Application of Multi-criteria Decision-making Methods for the Area of Recycling

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***Abstract* – In this paper, authors deal with the possible application of multi-criteria decision-making methods for the solution within the recycling process. The introduction of the paper describes different ways of application concerning multi-criteria decision-making in the various areas by the help of a literature review. The second part of the paper describes the used methodology of a research, and the third of this paper presents results of the case study, realized in the production enterprise within recycling processes of plastic wastes. The solution comprising multi-criteria decision-making process can solve the evaluation of a technological device in order to elevate recycling of plastic waste. This procedure can be an instruction or guide for a suitable, effective and useful solution for the realization of waste management in enterprises.**

***Keywords* – Decision making, Method, Waste, Recycling.**

1. Introduction

Different people have different views of a problem, different decisions, and these decisions differ in information accessibility, complexity, etc. On condition that individuals are confronted with different information, situations, problem solution, they can face a decision-making process [1]. Decision makers can find the problem solution by assessing the variety of alternatives with the consequent selection of the best solution using a set of criteria [2]. At the same time, it is needed to emphasize that it is possible to see the application of decision-making methods in various areas, for example, project management, supplier selection, etc. For example, authors Pohekar and Ramachandran used multi-criteria decision making and its application for energy planning [3]. Authors Ho, Xu and Key presented a research paper in which multi-criteria decision making approaches are used for supplier evaluation and selection [4]. Similar research idea is from authors Boran et al. They used a multi-criteria intuitionistic fuzzy group decision making for supplier selection [5]. Authors Zeng, Min and Nigel used decision-making in the area of construction industry. They applied a fuzzy based decision-making methodology to construction project risk assessment [6]. Connection of decision-making theory and financial area authors Merigó and Gil-Lafuente searched [7]. They presented a new decision-making technique and its application in the selection of financial product [7]. Authors in [8], [9], [10] applied decision-making idea in the area of transport and transport process. In the same manner, authors in [11], [12] used multi-criteria in the form of optimization and modelling of road traffic flows considering social and economic aspects. Authors Gasparik et al. dealt with new methodology for assessing transport and its connection with the integrated transport network [13]. The way of modified application of decision-making method is presented in [14], [15]. Multi-criteria decision analysis was, for example, used in the research of authors Huang, Keisler and Linkov [16]. Authors in their research presented the application of multi-criteria decision analysis in the area of environment, and presented an idea that decision-making requires consideration of trade-off among social, political, economic and environmental impact. According to these authors multi-criteria decision making is especially valuable in the environmental field [16].

DOI: 10.18421/TEM83-19
https://dx.doi.org/10.18421/TEM83-19

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Received: 18 April 2019.
Revised: 25 July 2019.
Accepted: 30 July 2019.
Published: 28 August 2019.

Authors who used a connection of environmental problems and decision-making methodology were Senthil, Srirangacharyulu and Ramesh [17]. They used decision-making methodology for the selection and evaluation of reverse logistics operating channels. And the connection of environment and decision-making methods presents the main idea of the realized research. Strictly speaking, solution of the area of wastes was their point. One of possible ways how to solve the problem of wastes is the application of waste management based on wastes collection, separation, processing and recycling. And decision-making can be also supported by using decision-making methods. In this paper, we revisit and also add elements to our earlier research study, within the context of using different decision-making approaches and methods [18]. One of the research activities was realized in the enterprise production dealing with producing products, whose main part is a plastic material. This enterprise has well-organized waste management, and they also realize the recycling of plastic waste during the production process. The enterprise made a decision about extending the recycling process by the help of innovation of the recycling process. This innovation was in the form of a new device for recycling of plastic waste. The enterprise speculated about knife mills (KM), in which the mill produced plastic waste in the form of grains, which are returned subsequently to the process of initial production of plastic materials, and the final decision was made by application of multi-criteria decision-making.

2. Methodology of research

As it is mentioned in [19] multi-criteria decision making is a very well-known part of decision-making, and it is presented by the branch of a general scale of models dealing with decision problem, taking into account a number of decision criteria. Multi-criteria decision-making methods are discrete and have a restricted number of alternatives [19]. Multi-criteria decision-making consists of the following steps [18], [19]:

1. Definition of criteria with an evaluation of variants,
2. Determination of weights for criteria (non-standardized k_i, or standardized form α_i),
3. Calculation of total utility of variants,
4. Selection – determination of the optimal variant, the effectiveness of variants is in some cases evaluated as the ration of the total utility and price (costs).

It is possible to determine the weights of criteria in two ways, by direct methods of determining the weights for criteria (weights of criteria are evaluated and defined by the decisive object) and indirect methods of determining the weights for criteria (the value of weight is determined by comparing all defined criteria with each other). Indirect methods reduce subjectively. The next step after objectification of the weight for criteria, is a realization of group determination of weights for criteria, in regard to implementation of indirect methods of weights standardization (mathematical approach) and phased changing of values of weights (using several methods and their comparison).

The values of weights for criteria are in a non-standardized form. Therefore, it is necessary to convert them into a standardized form and the sum of the standardized weights of criteria is equal to one [20].

$$\sum_{i=1}^{n} \alpha_i = 1 \quad (1)$$

Where α_i is the weight of i standardized criterion. The values of weights from non-standardized form to standardized form can be converted by the equation:

$$\alpha_i = \frac{k_i}{\sum_{i=1}^{n} k_i} \quad (2)$$

Where k_i is the weight of i non-standardized criterion, n is the number of criteria [20].

The calculation of the total utility of variants can be realized by simple – direct methods or by more complex – indirect methods. Direct methods present methods, in which variants are evaluated by the defined criterion concerning decision-making subject, but the solution is very simple and too subjective. Indirect methods represent the evaluation of variants by the defined criteria that can be calculated (for example pairwise comparison, or AHP method – Saaty`s method). The method of pairwise comparison uses for determination of the total utility of variants U_j the equation (3) [20]:

$$U_j = \sum_{i=1}^{n} \alpha_i u_{ij} \quad (3)$$

In which m is the number of variants, n is the number of defined criteria, α_i is the weight of i criterion, u_{ij} is the utility of j variant by the i criterion, V_j is the evaluated variant and U_j is the total utility of variant. Variant V_j (evaluated variant) for which maximum, or minimum hold (by the type of the task) meets the defined criteria the best and this is the searched solution. Saaty`s method or Analytical Hierarchy Process (AHP) was developed by Saaty (presented for example in the publication 'The analytic hierarchy process' in 1980). This method is based on the decomposition problem which comprises hierarchy of the problem and its goal, criterions, sub-criterions and also sub-levels of this hierarchy [18]. The method progresses to comparison in pairs, assessing of relative preference. The Saaty`s method has a scale of 1 to 9, in which 1 presents equal importance, 3 presents moderately more, 5 presents strongly more, 7 presents very strongly and 9 presents extremely more importance. And the values 2,4,6,8 present compromise values of the importance. This ratio scale is also used for verbal comparison and it is used for weighting with the result of the final scale vector for alternatives or variants.

This final vector presents the relative importance for variants. The next step of this method is a pairwise comparison obtained by the equation [19], [20]:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{21} & a_{2n} \\ a_{n1} & a_{n2} & a_{nn} \end{bmatrix} \quad (4)$$

In which: A is the matrix, i element, j element and a_{ji} is the position obtained by pairwise comparison of these elements. This vector is multiplied with the coefficient of weight, and this process is repeated for each level and variants, so the values of partial utilities for variants by the defined criteria are defined for each defined criterion, i.e. how many criteria are defined, so many times it is necessary to make Saaty's calculation. The results are the overall weight coefficient and the alternative with the highest weight is the best alternative for the solution.

3. Case study

As it was mentioned, the research used a multi-criteria decision making for evaluation three types of knife mills. We especially applied two methods of multi-criteria decision-making, namely method of paired comparison and Saaty`s method. These methods helped to select criteria for comparison, and also they were applied for evaluating the partial utility of variants by the selected criteria. At the beginning of the decision-making, the researcher determined six criteria which describe the characteristics of recycling devices. These criteria were consulted in the researched enterprise (at the department of quality, plastic production and logistics). The research deliberates with these criteria output of the material (kg/h), complexity of service, accessories, input parts, service and purchase price. The first variant (Variant 1) has the output from 15 to 50 kg/h, simple complexity of service, accessory is a screen, input part for the size 210x460 mm^2, purchase price 5100 EUR, the second variant of the knife mill (Variant 2) has the output from 25 to 50 kg/h, simple complexity of service, accessory is a screen, input part for the size 180x300 mm^2, purchase price 3900 EUR and the third variant of the knife mill (Variant 3) has the output 52 kg/h, complicated complexity of service, accessory is a screen, input part for the size 358x400 mm^2, purchase price 5075 EUR [21], [22]. The first comparison of criteria was by Saaty`s method. Saaty`s method uses a specific scale according to the importance of criteria by evaluation of the defined criteria among themselves. This scale is presented by the value from 1 - equally important criteria, 3 - the first criterion is weak more importantly second, 5 – the first criterion is more important than the second, 7 – the first criterion is markedly more important than the second, up to the 9 – the first criterion is absolutely more important than the second. Evaluation of criteria was realized by the evaluated enterprise. Relating to these results, it was realized the calculation for standardization of the weights of criteria. Evaluation of the defined criteria is presented in Table 1. The matrix includes evaluation of criteria for the selected variants, and it is needed to realize the standardization of weights for the evaluated variants. These standardized weights with their calculation are presented in Table 2. In order to verify the results of the criteria evaluation, a method of pairwise comparison was developed, in which the individual criteria are compared with each other by the same group of experts, as in the case of the Saaty`s method. The evaluation of criteria and the subsequent calculations related to the used method are presented in Table 3. After elaboration of both methods for evaluation of the selected criteria, we obtained standardized weights for individual criteria. The summarization of the standardized weights of criteria is presented in Table 4.

Table 1. Evaluation of the defined criteria (Saaty`s method)

Criterion	A	B	C	D	E	F
A	1	3	7	1/3	5	1/5
B	1/3	1	5	1/5	3	1/7
C	1/7	1/5	1	1/7	1/3	1/9
D	3	5	7	1	7	1/3
E	1/5	1/3	3	1/7	1	1/7
F	5	7	9	3	7	1
Sum	9,68	16,53	32	4,82	23,33	1,93

Table 2. Calculation of standardized weights of criteria (Saaty`s method)

Criterion	A	B	C	D	E	F	Sum	α_i
A	0,103	0,182	0,219	0,069	0,214	0,104	0,891	0,149
B	0,034	0,061	0,156	0,042	0,129	0,074	0,496	0,083
C	0,015	0,012	0,031	0,030	0,014	0,057	0,159	0,027
D	0,310	0,302	0,219	0,207	0,300	0,173	1,511	0,251
E	0,021	0,020	0,094	0,030	0,043	0,074	0,282	0,047
F	0,517	0,423	0,281	0,622	0,300	0,518	2,661	0,443
Sum	1	1	1	1	1	1	6	1
	6							

Table 3. Evaluation of criteria (method of pairwise comparison)

Criteria	A	B	C	D	E	F	K_i	+1	α_i
A	-	A	A	D	A	F	3	4	0,190
B	-	-	B	D	B	F	2	3	0,143
C	-	-	-	D	E	F	0	1	0,048
D	-	-	-	-	D	F	4	5	0,238
E	-	-	-	-	-	F	1	2	0,095
F	-	-	-	-	-	-	5	6	0,286
Sum								21	1

Table 4. Summarization of standardized weights for the selected methods

Criteria	Saaty`s method	Method of pairwise comparison
A	0,149	0,190
B	0,083	0,143
C	0,027	0,048
D	0,251	0,238
E	0,047	0,095
F	0,443	0,286

It is evident from this table, that in both cases of evaluation, the most important criterion is the criterion F (the price of knife mills). The worst ranking has the criterion C (accessory of knife mill). Nevertheless, this criterion is important in decisions making. The difference between these two criteria is clearly visible in the graph shown in Figure 1, while the difference between other criteria is not so significant.

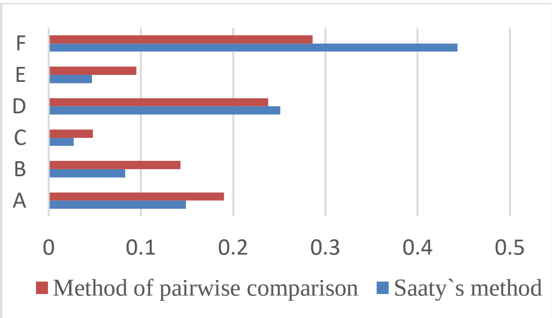

Figure 1. Difference between the used methods

The next step of the decision-making was the determination of partial utilities. This was realized by Saaty`s method and the method of pairwise comparison. The first criterion for comparison was the criterion A, which represents the output. This specifies how many kgs of input material (plastic waste from the plastic pressroom) is able to process the selected device per hour. This is an important factor for time separation. Table 5 represents the calculation of partial utility of variants by criterion A, obtained by the Saaty`s method.

The next step was a calculation of partial utilities regarding variants by the method of pairwise comparison (Table 6).

The complexity of service for recycling devices presents another criterion for comparison of devices. Table 7 and 8 contain calculations of the partial utility of variants according to the selected method of multi-criteria decision making according to criterion B, the difficulty of service. Criterion C presents the accessory of the device (for example screen with the different diameter with the impact on the size of re-granular plastic waste).

Table 5. Calculation of partial utilities by criterion A, Saaty`s method

A	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	5	3	0,652	0,789	0,429	1,87	0,623
V2	1/5	1	3	0,131	0,158	0,429	0,718	0,239
V3	1/3	1/3	1	0,217	0,053	0,142	0,142	0,138
Sum	1,533	6,333	7	1	1	1		1
				3				

Table 6. Calculation of partial utility by criterion A, a method of pairwise comparison

A	V1	V2	V3	K_i	Standardized weigths α_i
V1	-	V1	V1	2	0,667
V2	-	-	V2	1	0,333
V3	-	-	-	0	0,000
Sum				3	1

Table 7. Calculation of partial utilities by criterion B, Saaty`s method

B	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	1/3	5	0,238	0,226	0,385	0,849	0,283
V2	3	1	7	0,714	0,677	0,538	1,929	0,648
V3	1/5	1/7	7	0,048	0,097	0,077	0,222	0,074
Sum	4,2	1,476	13	1	1	1		1
					3			

Table 8. Calculation of partial utility by the criterion B, method of pairwise comparison

B	V1	V2	V3	K_i	Standardized weigths α_i
V1	-	V2	V1	1	0,333
V2	-	-	V2	2	0,667
V3	-	-	-	0	0,000
Sum				3	1

Table 9 Calculation of partial utilities by criterion C, Saaty`s method

C	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	1/3	1/5	0,111	0,077	0,131	0,319	0,107
V2	3	1	3	0,333	0,231	0,217	0,781	0,260
V3	5	1/3	1	0,556	0,692	0,652	1,9	0,633
Sum	9	1,667	4,2	1	1	1		1
					3			

Partial-utility of variants for this criterion is presented by the Tables according to the used methods, Table 9 presents Saaty`s method and method of pairwise comparison is presented in Table 10. The input port is a technical feature of the device, with an impact on the plastic waste processing (for example the size of plastic waste created at the department of plastic production. The size of the plastic waste has to be suitable for the input port of this device.

Therefore, this criterion was included in the criteria for the selection of suitable recycling device (marked with D). Table 11 contains a calculation of partial utilities by the Saaty`s method (for the selected variants). Partial utilities depending on the criterion D were calculated also by the method of pairwise comparison (presented by Table 12).

Table 10. Calculation of partial utilities by criterion C, a method of pairwise comparison

C	V1	V2	V3	K_i	α_i
V1	-	V2	V3	0	0,000
V2	-	-	V2	2	0,667
V3	-	-	-	1	0,333
Sum				3	1

Table 11. Calculation of partial utilities by criterion D, Saaty`s method

D	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	1/3	3	0,231	0,217	0,333	0,781	0,260
V2	3	1	5	0,692	0,652	0,556	1,9	0,633
V3	1/3	1/5	1	0,077	0,131	0,111	0,319	0,107
Sum	4,333	1,533	9	1	1	1		1
				3				

Table 12. Calculation of partial utility by the criterion D, method of pairwise comparison

D	V1	V2	V3	K_i	Standardized weigths α_i
V1	-	V2	V1	1	0,333
V2	-	-	V2	2	0,667
V3	-	-	-	0	0,000
Sum				3	1

The next criterion is a service provided by companies that produce the device. The important factor is the best service (the best service has the highest number). Table 13 and 14 contains information based on the calculation of partial utility according to the criterion E for all defined variants. Table 13 presents a calculation by Saaty`s method, and Table 14 presents a calculation by the method of pairwise comparison. The last, but the most important criterion is the criterion F. This criterion represents the purchase price of the device. This greatly affects the choice of recycling devices, and this is the main criterion by the selection of the recycling device. Partial utilities for variants were (as in the previous variants) calculated using two methods (Table 15 presents calculation by the Saaty`s method and Table 16 presents a calculation by the method of pairwise comparison).

Table 13. Calculation of partial utility by criterion E, Saaty`s method

E	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	1/7	1/5	0,077	0,106	0,033	0,216	0,072
V2	7	1	5	0,538	0,745	0,806	2,089	0,696
V3	5	1/5	1	0,385	0,149	0,161	0,695	0,232
Sum	13	1,343	6,2	1	1	1		1
					3			

Table 14. Calculation of partial utility by the criterion E, method of pairwise comparison

E	V1	V2	V3	K_i	Standardized weigths α_i
V1	-	V2	V3	0	0,000
V2	-	-	V2	2	0,667
V3	-	-	-	1	0,333
Sum				3	1

Table 15. Calculation of partial utility by the criterion F, Saaty`s method

F	V1	V2	V3	V1	V2	V3	Sum	Standardized weigths α_i
V1	1	1/3	7	0,242	0,032	0,863	1,137	0,379
V2	3	1	1/9	0,724	0,097	0,014	0,835	0,278
V3	1/7	9	1	0,034	0,871	0,123	1,028	0,343
Sum	4,143	10,333	8,111	1	1	1		1
					3			

Table 16. Calculation of partial utility by the criterion F, method of pairwise comparison

F	V1	V2	V3	K_i	α_i
V1	-	V2	V3	0	0,000
V2	-	-	V2	2	0,667
V3	-	-	-	1	0,333
Sum				3	1

By calculation of partial utilities, for both methods, it was necessary to calculate the total utility of variants, thus, the suitable recycling device for processing plastic waste at the department of plastic pressroom was selected.

For the selection of a suitable variant, it is needed to calculate the total utility of variants. Calculation of the standardized weights of criteria for knife mills was recorded in the sum table of utilities (such as standardized weights of partial utilities for variants according to the defined criteria). Particular information was needed in order to realize the calculation for the selection of suitable recycling device at the department of the plastic pressroom.

From the calculation obtained by the Saaty`s method, it is evident that the suitable device for this is presented by variant 2.

This total calculation is presented in Table 17.

For precision of calculation, it was applied the calculation of total utility of devices using the method of paired comparison. This confirmed that the variant 2 is suitable for processing plastic waste at the department for plastic production.

Calculation of total utility by the method of paired comparison is presented in Table 18. The results of the calculations of the two applied methods were summarized and illustrated by the graph, which represents the total utilities of variants by both methods of decision making (Figure 2), and it is possible to see that the variant 2 is better in comparison with the selected variants, for both methods.

Table 17. Calculation of total utility for recycling devices

	Calculation of total utility using Saaty`s method						
	Variants	Variant 1		Variant 2		Variant 3	
Criterion x_i	Weight of criterion α_i	Utility u_i	α_i x u_i	Utility u_i	α_i x u_i	Utility u_i	α_i x u_i
A	0,149	0,623	0,093	0,239	0,036	0,138	0,021
B	0,083	0,283	0,023	0,648	0,054	0,074	0,006
C	0,027	0,107	0,003	0,260	0,007	0,633	0,017
D	0,251	0,260	0,056	0,633	0,159	0,107	0,027
E	0,047	0,072	0,003	0,696	0,033	0,232	0,011
F	0,443	0,379	0,168	0,278	0,124	0,343	0,152
Total utility U_j	1	$\sum$	0,346	$\sum$	0,413	$\sum$	0,234
	Calculation of total utility using the method of pairwise comparison						
	Variants	Variant 1		Variant 2		Variant 3	
Criterion x_i	Weight of criterion α_i	Utility u_i	α_i x u_i	Utility u_i	α_i x u_i	Utility u_i	α_i x u_i
A	0,190	0,667	0,128	0,333	0,063	0,000	0,000
B	0,143	0,333	0,048	0,667	0,095	0,000	0,000
C	0,048	0,000	0,000	0,667	0,032	0,333	0,016
D	0,238	0,333	0,079	0,667	0,159	0,000	0,000
E	0,095	0,000	0,000	0,667	0,063	0,333	0,032
F	0,286	0,000	0,000	0,667	0,191	0,333	0,095
Total utility U_j	1	$\sum$	0,225	$\sum$	0,603	$\sum$	0,143

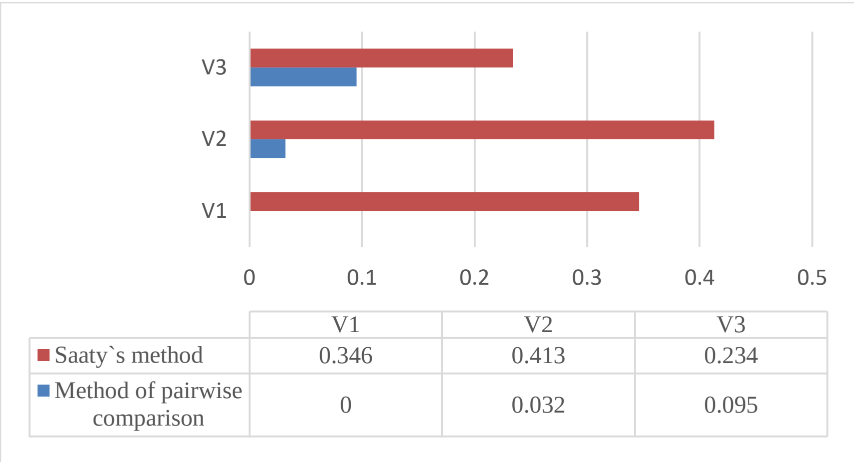

Figure 2. Comparison of the results

4. Conclusion

Decision making is a common part of every human activity. An effective tool is the application for multi-criteria decision-making, and its use is possible in several areas. This article presents the application for multi-criteria decision-making in the area of recycling.

The research was realized by a case study in the production enterprise with massive production of plastic waste. The idea of this enterprise was to realize recycling process and to find a way how to reuse created plastic waste. Researchers in collaboration with the management proposed the reverse application of plastic waste in the initial production process in the form of plastic waste recycling. The main problem was to find the best recycling device for this type of plastic waste, and therefore researchers used the methodology and methods which comprise decision-making. Two methods of multi-criteria decision making were applied for this selection, namely the method of pairwise comparison and Saaty`s method. The first step was the definition of the main criteria. The research deliberates with these criteria - output of the material (kg/h), the complexity of service, accessories, input parts, servicing, and purchase price. These methods were also applied by evaluation of partial utilities of variants according to the selected criteria. The realized evaluation by these methods helps the enterprise to make a decision for implementation of the recycling process.

Implementation of the recycling process regarding this enterprise would provide the company recycling of produced plastic waste and it can save material sources, and also use the produced plastic granulate for production the new products. This activity has not only the environmental aspect, but also the economic aspect in the form of cost reduction for the purchase regarding sources for production. The proposed process of recycling was implemented within the enterprise production scheme, as reverse material flow.

Acknowledgements

This work is a part of the projects VEGA 1/0063/16, VEGA 1/0403/18, VEGA 1/0638/19, KEGA 012TUKE-4/2019, KEGA 013TUKE-4/2019, APVV SK-SRB-18-0053.

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