0	0	0	0.2	0	0	0	0
C3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0.5	0	0	0
C3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
C4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
C5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
Goa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A4. AHP limit supermatrix

	A1	A2	A3	A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1	C3.2	C4.1	C4.2	C5.1	C1	C2	C3	C4	C5	Goal
A1	0	0	0	0	0.251	0.257	0.208	0.310	0.196	0.180	0.310	0.257	0.347	0.350	0.224	0.370	0.05	0.119	0.125	0.174	0.149	0.025	0.079
A2	0	0	0	0	0.265	0.282	0.377	0.251	0.266	0.223	0.251	0.281	0.141	0.200	0.135	0.247	0.45	0.154	0.127	0.085	0.095	0.225	0.092
A3	0	0	0	0	0.259	0.277	0.208	0.304	0.215	0.184	0.304	0.277	0.359	0.274	0.192	0.012	0.05	0.124	0.128	0.158	0.051	0.025	0.065
A4	0	0	0	0	0.225	0.184	0.208	0.135	0.323	0.413	0.135	0.185	0.153	0.176	0.449	0.370	0.45	0.103	0.119	0.082	0.205	0.225	0.098
C1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.167	0	0	0	0	0.022
C1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.167	0	0	0	0	0.022
C1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.167	0	0	0	0	0.022
C2.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.013
C2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.013
C2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.013
C2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.013
C2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.013
C3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0.033
C3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0.033
C4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.033
C4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.033
C5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.067
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.067
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.067
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.067
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.067
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.067
Goa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A5. ANP limit supermatrix

	A1	A2	A3	A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1	C3.2	C4.1	C4.2	C5.1	C1	C2	C3	C4	C5	Goal
A1	0	0	0	0	0.134	0.142	0.208	0.157	0.131	0.133	0.189	0.257	0.347	0.232	0.121	0.187	0.05	0.095	0.101	0.155	0.098	0.025	0.068
A2	0	0	0	0	0.136	0.140	0.377	0.139	0.157	0.140	0.177	0.281	0.141	0.114	0.105	0.147	0.45	0.112	0.099	0.069	0.080	0.225	0.081
A3	0	0	0	0	0.138	0.147	0.208	0.157	0.140	0.136	0.194	0.277	0.359	0.211	0.115	0.087	0.05	0.098	0.105	0.150	0.065	0.025	0.063
A4	0	0	0	0	0.104	0.095	0.208	0.099	0.165	0.164	0.107	0.185	0.153	0.110	0.197	0.152	0.45	0.074	0.084	0.071	0.112	0.225	0.078
C1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.126	0	0	0	0	0.019
C1.2	0	0	0	0	0.256	0	0	0	0	0	0	0	0	0	0	0	0	0.190	0	0	0	0	0.029
C1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.126	0	0	0	0	0.019
C2.1	0	0	0	0	0.128	0.262	0	0	0	0	0	0	0	0	0	0	0	0.095	0.078	0	0	0	0.026
C2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.134	0	0	0	0.078	0	0.045	0	0.019
C2.3	0	0	0	0	0.032	0.066	0	0.138	0.148	0	0	0	0	0	0.168	0	0	0.016	0.111	0	0.056	0	0.030
C2.4	0	0	0	0	0.048	0.098	0	0.207	0.074	0.286	0	0	0	0	0.084	0.286	0	0.024	0.146	0	0.117	0	0.048
C2.5	0	0	0	0	0.024	0.049	0	0.103	0.185	0.143	0.333	0	0	0	0.076	0.143	0	0.012	0.171	0	0.070	0	0.040
C3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0	0	0	0.032	0.026	0.333	0	0	0.043
C3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.222	0	0	0.029
C4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.178	0	0.029
C4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.178	0	0.029
C5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.058
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058
Goa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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