An Ontology-Based Knowledge Representation of MCDA Methods

Jarosław Wątróbski[1] and Jarosław Jankowski[1,2(✉)]

[1] West Pomeranian University of Technology,
Żołnierska 49, 71-210 Szczecin, Poland
jwatrobski@wi.zut.edu.pl,
jaroslaw.jankowski@pwr.edu.pl

[2] Department of Computational Intelligence,
Wrocław University of Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Abstract. Multiple-criteria decision analysis methods are widely used as tools supporting a decision problem. The article presents the taxonomy of the methods, which takes into consideration the most essential characteristics. This taxonomy, in the conceptualization process, was written by means of description logic and then it was implemented in the OWL language in the form of ontology representing field knowledge in the scope of MCDA methods. The research also considers the ontology verification prepared with the use of competency questions.

Keywords: Ontology · Multiple-criteria decision analysis (MCDA) · Knowledge management

1 Introduction

Along with the development of operational research, an alternative approach evolution of MCDA methods has been observed. This alternative approach applies both in theoretical studies that result in the continuous development of existing methodologies and techniques, as well as the application layer covering new areas of application methods in business practice. The result of the aforementioned statement is the demand for the development of dedicated approaches adjusted to the specifics of the problem. This is supported by a detailed literature review, where research in various scientific disciplines is effectively conducted with the use of a number of multi-criteria methods [35, 39]. Combined with a variety of specific decision problems discussed by the authors of studies in this area, the natural direction of research can be an attempt to systematize the knowledge in this field [21]. Large heterogeneity of domain knowledge including available scientific publications and the existing decision support systems is an additional prerequisite for undertaking research in this field. In the literature, one can notice attempts to develop models of knowledge representation of MCDA problems and methods areas. For example, the paper [29] demonstrates an ontology designed to describe the structure of decision-making problems. In [31] an ontological representation of the AHP method and a set of inference rules was presented. Earlier studies of

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systematized knowledge about various aspects of decision-making are shown in [32, 33]. Article [32] discusses the use of ontology knowledge model integrating knowledge about decision-making process (i.e. a set of alternatives, preferences). The proposed approach was later extended by additional ontology components [33]. Presented works deal with the problem of systematization of knowledge about the various MCDA methods only to a small extent. The knowledge about the characteristics of the different MCDA methods, their environmental context and use cases [30] is not included in characterized ontologies.

This article constitutes part of wider works which aim is to construct the ontology of MCDA methods which allows to choose a proper method depending on the characteristics of decision problems. This ontology, in its final form, should take into consideration aspects such as: characteristics of individual methods, information about the environmental context of their applications and concrete cases of application of the MCDA methods to solve specific decision problems. The possible construction of such a repository in the form of ontology allows formal specification and analysis of the various MCDA methods, as well as consequent sharing and reusing that domain knowledge [24]. The diagram depicting the construction of discussed ontology is presented in Fig. 1.

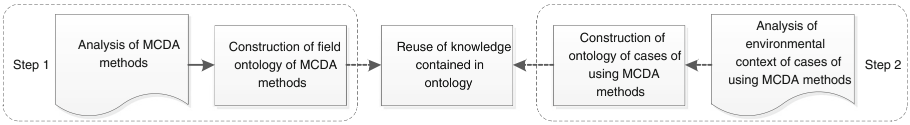


Fig. 1. Process of constructing ontology of MCDA methods and their applications

The aim of this paper is to develop the first stage of such solution, i.e. domain ontology containing knowledge model of MCDA methods. In order to construct such a solution, literature related to MCDA methods was reviewed and analyzed. This formed the basis of the development of a taxonomy and ontology. The study was divided into two parts: a discussion of the literature as well as the development of a taxonomy together with the practical verification of author's ontology using competency questions. The work constitutes a continuation of research described in the article [25]. The taxonomy, presented in the work, of a subset of MCDA methods was completed in this study. Furthermore, functional ontology for a broaden set of MCDA methods was worked out and verified. The engineer form of the ontology was presented with the use of the OWL standard and is available online [37].

2 Methods of Multi-Criteria Decision Analysis

The development of two main groups of methods and directions: approaches based on value/utility theory and outranking relations [19] is based on the research into the MCDA area. The utility theory-based approach derives from the American MCDA school. Two types of relationships between alternatives are determine: indifference ($a_i \, I \, a_j$) and preference ($a_i \, P \, a_j$) of one alternative over another. The methods in this group leave out non-comparability of the decision variants and assume transitivity and completeness of preference [19]. Methods based on outranking relations stem from the European MCDA school. Methods from this group frequently expand a set of basic preferential situations with the result that includes indifference of decision variants (a_i I a_j), weak preference one variant over another (a_i Q a_j), the strict preference of a variant of the decision-making relative to the other (a_i P a_j), and incomparability between data variations (a_i R a_j) [34]. Moreover, the preferential situations can be combined in "outranking" relation which contains the situations of indifference, strong and weak preference (a_i S a_j) [34]. In the literature two basic operational approaches can be distinguished to aggregate performance of variants: (1) aggregate to a single criterion (American school), (2) aggregation by using the outranking relationship (European MCDA school) [34]. Also, mixed (indirect) approaches, which combine elements of American and European decision-making schools, are applied. An example of this approach can be a group of PCCA (Pairwise Criterion Comparison Approach) methods [18]. A number of researchers acknowledge that the discussed groups of methods also differ in the occurrence of the criteria compensation effect. The compensation itself is that bad performance on one attribute can be compensated by good performance on other attributes [34]. While the difference between the two discussed groups of methods lies in the fact that in methods based on the value/utility theory there is a compensation, whereas methods employing the outranking relation by many researchers are considered non-compensatory [19]. Roy specifies that the difference refers to operational approaches in particular [34]. However, other researchers claim that the methods employing an exceeding relation are characterized by partial compensation [20]. Particularly Guitouni and Martel [21] state that there are no unanimous definitions or principles to characterize the degree of compensation. They distinguish three degrees of compensation (1) absolute compensation - a good performance on one criterion can easily counterbalance a poor one on another, e.g. weighted sum; (2) no compensation - some dimensions are important enough to refuse any kind of compensation or trade-offs, e.g. lexicographic method; (3) partial compensation - some kind of compensation is accepted between the different dimensions or criteria. They classify the majority of American and European Schools methods as the last group. MCDA methods also differ in nature and characteristics of data which are used in them [21]. The nature of date is closely related to the measurement scale. The data can be qualitative or quantitative and therefore can be expressed in the ordinal (qualitative) or cardinal (quantitative) scale. Moreover, the cardinal scale can be ratio or interval [22]. The characteristics of the data used refers to whether the data is certain or not [19]. Certain data, named also deterministic, is expressed in a crisp form, whereas uncertain data (non-deterministic) is represented by some kind of distribution (discrete or continuous) [21]. Furthermore, many new methods based on the fuzzy set theory enable to express uncertain data in a fuzzy form [34]. All the elements characterized above were taken into consideration in the prepared taxonomy and ontology. Based on an analysis of the literature, a complex set of available MCDA methods was identified. Part of the set was presented in the paper [25], whereas its development was included in this article.

In the future research one needs to take into consideration the decision-making issues considered by means of individual methods and their characteristics resulting from the uniqueness of a decision problem (e.g. the ability of a method to apply qualitative, quantitative or relative criteria weights, the ability to compare the productivity of variants, applying threshold values for the criteria comparisons of variants).

3 Constructing Ontology of Multi-Criteria Decision Analysis Methods

In the literature ontology is treated as the specification of conceptualization providing a description of the concepts and relationships that take place between them [27]. The application of ontologies as a solution supporting the choice of a given MCDA method is designed to assist the user in selecting the proper solution for a particular decision situation described using a specific criteria. Also, the ontology ought to provide detailed information about various MCDA methods. The first action in the construction of ontology is to develop a taxonomy of the MCDA methods. The identification and analysis of 20 MCDA methods was allowed to create a set of criteria and sub-criteria characterizing different solutions. A total set was formed comprising four main criteria (available binary relations, linear compensation effect, the type of aggregation and the type of preferential information) as well as 16 sub-criteria. This collection was the basis for the construction of taxonomies of analyzed solutions as well. Table 1 depicts the taxonomy of a subset of MCDA methods. The individual positons of Table 1 are characterized in Chapter 2. The subset extends the state of authors' research presented in [25].

Taxonomy presented in Table 1 should be converted to an ontological form and requires distinguishing the concept on the basis of criteria and sub-criteria and establishing their hierarchy [26]. In the ontology there are four types of taxonomic relations: the conclusion of the concepts, concepts separation, division, and total partition. Containment (subsumption) (Subclass-Of) concept C_1 in the concept of C means that C_1 is a subclass of (detailing of) C. This is due to concept C_1's inheritance of attributes of concept C. The subsumption of the concepts can be understood as the inclusion of the sets, as shown in Fig. 2(a). Severability (Disjoint-Decomposition) concepts C_1 and C_2 containing the concept of C means each occurrence (instance) of concept C affects the simultaneous occurrence of concept C_1 or C_2, but the occurrence of C_1 and C_2 cannot be at the same time. Furthermore, it may be the instance of C in the absence of the occurrence of concepts C_1 or C_2. Acceptable occurrences of concepts (instances I_1, I_2, I_3) while maintaining severability are shown in Fig. 2(b). The complete division (Exhaustive-Decomposition) concepts C_1 and C_2 containing a concept C is that each instance of C must be occurrence concept C_1, C_2 or both C_1 and C_2. In other words, the occurrence of concept C is also contained in the occurrence of total concepts C_1 and C_2. This situation is shown in Fig. 2(c) where a partition created with concepts C_1 and C_2 contained in the concept C is that each instance of concept C is also the occurrence concept C_1 or C_2. Partition concepts C_1 and C_2 can be understood as the sum of disjoint sets, as shown in Fig. 2(d). Figure 3 depicts a graphical diagram of a set of criteria and sub-criteria of constructed ontology. The authors decided to use concepts in the ontology, since the instances of concepts had been reserved in this case for reference

Table 1. Taxonomy of selected MCDA methods

Criterion	Available binary relations					Linear compensation effect			Type of aggregation			Type of preferential information					
Method name	I	P	Q	R	S	No	Total	Partial	Single criterion	Outranking	Mixed	Deterministic	Cardinal	Non-deterministic	Ordinal	Fuzzy	Reference
IDRA	Y	Y						Y			Y	Y	Y	Y			[1]
MAPPAC	Y	Y	Y	Y				Y			Y	Y	Y				[2]
PRAGMA	Y	Y		Y				Y			Y	Y	Y				[3]
PACMAN	Y	Y	Y	Y				Y			Y	Y	Y		Y		[4]
ARGUS	Y			Y	Y			Y		Y		Y		Y	Y		[5]
QUALIFLEX				Y	Y			Y			Y	Y			Y		[6]
Lexicographic method	Y	Y				Y			Y			Y	Y		Y		[7]
TACTIC	Y	Y		Y				Y		Y		Y	Y	Y			[8]
MACBETH	Y	Y						Y	Y			Y	Y	Y	Y		[9]
Fuzzy AHP	Y	Y						Y	Y			Y	Y	Y		Y	[10]
ANP	Y	Y						Y	Y			Y	Y	Y			[11]
Fuzzy ANP	Y	Y						Y	Y			Y	Y	Y		Y	[12]
Fuzzy PROMETHEE I	Y	Y		Y				Y		Y		Y	Y	Y	Y	Y	[13]
Fuzzy PROMETHEE II	Y	Y						Y		Y		Y	Y	Y	Y	Y	[13]
NAIADE I				Y	Y			Y		Y		Y	Y	Y	Y	Y	[14]
NAIADE II					Y			Y		Y		Y	Y	Y	Y	Y	[14]
PAMSSEM I				Y	Y			Y		Y		Y	Y	Y	Y	Y	[15]
PAMSSEM II					Y			Y		Y		Y	Y	Y	Y	Y	[15]
Fuzzy TOPSIS	Y	Y					Y		Y			Y	Y	Y		Y	[16]
COMET	Y	Y					Y		Y			Y	Y	Y	Y	Y	[17]

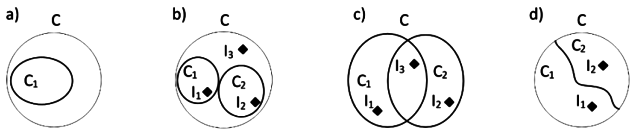


Fig. 2. Taxonomic relations between ontology concepts: (a) subsumption, (b) disjoint-decomposition, (c) exhaustive-decomposition, (d) partition

literature cases of applying individual methods in accordance with the structure of a decision problem. Such instances will be attached to the ontology in the future.

Part of ontology (set of criteria) written in the form of description logics [28] was concluded in expressions (1) – (10). Parts (1) – (4) of expressions indicate the criteria containing a (subsumption) in the concept of "Criterion". Expression (5) means the individual criteria are disjoint. Separation is used here because the individual criteria are independent of each other, but the taxonomy can be added to the new criteria. Records (6) – (8) describe the contents of the concept of "Linear compensation effect". The expressions (9) and (10) define a partition of concepts included in the criterion of "Linear compensation effect". It should be done due to the fact that the content of the concept of "Linear compensation effect" is complete and will not be added to it in the future. In addition, one method may meet only one of the sub-criteria (e.g. only supports the "Partial linear compensation effect"). In a similar manner a space is defined as the criterion "Type of aggregation".

$$\text{Linear compensation effect} \subseteq \text{Criterion} \quad (1)$$

$$\text{Available binary relations} \subseteq \text{Criterion} \quad (2)$$

$$\text{Type of aggregation} \subseteq \text{Criterion} \quad (3)$$

$$\text{Type of preferential information} \subseteq \text{Criterion} \quad (4)$$

$$\begin{gathered}\text{Linear compensation effect} \equiv \neg\text{Available binary relations}\ldots \\ \ldots \equiv \neg\text{Type of aggregation} \equiv \neg\text{Type of preferential information}\end{gathered} \quad (5)$$

$$\text{No linear compensation effect} \subseteq \text{Linear compensation effect} \quad (6)$$

$$\text{Partial linear compensation effect} \subseteq \text{Linear compensation effect} \quad (7)$$

$$\text{Total linear compensation effect} \subseteq \text{Linear compensation effect} \quad (8)$$

$$\begin{gathered}\text{Linear compensation effect} \equiv \text{No linear compensation effect} \ldots \\ \ldots \cup \text{Partial linear compensation effect} \cup \text{Total linear compensation effect}\end{gathered} \quad (9)$$

$$\begin{gathered}\text{No linear compensation effect} \equiv \neg\text{Partial linear compensation effect} \ldots \\ \ldots \equiv \neg\text{Total linear compensation effect}\end{gathered} \quad (10)$$

A bit otherwise specified content criteria include "Type of preferential information" and "Available binary relations". In the case of the criterion "Type of preferential information" and its sub-criteria, complete division was applied, which describes the expressions (11) – (16). Complete division was used due to the fact that different methods of MCDA can simultaneously use different types of preferential information, but there is no other type of preferential information than those in the concept of "Type of preferential information" (the contents of this concept is complete).

$$\text{Cardinal} \subseteq \text{Type of preferential information} \quad (11)$$

$$\text{Fuzzy} \subseteq \text{Type of preferential information} \quad (12)$$

$$\text{Non-deterministic} \subseteq \text{Type of preferential information} \quad (13)$$

$$\text{Deterministic} \subseteq \text{Type of preferential information} \quad (14)$$

$$\text{Ordinal} \subseteq \text{Type of preferential information} \quad (15)$$

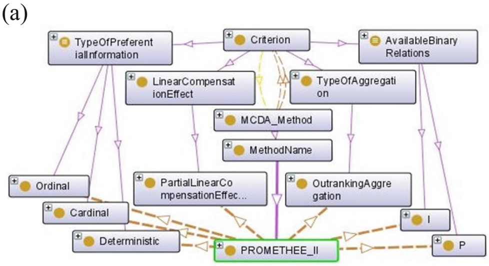
$$\text{Type of preferential information} \equiv \text{Cardinal} \cup \text{Fuzzy}\ldots \\ \ldots \cup \text{Non-deterministic} \cup \text{Deterministic} \cup \text{Ordinal} \tag{16}$$

In a similar way the space of criterion “Available binary relations” was defined. Inside criterion “Available binary relations” including relations R, S, I, P, Q complete division was applied. Exhaustive-decomposition was used due to the fact that the other type of relation between variants evaluated with the use MCDA methods does not exist. Meanwhile these relations can exist together in single method. The ontology offers a set of MCDA methods shown in Table 1, with a set of differentiating criteria and a network of taxonomic relationships between concepts (relations between different classes of instances). Using this ontology, it is possible to select methods based on selected criteria. This is the base for a simple reusable but structured domain knowledge area. Based on preset criteria a user can obtain detailed information about the satisfying method (methods) with its specific taxonomic characteristics. A sample set of results is depicted in Fig. 3a, illustrating a method (here Promethee II) which met the criteria for the query: binary relations P and I, the partial effect of linear compensation, aggregation using outranking relations, the type of preferential information – ordinal, cardinal and deterministic. To answer the ontology’s competence question, the Protege editor’s extension named “DL Query” was used. The tool allows formulating questions and asking the ontology the questions in accordance with the Manchester OWL (Web Ontology Language) [23] syntax and writing the question in the form of the ontology classes. The question had the form of: “*MCDA_Method and (hasCriterion some P and hasCriterion some I and hasCriterion some PartialLinearCompensationEffect and hasCriterion some OutrankingAggregation and hasCriterion some Ordinal and hasCriterion some Cardinal and hasCriterion some Deterministic)*”. A sample reasoning process [40] has the following course in this case: *PROMETHEE_II SubClassOf hasCriterion some I; isCriterion inverseOf hasCriterion; isCriterion Range MCDA_-Method; PROMETHEE_II SubClassOf hasCriterion some P; PROMETHEE_II SubClassOf hasCriterion some OutrankingAggregation; PROMETHEE_II SubClassOf hasCriterion some PartialLinearCompensationEffect; PROMETHEE_II SubClassOf hasCriterion some Ordinal; PROMETHEE_II SubClassOf hasCriterion some Cardinal; PROMETHEE_II SubClassOf hasCriterion some Deterministic*. The key stage in the presented reasoning is concluding a reverse relation isCriterion and hasCriterion as well as determining the scope of the relation isCriterion to the concept MCDA_-Method. On the basis a reasoning mechanism is able to conclude that the concept PROMETHEE_II is a subclass of the concept MCDA_Method. A further query to the ontology was created using the SPARQL language [36]. Inquiries to the knowledge base in SPARQL may relate only to the knowledge stored permanently and not that up to date by the inference. This allows a new structure of the knowledge base to be obtained that contains all the relationships between concepts and instances established through the mechanism of the applicant. Having deduced form prepared query ontology instances of multi-criteria methods, which use binary relations P and I and the aggregate results of the evaluation using outranking relations. The structure of competence query is listed below:

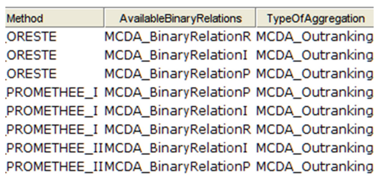
```
SELECT ?Method ?AvailableBinaryRelations ?TypeOfAggregation
WHERE {      ?Method rdf:type :MCDA_Method.
             ?Method rdf:type :MCDA_BinaryRelationP.
             ?Method rdf:type :MCDA_BinaryRelationI.
             ?Method rdf:type :MCDA_OutrankingAggregation.
             ?Method rdf:type ?AvailableBinaryRelations.
FILTER( REGEX(STR(?AvailableBinaryRelations),'BinaryRelation')).
             ?Method rdf:type ?TypeOfAggregation.
FILTER( REGEX(STR(?TypeOfAggregation),'Aggregation'))}
```

In the clause “SELECT” are defined variables that are to be displayed in the results, and in the clause “WHERE” are defined relationships that should exist between the variables. The relation of “rdf: type” specifies instances of a particular class. The competence query results are shown in Fig. 3b. The use of ontology as a tool to support the selection of the MCDA method allows a solution to be chosen that takes into account user-defined criteria on the basis of which only the MCDA methods or literature reference solutions that meet user-specified environmental determinants and decision-making are designated.

(a)



(b)



Method	AvailableBinaryRelations	TypeOfAggregation
ORESTE	MCDA_BinaryRelationR	MCDA_Outranking
ORESTE	MCDA_BinaryRelationI	MCDA_Outranking
ORESTE	MCDA_BinaryRelationP	MCDA_Outranking
PROMETHEE_I	MCDA_BinaryRelationP	MCDA_Outranking
PROMETHEE_I	MCDA_BinaryRelationI	MCDA_Outranking
PROMETHEE_I	MCDA_BinaryRelationR	MCDA_Outranking
PROMETHEE_II	MCDA_BinaryRelationI	MCDA_Outranking
PROMETHEE_II	MCDA_BinaryRelationP	MCDA_Outranking

Fig. 3. Results of the Manchester OWL competence query (a), and results of the SPARQL language competence query (b)

The same ontology contains the complete set of domain knowledge about the MCDA methods. This ontology has been built using Protege 4, using the OWL [28]. The MCDA ontology is available in [37] and the effect of the reasoner is given in [38].

4 Conclusion

This article deals with the issue of the construction of ontology of MCDA methods. On the basis of the analysis of MCDA methods a taxonomy characterizing the different solutions was demonstrated. It constituted the basis for the construction of ontology of

MCDA methods. The findings confirmed the possibility of the conceptualization of knowledge in the area of MCDA methods. The application of the proposed ontology supports the decision-maker's correct choice of a multi-criteria method and allows for full domain knowledge about each one. It ought to be noted that the standard employed for the construction of the ontology ensures compliance with international semantic standards. This makes it possible to further use the developed solution as well as its connection to other ontologies in various fields within the growing trend of knowledge engineering. Additional research needs to be supplemented by ontology of reference cases of the application of each method in various areas (management, logistics, environment, medicine, etc.). For ontology, further criteria characterizing the various methods and the environmental context of their use can be attached. It allows for the greater use of the adequacy of the reasoner and asks for the use of various methods in decision problems using SWRL language rules.

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References

1. Greco, S.: A new PCCA method: IDRA. Eur. J. Oper. Res. **98**(3), 587–601 (1997)
2. Matarazzo, B.: Multicriterion analysis of preferences by means of pairwise actions and criterion comparisons. Appl. Math. Comput. **18**(2), 119–141 (1986)
3. Matarazzo, B.: Preference ranking global frequencies in multicriterion analysis (Pragma). Eur. J. Oper. Res. **36**(1), 36–49 (1988)
4. Giarlotta, A.: Passive and Active Compensability Multicriteria ANalysis (PACMAN). J. Multi-Criteria Decis. Anal. **7**(4), 204–216 (1998)
5. De Keyser, W.S.M., Peeters, P.H.M.: ARGUS – a new multiple criteria method based on the general idea of outranking. In: Paruccini, M. (ed.) Applying Multiple Criteria Aid for Decision to Environmental Management, pp. 263–278. Kluwer, Dordrecht (1994)
6. Paelinck, J.H.P.: Qualitative multiple criteria analysis, environmental protection and multiregional development. Pap. Reg. Sci. Assoc. **36**(1), 59–74 (1976)
7. Fishburn, P.C.: Exceptional paper-lexicographic orders, utilities and decision rules: a survey. Manage. Sci. **20**(11), 1442–1471 (1974)
8. Vansnick, J.C.: On the problem of weights in multiple criteria decision making (the noncompensatory approach). Eur. J. Oper. Res. **24**(2), 288–294 (1986)
9. Bana e Costa, C.A., Vansnick, J.C.: MACBETH — An interactive path towards the construction of cardinal value functions. Int. Trans. Oper. Res. **1**(4), 489–500 (1994)
10. Mikhailov, L., Tsvetinov, P.: Evaluation of services using a fuzzy analytic hierarchy process. Appl. Soft Comput. **5**(1), 23–33 (2004)
11. Saaty, T.L.: The Analytic Network Process. RWS Publications, Pittsburgh (2001)
12. Promentilla, M.A.B., Furuichi, T., Ishii, K., Tanikawa, N.: A fuzzy analytic network process for multi-criteria evaluation of contaminated site remedial countermeasures. J. Env. Manag. **88**(3), 479–495 (2008)

13. Wang, T.C., Chen, L.Y., Chen, Y.H.: applying fuzzy PROMETHEE method for evaluating IS outsourcing suppliers. In: Fifth International Conference on Fuzzy Systems and Knowledge Discovery, vol. 3, pp. 361 – 365 (2008)
14. Munda, G.: Multicriteria Evaluation in a Fuzzy Environment. Theory and Applications in Ecological Economics. Physica-Verlag, Heidelberg (1995)
15. Guitouni, A., Martel, J.M., Belanger, M., Hunter, C.: Managing a Decision Making Situation in the Context of the Canadian Airspace Protection. DOCUMENT DE TRAVAIL 1999-021 (1999)
16. Chen, C.T., Lin, C.T., Huang, S.F.: A fuzzy approach for supplier evaluation and selection in supply chain management. Int. J. Prod. Econ. **102**(2), 289–301 (2006)
17. Sałabun, W.: The characteristic objects method: a new distance-based approach to multicriteria decision-making problems. J. Multi-Criteria Decis. Anal. **22**(1–2), 37–50 (2015)
18. Martel, J.M., Matarazzo, B.: Other outranking approaches. In: Figueira, J., Greco, S., Ehrgott, M. (eds.) Multiple Criteria Decision Analysis: State of the Art Surveys, pp. 197–262. Springer, Boston (2005)
19. Bana e Costa, C.A., Vincke, P.: Multiple criteria decision aid: an overview. In: Bana e Costa, C.A. (ed.) Readings in Multiple Criteria Decision Aid, pp. 3–14. Springer, Berlin Heidelberg (1990)
20. Bagheri Moghaddam, N., Nasiri, M., Mousavi, S.M.: An appropriate multiple criteria decision making method for solving electricity planning problems, addressing sustainability issue. Int. J. Env. Sci. Technol. **8**(3), 605–620 (2011)
21. Guitouni, A., Martel, J.M.: Tentative guidelines to help choosing an appropriate MCDA method. Eur. J. Oper. Res. **109**(2), 501–521 (1998)
22. Roy, B.: Paradigms and challenges. In: Figueira, J., Greco, S., Ehrgott, M. (eds.) Multiple Criteria Decision Analysis: State of the Art Surveys, pp. 3–24. Springer, Boston (2005)
23. W3C Working Group, http://www.w3.org/TR/owl2-manchester-syntax/
24. Hepp, M.: Ontologies: state of the art, business potential, and grand challenges. In: Hepp, M., de Leenheer, P., de Moor, A., Sure, Y. (eds.) Ontology Management. Semantic Web, Semantic Web Services, and Business Applications, pp. 2–23. Springer, Heidelberg (2008)
25. Wątróbski, J., Jankowski, J.: Knowledge management in MCDA domain. In: Proceedings of the Federated Conference on Computer Science and Information Systems. Annals of Computer Science and Information Systems, vol. 5, pp. 1445–1450 (2015)
26. Ziemba, P., Jankowski, J., Watróbski, J., Becker, J.: Knowledge management in website quality evaluation domain. In: Núñez, M., Nguyen, N.T., Camacho, D., Trawinski, B. (eds.) ICCCI 2015. LNCS, vol. 9330, pp. 75–85. Springer, Heidelberg (2015). doi:10.1007/978-3-319-24306-1_8
27. Gruber, T.R.: A translation approach to portable ontology specifications. Knowl. Acquisition **5**(2), 199–220 (1993)
28. http://protege.stanford.edu/
29. Chai, J., Liu, J.N.K.: An ontology-driven framework for supporting complex decision process. In: World Automation Congress (WAC) (2010)
30. Wątróbski, J., Jankowski, J., Piotrowski, Z.: The selection of multicriteria method based on unstructured decision problem description. In: Hwang, D., Jung, J.J., Nguyen, N.-T. (eds.) ICCCI 2014. LNCS, vol. 8733, pp. 454–465. Springer, Heidelberg (2014)
31. Liao, X.Y., Rocha Loures, E., Canciglieri, O., Panetto, H.: A novel approach for ontological representation of analytic hierarchy process. Adv. Mater. Res. **988**, 675–682 (2014)
32. Kornyshova, E., Deneckere, R.: Using an ontology for modeling decision-making knowledge. Front. Artif. Intell. Appl. **243**, 1553–1562 (2012)

33. Kornyshova, E., Deneckère, R.: Decision-Making ontology for information system engineering. In: Parsons, J., Saeki, M., Shoval, P., Woo, C., Wand, Y. (eds.) ER 2010. LNCS, vol. 6412, pp. 104–117. Springer, Heidelberg (2010)
34. Roy, B.: Multicriteria Methodology for Decision Aiding. Springer, Dordrecht (1996)
35. Velasquez, M., Hester, P.T.: An analysis of multi-criteria decision making methods. Int. J. Oper. Res. **10**(2), 56–66 (2013)
36. Della Valle, E., Ceri, S.: Querying the semantic web: SPARQL. In: Domingue, J., Fensel, D., Hendler, J.A. (eds.) Handbook of Semantic Web Technologies, pp. 299–363. Springer, Berlin (2011)
37. http://tinyurl.com/ontoMCDAext
38. http://tinyurl.com/ontoMCDAext-inferred
39. Piegat, A., Sałabun, W.: Comparative analysis of MCDM methods for assessing the severity of chronic liver disease. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.). LNCS, vol. 9119, pp. 228–238Springer, Heidelberg (2015)
40. Ziemba, P., Jankowski, J., Wątróbski, J., Wolski, W., Becker, J.: Integration of domain ontologies in the repository of website evaluation methods. In: Proceedings of the Federated Conference on Computer Science and Information Systems. Annals of Computer Science and Information Systems, vol. 5, pp. 1585–1595 (2015)