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Application of Integrated AHP-TOPSIS Method in Hybrid Natural Fiber Composites Materials Selection for Automotive Parking Brake Lever Component

[1,2]M.R. Mansor, [1]S.M. Sapuan, [1,3]E.S. Zainudin, [1]A.A. Nuraini and [4]A. Hambali

[1]Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[2]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3]School of Engineering and Design, Brunel University, Uxbridge Middlesex, UB8 3PH, United Kingdom
[4]Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

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ABSTRACT

Hybrid natural fiber composites made from the combination of natural fiber and synthetic fiber offers the performance solution while in the same time able to provide further balance between cost and sustainability requirements for automotive structural application. Despite such advantages, the task of designing such hybrid composites during materials selection process such as for matrix materials selection are very challenging considering the involvement of multiple conflicting requirements with varying attributes which are needed to be complied simultaneously by the candidate material. In this paper, multi-criteria decision making technique (MCDM) through the integration of Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method were applied in the materials selection of thermoplastic matrix for hybrid natural fiber composites formulation towards the design of automotive parking brake lever component. Based on literature review, four major types of automotive thermoplastic materials used for passenger car were selected as the materials candidate namely high density polyethylene, low density polyethylene, polypropylene and nylon 6. Moreover, four (4) main design criteria and ten (10) sub-criteria were applied in the selection process based on the product design specifications. The AHP method was first utilized to analyze the weightage of each criteria with respect to the goal and TOPSIS method was later applied to determine the best solution among the thermoplastic material candidates. The overall score shows that polypropylene is the most suitable thermoplastic matrix material for the hybrid natural fiber composites formulation for the intended application. The integrated AHP-TOPSIS method was also found able to provide systematic comparison and selection method to composites designers especially for automotive product development purposes involving hybrid natural fiber composites.

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INTRODUCTION

In recent years, new changes in automotive legislative which among them are the introduction of new European and Japanese legislations on vehicle end-of-life and vehicle emissions requirements especially for passenger vehicles has pushed automakers into exploring new innovative ideas as the solution to comply with the requirements for new vehicle development (Fontaras & Samaras, 2010). Among the research conducted is through the implementation of natural fiber composites as the substitution materials for conventional engineering materials normally applied in vehicle component production such as synthetic based polymer composites, most notably due to their renewability, low cost and low density advantages (Koronis, Silva, & Fontul, 2013; Rassiah & Megat Ahmad, 2013; Qatu, 2011). For automotive structural application, many success stories have been reported on the use of synthetic polymer composites as the chosen material for the component construction, where these materials stand out in both technical performance and lightweight criteria especially when compared to steel-based material (Duflou, Moor, Verpoest, & Dewulf, 2009; Imihezri, Sapuan, Ahmad, & Sulaiman, 2005; Sapuan, 2005; Sapuan and Abdalla, 1998). Nevertheless, as the automotive design are evolving

Corresponding Author: S.M. Sapuan, Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, UPM Serdang, Selangor, Malaysia
E-mail: sapuan@upm.edu.my

especially in order to compensate the newly introduced legislative as mentioned previously, new solution has to be explored to also acknowledge the importance of sustainability in the product design criteria, and thus, the potential of natural based polymer composites becomes more attractive to address the needs.

However, despite the advantages that can be provided by natural fibers as the composites reinforcement agent, there are still an inherent major limitation possessed by the material, which is low structural properties (such as strength and stiffness) as well as low dimensional stability compared to synthetic fibers, particularly due to its material composition and hydrophilic nature which limits their application especially for high load bearing condition (Akil *et al*., 2011; Faruk, Bledzki, Fink, & Sain, 2012, Chao *et al*., 2013). Again, there are many potential solution developed to improved the situation, such as through chemical modification of fibers, use of coupling agent for composites, and hybridization technique (Ishak *et al*., 2013). The later method, hybridization, involved the combination of at least two different types of fibers reinforced within a single matrix, where the combination can be made either from natural fibers with natural fibers or natural fibers with synthetic fibers. The hybridization technique has been acknowledged able to provide the balance between performance, cost and more recently environmental attributes for natural fiber composites in many specific applications (Jawaid & Abdul Khalil, 2011; LaRosa *et al*., 2013).

To begin with, this study is part of an automotive product development project where the composites hybridization technique using the combination of natural fiber with glass fiber is applied for development of structural automotive component, in specific the parking brake lever component. Former study made by the author(s) has successfully determine the best type of natural fiber to be hybridized with glass fiber towards the hybrid composites construction for parking brake lever application based on a set of design requirement derived from the new product design specifications (Mansor, Sapuan, Zainudin, Nuraini, & Hambali, 2013). By using Analytic Hierarchy Process (AHP) method in the analysis, it was found the kenaf natural fiber is the best candidate material to be selected for the hybrid composites. However, in similar report, a pre-defined thermoplastic resin, namely polypropylene was selected as the matrix material for the hybrid composites formulation based on literature review and author intuitive judgment, as a reference to laid the foundation for the materials selection process. Thus, continuing product development work is carried out in this study to determine scientifically and systematically what is really the best thermoplastic matrix to be aggregated with kenaf and glass fiber to form the hybrid composites. Four types of thermoplastic matrices normally applied in natural fiber composites application was selected as the candidate material, and several design criteria derived from the same product design specifications developed in the earlier study was applied in the selection process.

Moreover, an integrated AHP-TOPSIS multi criteria decision making method (MCDM) was utilized in this study for performing the decision making process of selecting the best thermoplastic matrix for the hybrid kenaf/glass fiber composites. Despite the success of AHP method application in gaining the needed answer for the previous study, there is also reported limitation of the approach where increase in computational time is expected especially if the higher selection criteria and number of alternatives are required in making the materials selection decision (Al-Harbi, 2001). Thus, in order to improved on the limitation, the AHP method is combined with another MCDM method, namely Technique for Order Preference by Similarity to Ideal Solution or TOPSIS, where the AHP method is utilized to determine the weight of the selection criteria and continued by TOPSIS method to perform the ranking task and proposed the best solution among the candidate materials. The synergetic effort was proven very successful in completing the many decision making process, especially when multiple criteria and alternatives with varying and conflicting attributes are present and have to be analyzed simultaneously in order to obtained the optimum decision, not only for materials selection problem but also in other areas related to design, engineering and manufacturing systems (Bahraminasab *et al*., 2014; Chakladar & Chakraborty, 2008; Lin, Wang, Chen, & Chang, 2008; Rao & Davim, 2008). The AHP method is well accepted to excel in quantifying the subjective judgments through its pair-wise comparison method as well as determining the consistency of the subjective judgments (Ariff, Salit, Ismail, & Nukman, 2009; Sapuan *et al*., 2011), which is much related to identifying consistently the weight of the criteria for the materials selection process. In the other hand, despite lacking in no specific weighting procedure embedded with it, the TOPSIS method is able to provide a relatively quick and easy decision, where its preferential ranking output can provides a better understanding of differences and similarities among alternatives which are very especially useful when dealing with a large number of alternatives and criteria which makes it suitable for linking with computer databases dealing with material selection (Jahan, Ismail, Sapuan, & Mustapha, 2010). Thus, by combining both methods, a more efficient way in analyzing the decision structure as well as determining the criteria weight can be achieved especially in dealing with practical and theoretical problems (Behzadian, Otaghsara, Yazdani, & Ignatius, 2012). As part of the concurrent engineering (CE) technique, these MCDM methodologies can also reduce the time to market and quality improvement especially in conceptual design stage for new product development (Sapuan, Osman & Nukman, 2006).

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Methodology:

In overall, the study performed involved several main phases, namely identification of candidate materials and their material properties, listing of the selection criteria and related sub-criteria, analyzing the candidate attributes with respect to the goal using integrated AHP-TOPSIS method, and finally selection of the best thermoplastic matrix for hybrid natural fiber composites formulation towards the design of automotive parking brake lever component based on the overall score obtained from the analysis results. In the initial phase, suitable thermoplastic material candidates were selected based on the list of typical thermoplastic resins used in natural fiber composites fabrication as suggested by Holbery and Houston (2006). Four thermoplastic matrices, namely polypropylene (PP), high density polyethylene (HDPE), low density polyethylene (LDPE) and nylon 6 were chosen as the potential matrix materials for the hybrid natural fiber composites formulation. Table 1 summarized the overall materials properties for the selected thermoplastic.

Table 1: Thermoplastic matrix material properties (Holbery and Houston, 2006; Anon, 2012).

Material Properties	Thermoplastic Matrix			
	PP	**LDPE**	**HDPE**	**Nylon 6**
Tensile strength (MPa)	26-41.4	40-78	14.5-38	43-79
Modulus Young (GPa)	0.95-1.77	0.055-0.38	0.4-1.5	2.9
Elongation (%)	15-700	90-800	2-130	20-150
Impact Strength (J/m)	21.4-267	>854	26.7-1068	42.7-160
Coefficient of Thermal Expansion (mm/mm/^{o}Cx10^5)	6.8-13.5	10	12-13	8-8.6
Density (g/cm^3)	0.899-0.920	0.910-0.925	0.94-0.96	1.12-1.14
Water Absorption – 24hours (%)	0.01-0.02	<0.015	0.01-0.2	1.3-1.8
Heat Deflection Temperature (^{o}C)	50-63	32-50	43-60	56-80
Process Melting Temperature (^{o}C)	160-176	105-116	120-140	215
Raw material cost (USD/lb)	0.95-0.98	1.05-1.07	0.89-0.91	2.08-2.12

Later, relevant performance criteria which need to be satisfied by the best thermoplastic candidate were identified and selected for the hybrid natural fiber composites. Based on the literature review, four (4) main design criteria related to the product design specifications (PDS) of the parking brake lever component developed by Mansor, Sapuan, Zainudin, Nuraini, and Hambali (2014) was applied for the materials selection process. Consequently ten (10) sub-criteria that correspond specifically to the main criteria were later defined based on the thermoplastic matrix materials properties as shown in Figure 1. For coefficient of thermal expansion, density, water absorption, process melting temperature and raw material cost sub-criteria, lower values are preferred for the thermoplastic materials to gain the improved technical performance and resistance to environmental effect as well as reduced product weight and cost. Table 2 summarized the decision criteria used in the AHP-TOPSIS analysis for the thermoplastic matrices based on the parking brake lever PDS.

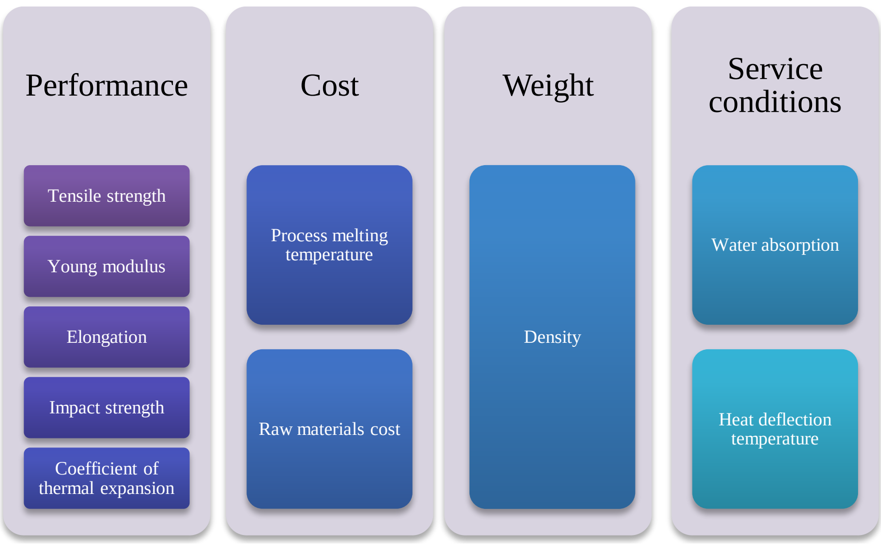

Fig. 1: Thermoplastic matrix materials selection main criteria and their corresponding material properties as sub-criteria.

Afterwards, the performance of the candidate materials with respect to the goal and criteria of the project was analyzed using integrated AHP-TOPSIS methods. The selection process using the integrated multi criteria decision making method (MCDM) was divided into two stages, first was determination of the weightage for the identified criteria based on AHP method and followed by ranking of the alternatives using TOPSIS method. The criteria weightages obtained were later used in the ranking process to attain the overall score of each candidate materials. Finally, the best thermoplastic matrix was chosen based on the highest score ranking between the listed candidate materials. The overall procedures for the weighting and ranking process using the integrated AHP-TOPSIS method used are summarized as below.

Table 2: Decision criteria used in the AHP-TOPSIS analysis for the thermoplastic matrices based on the parking brake lever PDS.

Overall goal: To select the best thermoplastic matrix for automotive parking brake lever using hybrid natural fiber composites		
Main Criteria	**Corresponding materials properties as sub-criteria**	**Aim**
i. Performance	Tensile strength, Young's modulus, Impact strength	Maximum value to provide the required structural strength of the final composites
	Elongation, Coefficient of thermal expansion	Minimum value to allow improved performance in term of deformation under physical and thermal loadings for the final composites
ii. Cost	Process melting temperature, Raw material cost	Minimum value to achieve lowest overall product cost specifically in term of material and manufacturing costs
iii. Weight	Density	Minimum value to attain lightweight property for the final composites
iv. Service condition	Water absorption, Heat deflection temperature	Minimum value to ensure final composites dimensional stability when exposed to surrounding moisture and temperature

Stage 1: Weighting of criteria using AHP method:

Step 1: A three level AHP hierarchy framework was constructed for the weighting process. At the first level, the goal of the analysis was defined which is to determine the best thermoplastic matrix for the hybrid natural fiber composites formulation. At the second and final AHP level, the selection main criteria and sub-criteria were defined respectively based on the parking brake lever product design specifications.

Step 2: Pair-wise comparison judgements were performed based on predefined rating value (Table 3) for each criteria with respect to goal and each sub-criteria with respect to the main criteria through AHP decision matrix. The number of pair-wise comparison evaluations depends on the number of criteria involved in the hierarchical framework, and is calculated using the $n(n\text{-}1)$ rule where n is the number of criteria.

Table 3: Importance scale for pair-wise comparison analysis.

Relative intensity	Definition
1	Equal importance
3	Slightly more importance
5	Essential or high importance
7	Very high importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgments
Reciprocals	Reciprocals for inverse comparison
Note: (i) if judgement value on the left side, actual judgement value is taken, and (ii) if judgement value on the right side, reciprocal value is taken	

Step 3: Pair-wise judgments were synthesized calculating priority vectors to determine the weightage of every criteria based on the normalized principle Eigenvectors. The Eigenvectors or the priority vector, w can be calculated as using Equation (1) (Mansor *et al*., 2014).

$$w = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i=1}^{a} a_{ij}}, \quad i, j = 1,2, \dots , n \qquad \text{Equation (1)}$$

where w is the priority vector (or eigenvector), a_{ij} is the importance scale, i.e. 1,3,5,…, and n is the number of criteria.

Step 4: The overall consistency ratio, CR for the overall judgments was calculated based on the principle Eigenvalues, consistency index, CI and relative index, RI. The consistency of the judgments made is checked through the CR value, where CR<10% is recommended for consistent judgment decisions. If CR>10%, step 2 until step 3 are repeated until acceptable CR value is achieved. The determination of the CR value can be calculated using equation (2) to Equation (4) (Hambali, Sapuan, Rahim, Ismail, & Nukman, 2011).

Consistency ratio, CR = CI/RI Equation (2)
where RI is the Random consistency index of the same order matrix

Consistency index, CI = $(\lambda_{max} - n)/(n - 1)$ Equation (3)
where n is the matrix size or criterion, and

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Principal Eigenvalue, $\lambda_{\max} = \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} a_{ij} \times w_j}{w_i} \quad i, j = 1,2, \ldots , n$ Equation (4)

Stage 2: Ranking of alternatives (thermoplastic matrix candidates) using TOPSIS method:

Step 5: The overall TOPSIS decision matrix was first formulated based on Equation (5)

$$D = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & X_{11} & X_{12} & \cdots & X_{1n} \\ A_2 & X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & X_{m1} & X_{m2} & \cdots & X_{mn} \end{matrix}$$ Equation (5)

where $A_1, A_2, \ldots, A_n$ are potential alternatives that decision makers need to select and $C_1, C_2, \ldots, C_n$ are criterion, which evaluated the alternative performance and was calculated, X_{ij} is the rating of alternative Ai with respect to criterion C_j when w_j is the weight of criterion C_j (Davoodi *et al*., 2011)

Step 6: The normalized decision matrix was calculated using Equation (6)

$n_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{m} X^2{}_{ij}}}$ where $i = 1,\ldots, m$, and $j = 1,\ldots,$ Equation (6)

Step 7: The weighted normalized decision matrix was determined using Equation (7)

$$V = N_D . W_{n\times n} = \begin{vmatrix} V_{1i} & \cdots & V_{1j} & \cdots & V_{1n} \\ \vdots & & \vdots & & \vdots \\ V_{m1} & \cdots & V_{mj} & \cdots & V_{mn} \end{vmatrix}$$ Equation (7)

where w_j is the weight of the ith attribute or criterion, and $\sum_{j=1}^{n} w_j = 1$

Step 8: The positive ideal and negative ideal solutions were calculated using Equation (8) and Equation (9):

$A^+ = \{({}^{max}{}_j v_{ij} ; i \in I)({}^{min}{}_j v_{ij} ; i \in J); i = 1, 2, \ldots, n\}$ Equation (8)

$A^- = \{({}^{min}{}_j v_{ij} ; i \in I)({}^{max}{}_j v_{ij} ; i \in J); i = 1, 2, \ldots, n\}$ Equation (9)

where I is associated with a benefit criterion, and J is associated with cost criterion.

Step 9: The separation measures were later calculated using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as Equation (10):

$d_{i^+} = \left\{\sum_{j=1}^{n} (v_{ij} - v_{j^+})\right\}^{1/2}; i = 1, 2, \ldots, m\}$ Equation (10)

Similarly, the separation from the negative ideal solution is given as Equation (11)

$d_{i^-} = \left\{\sum_{j=1}^{n} (v_{ij} - v_{j^-})\right\}^{1/2}; i = 1, 2, \ldots, m\}$ Equation (11)

Step 10: Finally, the relative closeness to the ideal solution values for every alternatives were determined where the relative closeness of the alternative A_i with respect to A^+ is determined using Equation (12). The ranking of alternatives is finally made by ranking the preference in decreasing order based on the indices

$cl_{i^+} = \frac{d_{i^-}}{(d_{i^+} - d_{i^-})}, 0 \leq cl_{i^+} \leq 1; i = 1, 2, \ldots, m$ Equation (12)

RESULTS AND DISCUSSION

The subjective judgments made to determine the relative importance of between each criterion with respect to the project goal were translated into empirical values in the weighting analysis using AHP method. Figure 2 shows an example of the pair-wise comparison judgments organized in a AHP decision matrix for sub-criteria with respect to Performance main criteria. Similar approach made by Hambali, Sapuan, Ismail, and Nukman (2010) was implemented in the judgment process between the sub-criteria with respect to the main criteria and main-criteria with respect to the goal which are based on user's experience and knowledge.

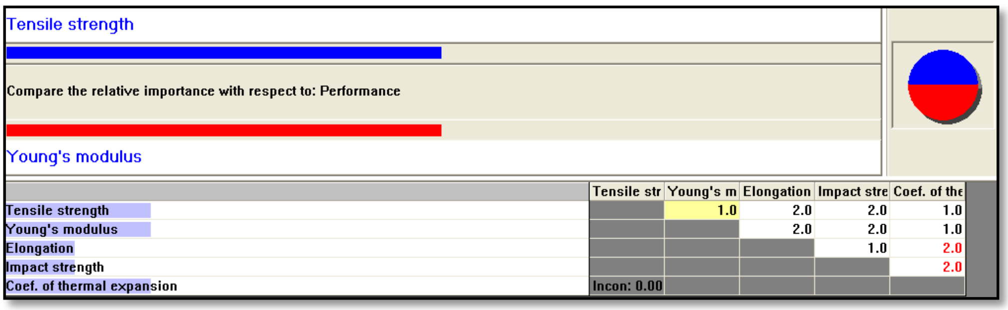

Fig. 2: Pair-wise comparison matrix of sub-criteria with respect to Performance main criteria.

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The final AHP results obtained corresponding to importance of each criterion are shown in Figure 3 for local weight and Figure 4 for global weight respectively. The global weight values were later transferred to the next ranking stage using TOPSIS method as inputs for the criteria weight. Results obtained also showed that very good consistency subjective judgments made were achieved in the AHP analysis indicated through overall CR values of less than 0.1 which further increase the level of confident of the results.

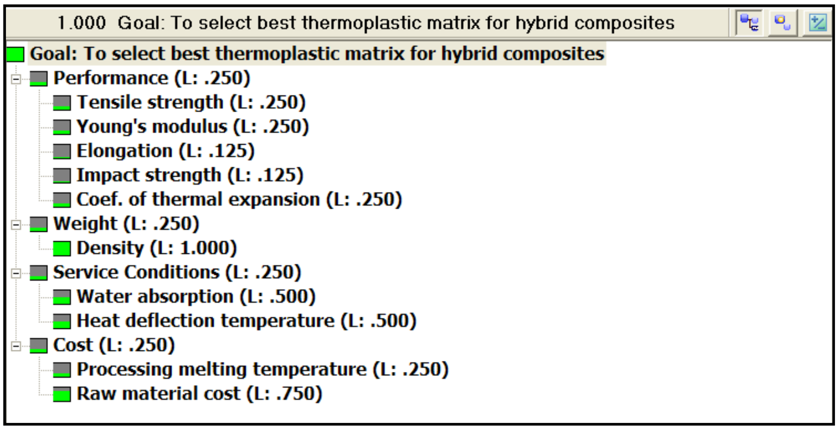

Fig. 3: Results of local weight for main criteria and sub-criteria using AHP.

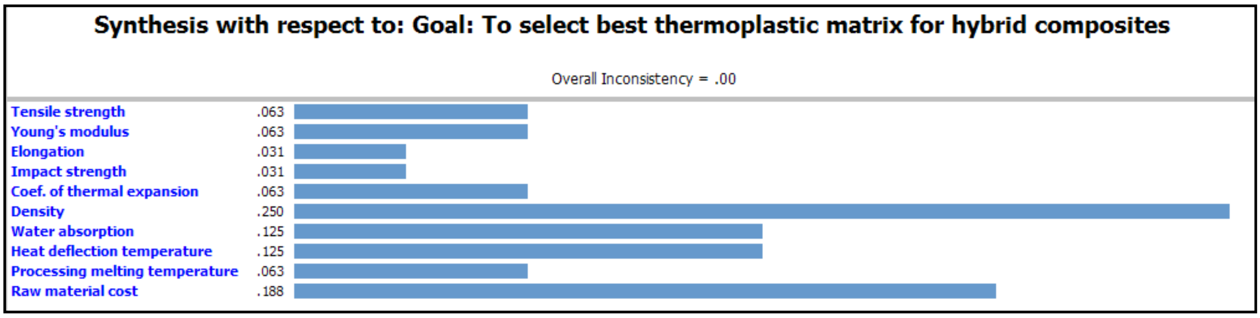

Fig. 4: Results of global weight for sub-criteria using AHP.

In the ranking process using TOPSIS method, decision matrix for thermoplastic matrix materials selection were created which includes information of the weight for each criterion derived in the earlier AHP analysis and average value properties of all the candidate materials as shown in Table 3 while Table 4-7 summarized the gathered outcomes of the TOPSIS analyses for normalized matrix, weighted normalized matrix, the positive and negative ideal solution matrix and separation of each alternative from the ideal solution as well as its relative closeness to the ideal solution respectively.

Table 3: Decision matrix for selecting the best thermoplastic matrix.

	Tensile strength	Modulus Young	Elongation	Impact Strength	Coefficient Thermal Expansion	Density	Water Absorption	Heat Deflection Temp.	Process Melting Temp.	Raw material cost
Weight	0.063	0.063	0.032	0.032	0.063	0.250	0.125	0.125	0.063	0.188
PP	33.70	1.360	357.50	144.20	10.15	0.910	0.015	56.5	168.0	0.965
LDPE	59.00	0.218	445.00	427.00	10.00	0.918	0.015	41.0	110.5	1.060
HDPE	26.25	0.950	66.00	547.35	12.50	0.950	0.105	51.5	130.0	0.900
Nylon 6	61.00	2.900	85.00	26.35	8.30	1.130	1.550	68.0	215.0	2.100

Table 4: Normalized matrix.

	Tensile strength	Modulus Young	Elongation	Impact Strength	Coefficient Thermal Expansion	Density	Water Absorption	Heat Deflection Temp.	Process Melting Temp.	Raw material cost
PP	0.355	0.406	0.615	0.203	0.491	0.464	0.010	0.513	0.522	0.358
LDPE	0.621	0.065	0.766	0.602	0.483	0.468	0.010	0.372	0.343	0.393
HDPE	0.276	0.284	0.114	0.771	0.604	0.484	0.068	0.467	0.404	0.334
Nylon 6	0.642	0.866	0.146	0.037	0.401	0.576	0.998	0.617	0.668	0.779

Table 5: Weighted normalized matrix.

	Tensile strength	Modulus Young	Elongation	Impact Strength	Coefficient Thermal Expansion	Density	Water Absorption	Heat Deflection Temp.	Process Melting Temp.	Raw material cost
PP	0.0222	0.0254	0.0194	0.0064	0.0307	0.1159	0.0012	0.0641	0.0326	0.0671
LDPE	0.0388	0.0041	0.0241	0.0190	0.0302	0.1169	0.0012	0.0465	0.0215	0.0737
HDPE	0.0173	0.0177	0.0036	0.0243	0.0378	0.1211	0.0084	0.0584	0.0252	0.0626
Nylon 6	0.0401	0.0541	0.0046	0.0012	0.0251	0.1440	0.1247	0.0771	0.0418	0.1460

Table 6: The positive and negative ideal solution matrix.

	Tensile strength	Modulus Young	Elongation	Impact Strength	Coefficient Thermal Expansion	Density	Water Absorption	Heat Deflection Temp.	Process Melting Temp.	Raw material cost
Positive ideal solution	0.0401	0.0541	0.0241	0.0243	0.0251	0.1159	0.0012	0.0771	0.0215	0.0626
Negative ideal solution	0.0173	0.0041	0.0036	0.0012	0.0378	0.144	0.1247	0.0584	0.0418	0.146

Table 7: Separation of each alternative from the ideal solution and its relative closeness to the ideal solution.

	Separation from positive ideal solution	Separation from negative ideal solution	Relative closeness from ideal solution
PP	0.0428	0.1523	0.7805
LDPE	0.0602	0.1517	0.7160
HDPE	0.0536	0.1483	0.7347
Nylon 6	0.1560	0.0595	0.2761

Figure 5 show the overall rank of the analyzed candidate thermoplastic matrices involved in selection. The rank was constructed from the relative to closeness form ideal scores obtained from the TOPSIS method. It can be observed that PP emerged with the highest score at the end of the exercise, followed by HPDE, LDPE and finally Nylon 6 thermoplastic matrix. Thus, it can be concluded that PP is the best thermoplastic matrix to be selected for the hybrid natural fiber composites formulation that satisfy all the required design specification for the intended application. Similarly, the potential of PP as the best thermoplastic matrix for automotive component construction was also reported by Girubha & Vinodh (2012) through case study on thermoplastic materials selection using Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method for automotive interior instrument panel component. Their findings revealed that PP is the best thermoplastic material for instrument panel construction due to its overall technical, cost and lightweight performance as well as environmental advantages. In addition, recent published market report by Dallas based TX Market Research Company and Consulting Firm also indicated that PP resin is currently dominating the global automotive market in automotive plastic for vehicle design, majorly due low cost and easy forming properties ahead to other thermoplastic materials (Anon, 2014).

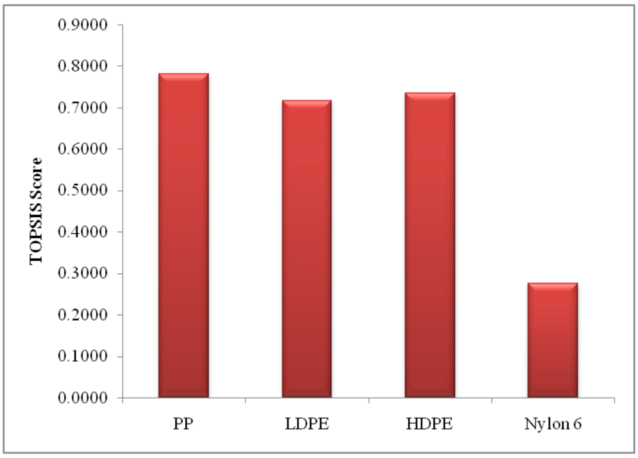

Fig. 5: Rank of thermoplastic matrix based on AHP-TOPSIS score.

Conclusions:

In conclusion, the materials selection exercise performed in this study using integrated AHP-TOPSIS methods showed that PP is the best thermoplastic matrix material for hybrid natural fiber composites formulation towards the development of automotive parking brake lever based on the component PDS. The PP matrix obtained the highest score from all the required design specifications compared to the other thermoplastic material candidates. Apart from that, as shown in previous section, the task of designing such hybrid composites during materials selection process such as for matrix materials selection are very challenging considering the involvement of multiple conflicting requirements with varying attributes which are needed to be complied simultaneously by the candidate material. Thus, the integrated AHP-TOPSIS method was also found able to provide systematic comparison and selection method to designers in completing the decision making process for composites thermoplastic materials selection especially for automotive product development purposes involving hybrid natural fiber composites.

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