

Sustainable Decision-Making using the COMET Method: An Empirical Study of the Ammonium Nitrate Transport Management

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Abstract—This paper investigates the problem of the sustainable ammonium nitrate transport. The significance of this problem is increasing, considered the occurrence of the worldwide agricultural production boost. The existing international regulations for the transport of the dangerous chemical substances are not sufficient to obtain a satisfactory solution for the sustainable transport. The main reason for that is the fact that the safety criteria can easily become dominated by the economic factors.

In this paper, the authors use the COMET method to identify a decision making model for the selection of the best scenario of sustainable transport. The COMET method is a new multi-criteria decision-making technique that is free of the rank reversal phenomenon. The identified model provides information about the global and local significance level of each of the criteria. The proposed approach can be easily expanded by using a greater number of criteria, depending on the particular problem analyzed. The proposed methodology is an efficient and highly accurate solution to make decisions based on experts' knowledge.

I. INTRODUCTION

THE ammonium nitrate is one of the most popular mineral fertilizers in Poland and in Europe. It supports a highly developed agricultural industry [1], [2]. The carriage of the ammonium nitrate is regulated by international legal standards due to its dangerous nature [3]. The process of the registration of the transport of the ammonium nitrate and its classification to a group of hazardous materials determines a number of guidelines on its transport [4]. The obligation to ensure the compliance of the carriage of the ammonium nitrate with international laws and regulations for transporting dangerous materials by rail (RID - Règlement concernant le transport International ferroviaire des marchandises Dangereuses) and road (ADR - L' Accord européen relatif au transport international des marchandises Dangereuses par Route), affects the final time and cost of the transport of the product [4], [5].

The sustainable transportation systems should not only be efficient, robust and economical, but also friendly towards the environment, which is the requirement of the modern times [6]. They should minimize the impact on the environment, such as air pollution, noise, etc [7]. The evaluation and selection of the best scenario for the transportation system

is a big challenge. Many popular evaluation methods, such as Economic-Effects Analysis (EEA), private investment analysis and CBA, are considering mainly the economic effects [8], sometimes neglecting the ecological, spatial or social aspects of the transport scenario [9]. Even if those latter aspects are taken into account, for example in a Social Cost-Benefit Analysis (SCBA), it remains difficult to obtain a monetary assessment of all the criteria [10]. This challenge can be solved with a usage of appropriate multi-criteria decision making (MCDM) methods, which are frequently used in transportation systems' management problems [11], [12].

Generally, the MCDA methods can be divided into two groups: American and European schools. The former are based on a functional approach – a utility or value function is used [13], [14]. Two types of relationship among the alternatives are used in these methods, namely, the indifference and the preference. The incomparabilities of the variants are skipped. The pronounced downside of these methods is the fact that they do not consider the expert judgements' variability and uncertainty [15]. The methods from the latter group are based on a relational model. The relations of weak or strong preference, indifference or incomparability are used most commonly [16], and the outranking relation is used in the aggregation process to provide the final rankings of the studied alternatives [17]. Unfortunately, although the ranking of alternatives is produced in the European school methods, the quantitative information on the differences between alternatives is often lost.

Apart from the aforementioned groups of methods, there has also been some research that connects the MCDA approach of both of them [18]. Additionally, methods based on a rule sets exist. A range of the MCDA methods, along with their assignment to the American, European, mixed or rule set approach, is presented in Table I.

The MCDA methods from all the aforementioned groups have been successfully used to facilitate decision making in various kinds of transport management: land [49], [50], [55], maritime [47], [54] and air [27] transport. Some of the researched transport management decision problems also included the carriage of hazardous materials [55]. A comparison

TABLE I
MCDM METHODS FROM AMERICAN AND EUROPEAN SCHOOLS, MIXED AND RULE SET BASED.

School	Method Name	Abbreviation	Preference relations	References
American	multi-attribute utility theory	MAUT	indifference, preference	[19]
	multi-attribute value theory	MAVT	indifference, preference	[20]
	analytic hierarchy process	AHP	indifference, preference	[21]
	analytic network process	ANP	indifference, preference	[22]
	simple multi-attribute rating technique	SMART	indifference, preference	[23]
	utility theory additive	UTA	indifference, preference	[24]
	measuring attractiveness by a categorical based evaluation technique	MACBETH	indifference, preference	[25], [26], [27]
European	technique for order preference by similarity to ideal solution	TOPSIS	indifference, preference	[28]
	ELimination Et Choix Traduisant la REalite (ELimination and Choice Expressing the REality)	ELECTRE	incomparability, outranking	[29], [30]
	Preference Ranking Organization METHod for Enrichment of Evaluations	PROMETHEE	indifference, preference, incomparability	[31]
	Novel Approach to Imprecise Assessment and Decision Environment	NAIADE	incomparability, outranking	[32]
	Organisation, Rangement Et Synthese de donnees relationnelles	ORESTE	indifference, preference, incomparability	[33]
	REGIME	REGIME	incomparability, outranking	[34]
	ARGUS	ARGUS	indifference, incomparability, outranking	[35]
	Treatment of the Alternatives according To the Importance of Criteria	TACTIC	indifference, preference, incomparability	[36]
	Methode d'Elimination et de Choix Incluant les relation d'ORDre	MELCHIOR	incomparability, outranking	[36], [37]
	Procedure d'Agregation Multicritere de type Surclassement de Synthese pour Evaluations Mixtes	PAMSSEM	incomparability, outranking	[38]
mixed	Multicriteria Evaluation with MixedQualitative and Quantitative Data	EVAMIX	indifference, preference	[39]
	QUALitative FLEXible multiple criteria method	QUALIFLEX	incomparability, outranking	[40]
	(Multicriterion Analysis of Preferences by means of Pair-wiseActions and Criterion comparisons	MAPPAC	indifference, preference, weak preference, incomparability	[16]
	Preference Ranking Globalfrequencies in Multicriterion Analysis	PRAGMA	indifference, preference, incomparability	[16]
	Passive and Active Compensability MulticriteriaAnalysis	PACMAN	indifference, preference, weak preference, incomparability	[41]
	Intercriteria Decision Rule Approach	IDRA	indifference, preference	[42]
rule set	Characteristic Objects Method	COMET	indifference, preference	[43]
	Dominance-based Rough Set Approach	DRSA	indifference, preference, weak preference, incomparability	[44]

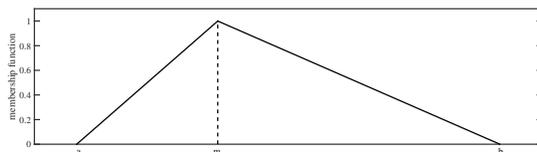


Fig. 1. An example of a triangular fuzzy number with the support $[a, b]$ and the core m .

of selected approaches of the MCDM methods' application in the transport management decision-making is presented in Table II. A further literature review can be found inter alia in [6], [57] and [58].

Unfortunately, the classical MCDM methods are often criticized for their possible shortcomings, such as the rank reversal phenomenon [59]. Therefore, new MCDM approaches have been developed to avoid the identified flaws. One of the issues considered is the fact that the decisions are often being made on the basis of multiple conflicting information sources. Based on these premises, a new MCDM method, Characteristic Objects Method (COMET) has been developed, which is

completely free of the Rank Reversal phenomenon [60].

The rest of this paper is organized as follows: in the next section, the Fuzzy Set Theory preliminaries are outlined. The third section describes the COMET method as a tool to identify the decision models. Subsequently, in section IV, an experiment to build a decision model for an exemplary ammonium nitrate transport is described and the results are presented. The conclusions and the possible future directions are presented in section V.

II. FUZZY SET THEORY: PRELIMINARIES

The development of fuzzy set theory was initiated by Lofti Zadeh, who presented the idea and the first conception of fuzzy sets in his "Fuzzy Sets" paper [61]. Today, the fuzzy set theory is a very important approach to the control and model creation in various scientific fields. Modeling with the usage of the fuzzy sets has proven to be an effective way to formulate the multi-criteria decision problems [62], [63], [64]. The basic notions and concepts of the Fuzzy Set Theory are defined below [65], [66], [67]:

Definition 1 The fuzzy set and the membership function

TABLE II
SAMPLE APPLICATIONS OF MCDA METHODS IN TRANSPORT MANAGEMENT SUSTAINABLE DECISION PROBLEMS.

Method	Application	Number of alternatives	Number of criteria	Reference
AHP	Selection of a location and design of a highway in a metropolitan area.	4	6	[45]
AHP	Selection of transportation fuels and policy for Singapore land transport.	10	6	[46]
AHP / EVAMIX	Evaluation of AGV Fleet Operation at Port Container Terminal. An attempt to increase of a container terminal productivity in order to reduce ship turnaround times.	12 scenarios	-	[47]
AHP / TOPSIS	Selection of alternative fuels for public transportation.	12	11	[48]
ANP	Selection of a third party logistic service provider.	-	23	[49]
ANP	Selection of a supplier.	-	10	[50]
Fuzzy AHP	Evaluation of environmental effects of 5 different transport modes.	5	9	[51]
Fuzzy TOPSIS	A methodology to support the outsourcing of the logistic services to third parties.	3	12	[52]
Fuzzy TOPSIS	Selection of the locations for urban distribution centers.	3	11	[53]
Fuzzy VIKOR	Creation of a decision-making model for the choice of a green reverse logistics solution.	6	5	[7]
MACBETH	Evaluation of air transport performance and efficiency. Self-benchmarking study of 3 airports.	-	8	[26]
MACBETH	Airlines Performance and Efficiency Evaluation, comparison of low cost carriers and legacy carriers.	6	18	[27]
MAPPAC / FANP	An integrated MAPPAC / FANP approach to the performance assessment of the Iranian maritime container terminals was researched.	6	18	[54]
ORESTE	A multi-criteria and multi-actor MCDA decision problem on the nuclear waste management.	27 actions	4	[55]
TOPSIS	Assessment of the improvement areas in the implementation of the green supply chain initiatives.	3	16	[56]

The characteristic function μ_A of a crisp set $A \subseteq X$ assigns a value of either 0 or 1 to each member of X , as well as the crisp sets only allow a full membership ($\mu_A(x) = 1$) or no membership at all ($\mu_A(x) = 0$). This function can be generalized to a function $\mu_{\tilde{A}}$ so that the value assigned to the element of the universal set X falls within a specified range, i.e., $\mu_{\tilde{A}} : X \rightarrow [0, 1]$. The assigned value indicates the degree of membership of the element in the set A . The function $\mu_{\tilde{A}}$ is called a membership function and the set $\tilde{A} = \{(x, \mu_{\tilde{A}}(x))\}$, where $x \in X$, defined by $\mu_{\tilde{A}}(x)$ for each $x \in X$, is called a fuzzy set [68], [69].

Definition 2 The triangular fuzzy number (TFN)

A fuzzy set \tilde{A} , defined on the universal set of real numbers \mathfrak{R} , is told to be a triangular fuzzy number $\tilde{A}(a, m, b)$ if its membership function has the following form (1) [68]:

$$\mu_{\tilde{A}}(x, a, m, b) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{m-a} & a \leq x \leq m \\ 1 & x = m \\ \frac{b-x}{b-m} & m \leq x \leq b \\ 0 & x \geq b \end{cases} \quad (1)$$

and the following characteristics (2), (3):

$$x_1, x_2 \in [a, b] \wedge x_2 > x_1 \Rightarrow \mu_{\tilde{A}}(x_2) > \mu_{\tilde{A}}(x_1) \quad (2)$$

$$x_1, x_2 \in [b, c] \wedge x_2 > x_1 \Rightarrow \mu_{\tilde{A}}(x_2) < \mu_{\tilde{A}}(x_1) \quad (3)$$

An example of triangular fuzzy number $\tilde{A}(a, m, b)$ is presented on Figure 1.

Definition 3 The support of a TFN \tilde{A}

The support of a TFN \tilde{A} is defined as a crisp subset of the \tilde{A} set in which all elements have a non-zero membership value in the \tilde{A} set (4):

$$S(\tilde{A}) = \{x : \mu_{\tilde{A}}(x) > 0\} = [a, b] \quad (4)$$

Definition 4 The core of a TFN \tilde{A}

The core of a TFN \tilde{A} is a singleton (one-element fuzzy set) with the membership value equal to 1 (5):

$$C(\tilde{A}) = \{x : \mu_{\tilde{A}}(x) = 1\} = m \quad (5)$$

Definition 5 The fuzzy rule

The single fuzzy rule can be based on the Modus Ponens tautology [68], [69]. The reasoning process uses the *IF – THEN*, *OR* and *AND* logical connectives.

Definition 6 The rule base

The rule base consists of logical rules determining the causal relationships existing in the system between the input and output fuzzy sets [69], [70].

Definition 7 The T-norm operator: product

The T-norm operator is a T function modeling the *AND* intersection operation of two or more fuzzy numbers, e.g. \tilde{A} and \tilde{B} . In this paper, only the ordinary product of real numbers is used as the T-norm operator [68], [69], [70] (6):

$$\mu_{\tilde{A}}(x) \text{ AND } \mu_{\tilde{B}}(y) = \mu_{\tilde{A}}(x) \cdot \mu_{\tilde{B}}(y) \quad (6)$$

III. THE CHARACTERISTIC OBJECTS METHOD

The COMET method is completely free of the Rank Reversal phenomenon. The basic concept of the COMET method

was proposed by prof. Piegat [69]. In the previous works, the accuracy of the COMET method was verified [71]. The formal notation of the COMET method should be briefly recalled [65], [66], [67].

Step 1. Definition of the space of the problem – the expert determines the dimensionality of the problem by selecting r criteria, C_1, C_2, \dots, C_r . Then, a set of fuzzy numbers is selected for each criterion C_i , e.g. $\{\tilde{C}_{i1}, \tilde{C}_{i2}, \dots, \tilde{C}_{ic_i}\}$ (7):

$$\begin{aligned} C_1 &= \{\tilde{C}_{11}, \tilde{C}_{12}, \dots, \tilde{C}_{1c_1}\} \\ C_2 &= \{\tilde{C}_{21}, \tilde{C}_{22}, \dots, \tilde{C}_{2c_2}\} \\ &\dots \\ C_r &= \{\tilde{C}_{r1}, \tilde{C}_{r2}, \dots, \tilde{C}_{rc_r}\} \end{aligned} \quad (7)$$

where c_1, c_2, \dots, c_r are the ordinals of the fuzzy numbers for all criteria.

Step 2. Generation of the characteristic objects – The characteristic objects (CO) are obtained with the usage of the Cartesian product of the fuzzy numbers' cores of all the criteria (8):

$$CO = C(C_1) \times C(C_2) \times \dots \times C(C_r) \quad (8)$$

As a result, an ordered set of all CO is obtained (9):

$$\begin{aligned} CO_1 &= C(\tilde{C}_{11}), C(\tilde{C}_{21}), \dots, C(\tilde{C}_{r1}) \\ CO_2 &= C(\tilde{C}_{11}), C(\tilde{C}_{21}), \dots, C(\tilde{C}_{r2}) \\ &\dots \\ CO_t &= C(\tilde{C}_{1c_1}), C(\tilde{C}_{2c_2}), \dots, C(\tilde{C}_{rc_r}) \end{aligned} \quad (9)$$

where t is the count of CO s and is equal to (10):

$$t = \prod_{i=1}^r c_i \quad (10)$$

Step 3. Evaluation of the characteristic objects – the expert determines the Matrix of Expert Judgment (MEJ) by comparing the CO s pairwise. The matrix is presented below:

$$MEJ = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1t} \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2t} \\ \dots & \dots & \dots & \dots \\ \alpha_{t1} & \alpha_{t2} & \dots & \alpha_{tt} \end{pmatrix} \quad (11)$$

where α_{ij} is the result of comparing CO_i and CO_j by the expert. The function f_{exp} denotes the mental judgment function of the expert. It depends solely on the knowledge of the expert. The expert's preferences can be presented as (12):

$$\alpha_{ij} = \begin{cases} 0.0, & f_{exp}(CO_i) < f_{exp}(CO_j) \\ 0.5, & f_{exp}(CO_i) = f_{exp}(CO_j) \\ 1.0, & f_{exp}(CO_i) > f_{exp}(CO_j) \end{cases} \quad (12)$$

After the MEJ matrix is prepared, a vertical vector of the Summed Judgments (SJ) is obtained as follows (13).

$$SJ_i = \sum_{j=1}^t \alpha_{ij} \quad (13)$$

Eventually, the values of preference are approximated for each characteristic object. As a result, a vertical vector P is

obtained, where the i -th row contains the approximate value of preference for CO_i .

Step 4. The rule base – each characteristic object and its value of preference is converted to a fuzzy rule as follows (14):

$$IF \ C(\tilde{C}_{1i}) \ AND \ C(\tilde{C}_{2i}) \ AND \ \dots \ THEN \ P_i \quad (14)$$

In this way, a complete fuzzy rule base is obtained.

Step 5. Inference and the final ranking – each alternative is presented as a set of crisp numbers, e.g., $A_i = \{a_{1i}, a_{2i}, \dots, a_{ri}\}$. This set corresponds to the criteria C_1, C_2, \dots, C_r . Mamdani's fuzzy inference method is used to compute the preference of the i -th alternative. The rule base guarantees that the obtained results are unequivocal. The bijection makes the COMET completely rank reversal free.

IV. THE AMMONIUM NITRATE TRANSPORT

The development of the production of the ammonium nitrate, which is one of the most popular fertilizers on the European market, entails the problems of its transport. Poland is one of the five world largest producers of the ammonium nitrate, realizing about 5.5% of the total world production. The biggest Polish plant producing ammonium nitrate – Zakłady Azotowe "Puławy", plans to expand its production lines by 2020, thus increasing the production of the fertilizer to the level of 1,200 tons per day.

The paper presents the sustainability model of decision making for transport management scenario where ammonium nitrate is transported from Puławy to Gdańsk. Based on the RID [5] and ADR [4] regulations, a set of 16 possible scenarios of ammonium nitrate transport, A_1 - A_{16} , was prepared. The alternatives A_1 - A_8 represent the rail transport scenarios, whereas the alternatives A_9 - A_{16} represent the road transport scenarios. The scenarios within each of the rail and road groups differ in the type of the container used during the transport. The COMET method and the expert's knowledge was used to create the decision model.

Step 1: Definition of the space of the problem

Based on the expert's knowledge, the dimensionality of the problem was determined to be equal to $r = 3$. The expert pointed out the three most important criteria for the evaluation of the hazardous materials' carriage:

- C_1 – time required for the transport, including loading and unloading time (in hours);
- C_2 – transport safety (a value from the range from 0 to 10, where 0 means low and 10 means high safety);
- C_3 – the cost of the transport of a single ton, including the cost of loading and unloading (PLN/ton).

The performance table of the alternatives A_1 - A_{16} and the criteria C_1 - C_3 is presented in Table III. It can be observed, that the rail alternatives are slightly cheaper, but significantly slower than the road ones. Regardless of the method of transport chosen, the alternatives using steel crates are characterized

TABLE III
THE PERFORMANCE TABLE OF THE ALTERNATIVES A_1 - A_{16} .

Alternative	Method	Container	Time [h]	Safety		Cost [PLN/ton]
				Linguistic	Numeric	
A1	RID	cistern	79	High	9	320
A2	RID	in bulk, closed container	78,5	High / Medium	7	262
A3	RID	in bulk, open container	78	Medium	5	252
A4	RID	steel crates	87	High	9	1837
A5	RID	cardboard boxes	86	Medium / Low	3	352
A6	RID	rigid DPPL	84	High / Medium	7	932
A7	RID	elastic DPPL	85	Medium	5	262
A8	RID	plastic canisters	96	High / Medium	7	498,6
A9	ADR	cistern	14,2	High	9	426,4
A10	ADR	in bulk, closed container	13,6	High / Medium	7	388
A11	ADR	in bulk, open container	13,2	Medium / Low	3	366
A12	ADR	steel crates	22,2	High	9	1917
A13	ADR	cardboard boxes	21,2	Low	2	432
A14	ADR	rigid DPPL	19,2	High / Medium	7	1012
A15	ADR	elastic DPPL	20,2	Low	2	342
A16	ADR	plastic canisters	31,2	Medium	5	579

by the highest price per ton, as opposed to the alternatives where the cargo is transported in bulk, in an open container.

Subsequently, the expert’s knowledge was used to divide the domain of each of the criteria to three triangular fuzzy numbers. The obtained division is expressed by (15):

$$\begin{aligned}
 C_1 &= \{10, 40, 100\} \\
 C_2 &= \{0, 5, 10\} \\
 C_3 &= \{200, 600, 2000\}
 \end{aligned}
 \tag{15}$$

The triangular fuzzy numbers for the criteria C_1 - C_3 are presented on Figures 2-4. The membership functions for the triangular fuzzy numbers *short*, *medium* and *long* for the criterion C_1 are defined in the equations (16)-(18) respectively. The membership functions for the TFNs for the criteria C_2 and C_3 can be defined in a similar manner.

$$\mu_{short}(C_1) = \begin{cases} 1 & C_1 = 10 \\ \frac{40-C_1}{30} & 10 \leq C_1 \leq 40 \\ 0 & C_1 \geq 40 \end{cases}
 \tag{16}$$

$$\mu_{medium}(C_1) = \begin{cases} \frac{C_1-10}{30} & 10 \leq C_1 \leq 40 \\ 1 & C_1 = 40 \\ \frac{100-C_1}{60} & 40 \leq C_1 \leq 100 \end{cases}
 \tag{17}$$

$$\mu_{long}(C_1) = \begin{cases} 0 & C_1 \leq 40 \\ \frac{C_1-40}{60} & 40 \leq C_1 \leq 100 \\ 1 & C_1 = 100 \end{cases}
 \tag{18}$$

Step 2: Generation of the Characteristic Objects

The characteristic objects OC_1 - OC_{27} were generated as a Cartesian product of the fuzzy numbers’ cores of each of the C_1 - C_3 criteria. The obtained characteristic objects are presented in the first four columns of Table IV and depicted on Figure 5.

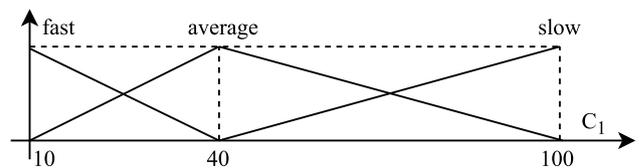


Fig. 2. The set of three triangular numbers for the transport time criterion (C_1).

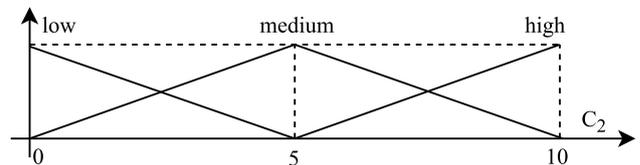


Fig. 3. The set of three triangular numbers for the transport safety criterion (C_2).

Step 3: Evaluation of the Characteristic Objects

Subsequently, the expert performed a pairwise comparison of the characteristic objects. As a result, the Matrix of Expert Judgement (MEJ) was determined, where each α_{ij} value was calculated with the usage of (12). The MEJ matrix is depicted on Figure 6, where the α_{ij} values of 0, 0.5 and 1 are represented by white, black and grey boxes respectively.

Next, the vertical vector of the Summed Judgements (SJ) was calculated with the usage of (13). The SJ vertical vector is presented in the fifth column of Table IV. Eventually, the SJ vector was used to approximate the values of preference, which rendered the P vertical vector of preference (see the sixth column of Table IV).

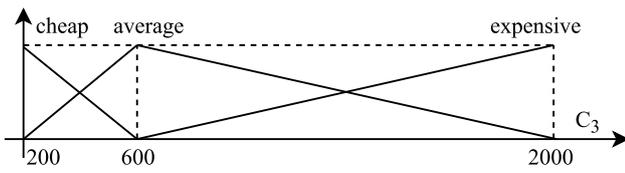


Fig. 4. The set of three triangular numbers for the transport cost criterion (C_3).

TABLE IV
THE RESULTS OF THE COMET METHOD.

CO_i	C_1	C_2	C_3	SJ	P
CO_1	10	0	200	16.5	0.65
CO_2	10	0	600	14.5	0.55
CO_3	10	0	2000	5	0.15
CO_4	10	5	200	22	0.90
CO_5	10	5	600	20.5	0.85
CO_6	10	5	2000	13	0.45
CO_7	10	10	200	26.5	1.00
CO_8	10	10	600	23.5	0.95
CO_9	10	10	2000	15.5	0.60
CO_{10}	40	0	200	14	0.50
CO_{11}	40	0	600	11	0.40
CO_{12}	40	0	2000	3	0.10
CO_{13}	40	5	200	20	0.80
CO_{14}	40	5	600	15.5	0.60
CO_{15}	40	5	2000	7.5	0.20
CO_{16}	40	10	200	23.5	0.95
CO_{17}	40	10	600	19	0.85
CO_{18}	40	10	2000	10	0.35
CO_{19}	100	0	200	8	0.25
CO_{20}	100	0	600	7.5	0.20
CO_{21}	100	0	2000	0.5	0.00
CO_{22}	100	5	200	14	0.50
CO_{23}	100	5	600	10	0.35
CO_{24}	100	5	2000	2.5	0.05
CO_{25}	100	10	200	17.5	0.70
CO_{26}	100	10	600	15.5	0.60
CO_{27}	100	10	2000	8.5	0.30

Step 4: The rule base

In the next step, each characteristic object and its performance was converted to a fuzzy rule with (6). A sample rule is presented below (19):

$$R_1 : \text{ IF } C_1 \sim 10 \text{ AND } C_2 \sim 0 \text{ AND } C_3 \sim 200 \text{ THEN } P \sim 0.65 \tag{19}$$

Step 5: Inference and the Final Evaluation

In the last step of the model creation, each alternative was presented as a set of crisp numbers corresponding to the C_1 - C_3 criteria. Mamdani's fuzzy inference method was used to

compute the preference P_i of each of the alternatives. The obtained P vertical vector, along with the resulting ranks of the alternatives, are presented in Table V.

According to the ranking generated by the COMET method, the A_9 alternative (i.e. ADR, cistern) is the best method of ammonium nitrate transport. It is fast, relatively cheap, and yet very safe. The second position was assigned to the A_{10} alternative, i.e. ADR, in bulk, closed container. This type of container renders the alternative only slightly less safe, but the time of the transport is shorter and the price is lower than in the A_9 alternative. The A_1 alternative is the best one from the RID alternatives and has the fourth position in the ranking. It provides high safety and a lower price than the aforementioned alternatives, however the time of transport is significantly longer. The A_{12} alternative, having the thirteenth position, is the worst one from the ADR group, and the A_4 alternative is considered to be the worst solution in the ranking. This is probably caused by the very high cost associated with the the steel crates' container type.

Sensitivity analysis

To verify the robustness of the obtained decision model, a sensitivity analysis was performed. Values of each of the C_1 - C_3 criteria were increased by 1%. The numeric and percentage difference between the original and the new P_i values for each A_1 - A_{16} alternative were calculated. Table VI demonstrates the highest and the lowest changes of the P value for all the A_1 - A_{16} alternatives. The absolute values of the percentage change vary from 0.0503% to 1.4602%, thus confirming the stability of the obtained decision model.

Comparison to a Linear Model

In the last step of the research, a linear model was created on the basis of the characteristic objects, to verify how the simplification of the model would affect the results. The linear model results were compared to the COMET method results. The formula from equation (20) was used to calculate the P'_i value for each of the A_1 - A_{16} alternatives. The coefficient of determination R^2 is presented in equation (21) and its value suggests that the linear model fits the COMET model very well. The seventh column of Table V contains the P' vertical vector, and the eighth column presents the difference between the preference calculated by the linear model and by the COMET method. As it can be noted, the difference between P and P' for the A_{12} alternative is equal to 6.91%, which shows, that despite the R^2 value being very close to 1, the linear model does not fit the COMET model perfectly well.

$$P = 0.5111 - 0.1453 \cdot C_1 + 0.1618 \cdot C_2 - 0.1966 \cdot C_3 \tag{20}$$

$$R^2 = 0.9644 \tag{21}$$

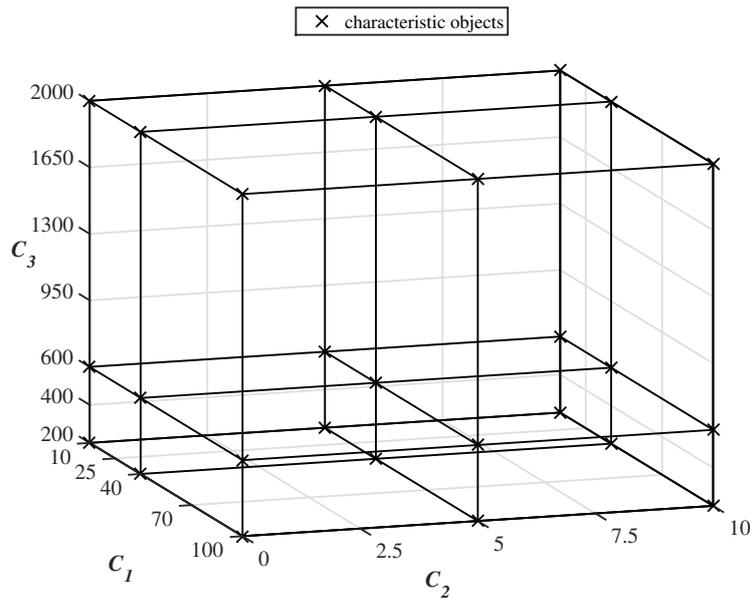


Fig. 5. Characteristic objects in the space of the problem

TABLE V
CONSIDERED ALTERNATIVES AND THEIR RESULTS

A_i	C_1	C_2	C_3	P	P rank	P'	diff
A_1	79	9	320	0.7169	4	0.7095	-1.04%
A_2	78.5	7	262	0.6585	8	0.6482	-1.57%
A_3	78	5	252	0.5881	10	0.5748	-2.27%
A_4	87	9	1837	0.3046	16	0.2998	-1.58%
A_5	86	3	352	0.4191	15	0.4415	5.35%
A_6	84	7	932	0.4367	14	0.4597	5.27%
A_7	85	5	262	0.5498	11	0.5456	-0.76%
A_8	96	7	498.6	0.5001	12	0.5223	4.45%
A_9	14.2	9	426.4	0.9378	1	0.9298	-0.86%
A_{10}	13.6	7	388	0.9007	2	0.8639	-4.09%
A_{11}	13.2	3	366	0.7542	3	0.7154	-5.15%
A_{12}	22.2	9	1917	0.4926	13	0.5267	6.91%
A_{13}	21.2	2	432	0.6421	9	0.6295	-1.96%
A_{14}	19.2	7	1012	0.7145	5	0.6866	-3.91%
A_{15}	20.2	2	342	0.6702	7	0.6558	-2.15%
A_{16}	31.2	5	579	0.6815	6	0.6713	-1.49%

V. CONCLUSIONS

The development of the agriculture and the increase of the demand for mineral fertilizers, ammonium nitrate being one of them, results in the intensification of the fertilizers' transport. Since the ammonium nitrate is classified as a hazardous material, there are many factors to consider when transporting it.

While many of the prior studies focused on the economic aspects of the problem, the MCDA methods allow to build transport management models that include the other, often conflicting, factors. The authors' contribution in this paper was to

create a sustainable transportation management decision model that incorporates some of the aforementioned criteria, yet is not prone to the rank reversal problem. Furthermore, it was demonstrated that the COMET method can be successfully employed in the ammonium nitrate transport management decision problems scope.

The problem of ammonium nitrate transport management was described in the paper. A methodology of sustainable decision model creation with the usage of the fuzzy set theory and the COMET method was presented. Eventually, an experiment was performed to evaluate sixteen alternative

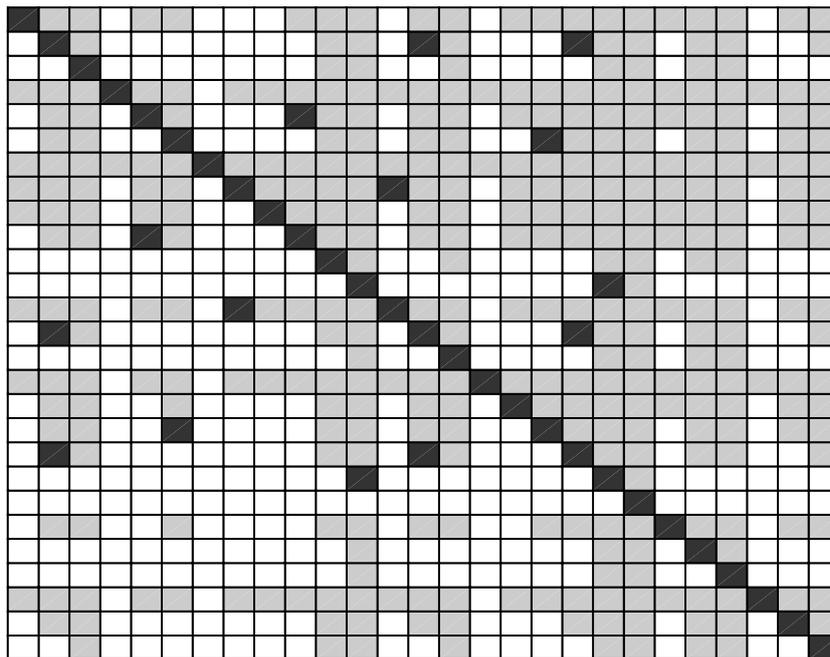


Fig. 6. The Matrix of Expert Judgement (MEJ).

TABLE VI
SENSITIVITY ANALYSIS FOR ALTERNATIVES ASSESSMENT IN RESPECT TO EACH CRITERION

	$C_1 + 1\%$		$C_2 + 1\%$		$C_3 + 1\%$	
	num.	per.	num.	per.	num.	per.
min. change	-0.0005	-0.0503%	0.0011	0.1592%	-0.0006	-0.0680%
max. change	-0.0041	-0.8926%	0.0042	1.3641%	-0.0056	-1.4602%

modes of the fertilizer transport on the route from Puławy to Gdańsk, based on the three most dominating ammonium nitrate transportation management criteria and the expert's knowledge.

In the first step of the experiment, the space of the problem was defined. Subsequently, the characteristic objects were generated. Next, the Matrix of Expert Judgment was created. In the fourth step, the rule base was defined, to allow to perform the inference and creation of the final ranking in the last step of the experiment. The robustness of the obtained ranking was then verified by the sensitivity analysis execution. Additionally, a linear model was created and its results were compared to the COMET ranking.

The research has identified possible areas of improvement and future work directions. This study was based on a set of the three dominating criteria, i.e. transport time, safety and cost. It would be beneficial to extend this set with additional criteria and thus create a complete hierarchy of ammonium nitrate transport management sustainable decision-making criteria. Furthermore, the hesitancy factors could be considered and a hesitant fuzzy version of the model could be created.

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