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Original article

The material selection of the heating plates used in the vulcanization process obtained using different MCDM methods

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ABSTRACT

The material selection problem is one of the most important steps in the development process of a part of any subassembly assembly, machine, product, etc. The material selection process needs a systematic and time-consuming approach to choose the optimal material to satisfy the product's requirements. That is to say, many confronting criteria and possible material types (alternatives) available, makes this problem Multi-Criteria Decision-Making problem (MCDM). This paper shows the applicability of the MCDM methodology in the material selection problem for steam heating plates for the vulcanization process used in the inner tube manufacturing process. Specifically, the criteria weights are obtained by CRITIC (Criteria Importance Through Intercriteria Correlation), ENTROPY and PIPRECIA (Pivot Pairwise Relative Criteria Importance Assessment) methods, while TOPSIS (Technique for the Order Preference by Similarity to Ideal Solution) method has been implemented in this process for evaluation and ranking of the possible alternatives (material types).

Key words: *Material selection, CRITIC, ENTROPY, PIPRECIA and TOPSIS method;*

1. INTRODUCTION

The material selection process represents one of the most challenging issues in the design and development of any structural element [1].
Generally, constructors-designers are choosing materials for their desired products based on their previous experience. That is to say, the recommendations from the textbooks or material suppliers added to important product's requirements, as well as desired material properties are also observed. Despite the engineers' experience and their knowledge about the materials, the ability to select the proper material from the wide spectrum of available materials is a challenging and time-consuming task [2].
The oldest and the basic material selection principle remains the same and it is by trial and error methods [3] which follows substantial costs and time in the development process, because of the improperly chosen material. Consequently, this means that improperly selected material can negatively affect productivity and profitability [1, 4]. Thus the proper methods and tools have been created to overcome problems as such.
In recent years, one of the approaches in the material selection process is a multi-criteria decision-making approach (MCDM approach).
When applied, MCDM methods can help decision-makers with objective and systematic evaluation of alternatives on multiple criteria [5]. The MCDM methodology provides an easy way to observe a wide range of possible alternative solutions (different material types) in comparison with the multiple confronting criteria (material characteristics, costs, construction requirements, etc.) [6].
Specifically, this paper shows the applicability of different MCDM methods in the material selection process of the heating plates used for the vulcanization process of the inner tubes.
The heating plates are responsible for the pre-heating (preparation phase) and the heating (production phase) of the mould in which the inner tube profile gets vulcanized. The vulcanization process is the last in the production of

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the inner tubes. Thus, the heating plates must properly maintain the heat inside the mould in order not to produce scrap tubes.
Those plates are maintaining one of the most important vulcanization parameters which are the temperature-pressure characteristics of the steam. Steam is used to "power" the heating plates and it transfers heat through them to the mould. The mould is getting proper temperature (defined by the production process) which is then transferred to the inner tube.
After the vulcanization process is over, the production cycle of the inner tube is done.
For the present research, CRITIC (Criteria Importance through Intercriteria Correlation), ENTROPY and PIPRECIA (Pivot Pairwise Relative Criteria Importance Assessment) method have been applied for the determination of the criteria weights. Individually determined criteria weights from each method will be summarized in one joined criteria weights set. Criteria weights determined in the previous step are going to be used in TOPSIS (Technique for the Order Preference by Similarity to Ideal Solution) method for evaluation and selection of the proposed alternative solutions.

2. LITERATURE REVIEW

The MCDM methodology has been attracted by many researchers. Thus, a variety of MCDM methods have been developed and applied to numerous subjects. One of the topics was a combination of the MCDM methodology and the material selection problem.
In order to evaluate alternatives, the criteria weights must be objectively calculated. This process represents the basic step for most MCDM methods. Some of them have the determination of the criteria weights embedded as one of the steps inside their methodology (e.g. AHP method). On the other hand, most of the MCDM methods combine with one (or more) methods which are applied only for the criteria weights determination. Those methods are: CRITIC, SWARA, AHP, ENTROPY, PIPRECIA, etc.
Since there is no specific MCDM method that should be applied for the material selection, many methods such as AHP, ANP, TOPSIS, VIKOR COPRAS, DEMATEL, ELECTRE, MOORA, PROMETHEE, etc. have been introduced.
The great majority of these methods have been used to material selection problem because of their user-friendly process [7, 8]. Although every MCDM method has its advantages and disadvantages, the most frequently used methods are TOPSIS, ELECTRE and AHP.
AHP is one of the most popular MCDM methods and it was successfully applied for reinforced composite composites material selection for automotive brake lever design [9]. Some researchers have made a comparative analysis of MCDM methods such as ELECTRE and PROMETHEE for pipe material selection in the sugar industry [1].
On the other hand, the TOPSIS method has been applied in comparison with the VIKOR method for the selection of microelectromechanical systems electrostatic actuators [10]. Also, a comprehensive MCDM-based approach using TOPSIS, COPRAS and DEA as an auxiliary tool for material selection problems was carried over [7].

3. MCDM METHODOLOGY

Decision analysis is concerned with the situations in which a decision-maker needs to make the best possible outcome among numerous possible solutions (specifically, material type) while considering a set of confronting criteria.
One of the most important steps in the material selection process is ranking and choosing the right material for a specific application.
MCDM methodology is rapidly growing in the material selection problem [1], because of their ability to evaluate and select materials by several involved factors rather than a single criterion [10].
Here, a brief description of the applied MCDM methods is given. In order to calculate criteria weights, the CRITIC, ENTROPHY and PIPRECIA method are used, while TOPSIS method is used for the evaluation of alternatives.

3.1 CRITIC Method

In decision-making problems criteria can be viewed as a source of information. The importance weight of criteria could reflect the amount of information contained in each of them [11]. The criteria weights obtained this way are „objective weights".
The CRITIC (Criteria Importance Through Intercriteria Correlation) method is a method for determining the objective criteria weights in the MCDM problem, introduced by Diakoulaki (1995) [12].
The criteria weights derived by this method combine the standard value deviation of the alternatives by each criterion and the correlation coefficient between those criteria [12].
The process of determining the criteria weights based on this method can be summarized in several steps.
Step 1. Calculate the transformations of performance values and obtain criteria vectors as follows (is the set of maximization criteria and is the set of minimization criteria):

$$r_{ij} = \frac{x_{ij} - x_j^-}{x_j^+ - x_j^-}, \forall K_j \in K' \tag{1}$$

$$r_{ij} = \frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}, \forall K_j \in K'' \tag{2}$$

where $x_j^+, j = 1,...n$ are the greatest values for each criterion, while $x_j^-, j = 1,...n$ are the lowest values for each criterion.

Step 2. Calculate the standard deviation σ_j of each criterion using the corresponding vector:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)^2}{m}}, j = 1,...n \quad (3)$$

Step 3. For each pair of the criteria, the correlation coefficient is calculated as an indicator of their mutual dependence:

$$\rho_{jk} = \frac{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)(r_{ik} - r_k)}{\sqrt{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)\sum_{i=1}^{m}(r_{ij} - \bar{r}_k)^2}}, j,k = 1,...n \quad (4)$$

Step 4. The amount of information C_j contained in the criteria j is determined in the following manner:

$$C_j = \sigma_j \sum_{k=1}^{n}(1 - \rho_{jk}), j = 1,...n \quad (5)$$

Step 5. Determine the criteria weights as follows:

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j}, j = 1,...n \quad (6)$$

3.2 ENTROPY Method

The Entropy Method is a method for determining the objective criteria weights in the MCDM problem, introduced by Claude Shannon (1984) [13].

Determination of objective criteria weights according to the Entropy Method is based on the measurements of uncertain information contained in the decision matrix and directly generates a set of weights for given criteria based on mutual contrast of individual criteria values of variants for each criterion and then for all the criteria at the same time [14, 15].

Determination of criteria weights w_j according to the Entropy Method is carried out in four steps [13].

Step 1. Normalization of the values of alternatives according to each of the criteria.

For criteria that are maximized:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{iu}}, \forall K_j \in K' \quad (7)$$

For criteria that are minimized:

$$r_{ij} = \frac{1/x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \forall K_j \in K'' \quad (8)$$

Step 2. The entropy E_j of all alternatives in terms of criteria k_j is calculated as follows:

$$E_j = \varepsilon \sum_{i=1}^{m} r_{ij} \ln r_{ij}, j = 1,...,n \quad (9)$$

where the constant is:

$$\varepsilon = \frac{1}{\ln m} \quad (10)$$

Step 3. The complement of entropy is called the degree of diversification d_j and is calculated as:

$$d_j = 1 - E_j, j = 1,...,n \quad (11)$$

Step 4. The weight coefficients suggest that the weights are directly proportional to the degree of diversification.

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, j = 1,...n \quad (12)$$

3.3 PIPRECIA Method

The Pivot Pairwise Relative Criteria Importance Assessment (PIPRECIA) Method for determining the weights of criteria was proposed by Stanujkic et al (2017) [16].

The process of determining the criteria weights based on this method can be summarized in several steps.

Step 1. Determine the set of relevant evaluation criteria and those in descending order, based on their expected significances.

Step 2. Determine the relative importance S_j of the criteria, in relation to the previous $j-1$ criterion, and do so for each particular criterion.

$$S_j = \begin{cases} >1, & if \quad C_j > C_{j-1} \\ 1, & if \quad C_j = C_{j-1} \\ <1, & if \quad C_j < C_{j-1} \end{cases} \quad (13)$$

Step 3. Calculate the coefficient k_j.

The coefficient k_j is being calculated for each criterion.

$$k_j = \begin{cases} 1, & j = 1 \\ 2 - S_j, & j > 1 \end{cases} \quad (14)$$

Step 4. Calculate the recalculated weight q_j.

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{j-1}}{k_j}, & j > 1 \end{cases} \quad (15)$$

Step 5. Calculate the relative weights of the evaluation criteria. The criterion weights reflecting the attitudes of each participant are obtained.

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k} \tag{16}$$

3.4 TOPSIS Method

TOPSIS (Technique for the Order Preference by Similarity to Ideal Solution) method was introduced by Hwang and Yoon (1981). The ordinary TOPSIS method is based on the concept that the best alternative should have the shortest Euclidean distance from the ideal solution (positive ideal solution – PIS) and at the same time the farthest from the anti-ideal solution (negative ideal solution – NIS). It is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion [5, 17].

TOPSIS method can be implemented using the following steps:

Step 1. Develop the decision matrix (X):

$$X = \left[x_{ij}\right]_{n\times m} \tag{17}$$

Step 2. Determine the normalized decision matrix which elements are r_{ij}:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{18}$$

Step 3. Obtain the weighted normalized decision matrix which elements v_{ij} are obtained by multiplying each column j of the normalized decision matrix by its associated weight w_j (obtained using the joint weights from CRITIC, ENTROPY and PIPRECIA methods for this paper purposes):

$$v_{ij} = r_{ij} \cdot w_j \tag{19}$$

Step 4. Determine the positive ideal and the negative ideal solutions:

$$V^+ = (v_1^+, v_2^+, ..., v_n^+) = \{(\max_i \{v_{ij} \mid j \in B\}), (\min_i \{v_{ij} \mid j \in C\})\} \tag{20}$$

$$V^- = (v_1^-, v_2^-, ..., v_n^-) = \{(\min_i \{v_{ij} \mid j \in B\}), (\max_i \{v_{ij} \mid j \in C\})\} \tag{21}$$

where B and C are associated with the maximization and minimization criteria sets, respectively.

Step 5. The distance from the ideal and anti-ideal solutions are calculated for each alternatives using the two Euclidean distances as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - V_j^+)^2} \tag{22}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - V_j^-)^2} \tag{23}$$

Step 6. Calculate the relative closeness of the i-th alternative Ai to the positive ideal solution:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{24}$$

The higher values of Pi indicate that the rank is better.

4. CASE STUDY

The production of the inner tubes consists of a couple of phases. It begins with the preparation phase in which the rubber mixture is being specifically prepared for the tube production regarding the inner tube type. After the rubber mixture is prepared and inner tube profiles produced, the assembly phase starts.

The assembly phase is responsible for the creation of the inner tube rough shape (the joint of both ends of the inner tube profile is made as well as the application of the valve on the upper side of the profile – opposite side of the joint). Inner tubes prepared this way need to complete the final production phase in order to meet the process requirements.

That phase is the vulcanization phase. The vulcanization phase is done on the curing presses inside the vulcanization moulds. The inner tube profile is placed inside the mould and the specified pressure and temperature outside the tube with specified pressure inside the inner tube during the required period of time make the final perspective to the inner tube profile. Those process parameters regard the pressure/temperature of the steam, which obtain the proper temperature of the mould and the compressed air is applied through the valve from the inside of the inner tube. A medium that distributes the heat from the steam to the mould is heating plates (Fig. 1).

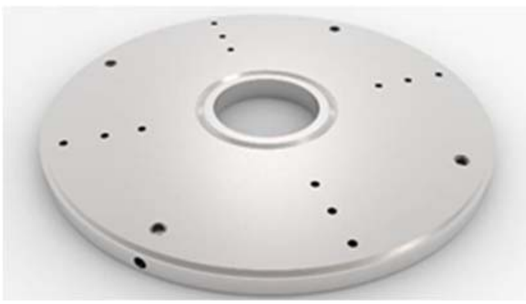

Fig. 1 *Heating plate for the vulcanization process.*

Heating plates must be manufactured specifically for the type of the mould with excellent heat distribution characteristic as well as durability in order to extend their life cycle. Thus, the selection of the optimal material is crucial.

4.1 Decision Matrix

The most important step for the MCDM application on a selected problem is the proper definition of the decision matrix. A properly defined decision matrix could reduce input errors and provide reliable and objective output data. The decision matrix represents a set of values for each alternative solution in comparison to each criterion.

The presented material selection problem involves a set of 5 criteria and 5 alternative solutions (materials) on which the decision matrix is formed (Table 1).

Table 1 - *The material selection of the heating plates problem decision matrix*

Criteria	C_1 [-]	C_2 [MPa]	C_3 [W/m-K]	C_4 [J/g-°C]	C_5 [GPa]
Alternatives	min	max	max	max	max
A_1	9	1000	45	480	210
A_2	3	360	49	470	190
A_3	6	570	53	470	190
A_4	7	590	58.6	460	210
A_5	4	370	47	470	190

The criteria set consist of 5 criteria (Table 2). Those chosen criteria are selected on the previous author's experience – literature review, type of the problem, as well as the previous and existing experience of the heating plates in use.

Table 2 - *Steel material selection criteria*

Properties of the steel material	***Symbol***
Cost [RSD/kg]	C_1
Ultimate tensile strength [MPa]	C_2
Thermal conductivity [W/m-K]	C_3
Specific heat [J/g-°C]	C_4
Modulus of elasticity [GPa]	C_5

C1 – Cost criterion was intended to be expressed in RSD/kg, but it is numerically represented by marks from the basic Saaty's scale. The reason for this was the intersection between wide price ranges for each of the selected materials provided by the local steel suppliers.
C2 – Ultimate tensile strength [MPa] is used to refer to the maximum stress a material can handle before becoming elongated, stretched or pulled.
C3 – Thermal conductivity [W/m-K] is defined as the rate at which heat is transferred by conduction through a unit cross-section area of a material when a temperature gradient exits perpendicular to the area [18].
C4 – Specific heat [J/g-oC] is the amount of heat per unit mass needed to increase the temperature of a material by one degree Celsius.
C5 – Modulus of elasticity [GPa] is defined as the slope of the straight-line portion of stress (σ) and strain (□) curve.
Only the first criterion is the minimization criterion where the lower attribute values are performed. On the other hand, the rest four criteria are maximization criteria where higher attribute values are desired.

The proposed set of alternative solutions consists of 5 steel materials represented by the SRPS EN and DIN standards in use (Table 3).

Table 3 - *Steel material selection alternatives*

Alternative solutions (steel materials)	
Standards: SRPS EN/DIN	***Symbol***
16MnCr5/1.7131	A_1
S235J/1.0038	A_2
E335/1.0060	A_3
C15/1.0401	A_4
S275N/1.0490	A_5

4.2 Criteria Weights

The criteria weights determination is one of the crucial steps in MCDM methodology.
Those weights are a significant source of subjectivity and they have a massive impact on the final solution. Thus, the sensitivity analysis must be performed to have a certain degree of consistency – objectivity.
The criteria weights for this paper's purposes are determined by three methods. The CRITIC, ENTROPY and PIPRECIA method have been applied (Table 4).

Table 4 - *The criteria weights obtained by different MCDM methods*

w_j	C_1	C_2	C_3	C_4	C_5
CRITIC	0.264	0.155	0.189	0.168	0.224
ENTROPY	0.491	0.472	0.028	0.001	0.008
PIPRECIA	0.155	0.141	0.202	0.269	0.234

The PIPRECIA method is declared as the subjective method in criteria weights determination because of the subjective evaluation of criteria importance between all selected criteria (every author has evaluated the criteria importance individually and those values are summarized for further calculations), while CRITIC and ENTROPY method does not determine the criteria weights on the same methodology.
After the criteria weights are determined by each method individually, those weights could be summarized into one joint criteria weights. The average criteria weights values are represented in Table 5 and those values are applied in the final step – alternative evaluation.

Table 5 - *Joint criteria weights*

	C_1	C_2	C_3	C_4	C_5
w_j	0.303	0.256	0.140	0.146	0.155

4.3 Evaluation of alternatives

The final step in MCDM methodology describes the evaluation of alternatives and their preferences.
For the evaluation process of the alternative solutions – steel materials, the TOPSIS method has been applied.
Complete alternative evaluation and ranking obtained with TOPSIS method as described in Section 3.3 and the assessment results are presented in Table 6.

Table 6 - *Complete rankings obtained by TOPSIS method*

Alternatives	*TOPSIS*
A_1	0.471
A_2	0.526
A_3	0.427
A_4	0.355
A_5	0.480

According to this table, preference is given as follows: Alternative A2 > Alternative A5 > Alternative A1 > Alternative A3 > Alternative A4. The best choice is Alternative A2, and the worst choice is Alternative A5.

4. CONCLUSION

This research has demonstrated the applicability of the MCDM methodology in the material selection for the heating plates inside the inner tube production process. The final results have shown the best-ranking score which is Alternative A2 (S235J/1.0038). This material represents the best possible evaluated alternative solution/ material for the heating plates.
That is to say, the selected material is proposed to the Company as the solution for the heating plates manufacturing. This way the experimental study would confirm the material selection process.
The improvement of this research from the MCDM point of view is in the better understanding of the problem and increasing the relative criteria and alternative sets.
Also, the thermal analysis could be obtained on the numerical model inside the finite element analysis (FEA). This way the behavior of the heating plates under the same working conditions and different types of steel materials could be observed. The material selection could be tested virtually before the heating plates manufacturing and testing in real conditions.

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NOTE

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