Application of Analytic Hierarchy Process (AHP) in the analysis of the fuel efficiency in the automobile industry with the utilization of Natural Fiber Polymer Composites (NFPC)

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Abstract. A systematic method of material analysis aiming for fuel efficiency improvement with the utilization of natural fiber reinforced polymer matrix composites in the automobile industry is proposed. A multi-factor based decision criteria with Analytical Hierarchy Process (AHP) was used and executed through MATLAB to achieve improved fuel efficiency through the weight reduction of vehicular components by effective comparison between two engine hood designs. The reduction was simulated by utilizing natural fiber polymer composites with thermoplastic polypropylene (PP) as the matrix polymer and benchmarked against a synthetic based composite component. Results showed that PP with 35% of flax fiber loading achieved a 0.4% improvement in fuel efficiency, and it was the highest among the 27 candidate fibers.

1. Introduction

Currently, natural fuel resources are running low and this phenomenon receiving attention globally. The escalating fuel consumption for transportation is one of the major reasons of natural fuel resource depletion. However, this issue can be alleviated if weight reduction can be achieved on vehicles by utilizing natural fiber polymer composites (NFPCs) as replacements to conventional materials such as metals and synthetic fiber polymer composites for certain vehicle components \[1, 2\].

Synthetic-fiber polymer composites such as embedding glass or carbon fibers in a plastic matrix as alternatives to the steel or aluminium components may avert the fuel consumption issue. They possesses strengths, stiffness, and other mechanical properties, that are similar to a plain steel or aluminium component, with the additional benefit of being a much lighter material. Thus, started the easiest solution to increasing the efficiency, as reducing weight and maintaining the strength is very much desired in this industry.

However, the problem now lies within replacing these synthetic fiber polymer composites with those NFPCs to ascertain same or stronger properties than the synthetic counterparts and help the automobile industry “go green” \[3\]. Therefore, this study aims to perform statistical analysis using Analytic Hierarchy Process (AHP) to assess the benefits of utilizing various NFPCs to obtain multiple options of candidate fibers to justify the grounds of replacing synthetic fibers in the automobile industry to achieve better fuel efficiency.
1.1. The rule of composites mixtures

Composites composed of two or more materials (i.e. matrix and reinforcement phase). The “rule of mixtures” is a theory that involves predicting the final composites properties based on the weighted average of the constituents’ properties. Example of this rule would apply to the density ($\rho$) and among other properties, and thus the following equation may be written:

$$m_c = m_m + m_r$$

Where, $m_c$ is the mass of the composite (kg), $m_m$ is the mass of the matrix phase (kg), and $m_r$ is the mass of the reinforcement phase (kg).

Given the relation that volume, mass and density have in common, i.e. density is the ratio of mass over volume. Therefore, the following equation is formed.

$$\rho_c = f_m \rho_m + f_r \rho_r$$

Where, $f_m$ and $f_r$ are the volume fractions of matrix and reinforcing phase with respect to the composite and final phase. For this research, it is assumed that the composite’s fibers are aligned in the longitudinal direction [4]. Therefore, by using the equation (2) for density and similar models for the other properties, the predicted properties are computed using MATLAB and the results were recorded in the database. The input data is based from various sources [5, 6, 7, 8] and a sample of the data at 60% natural fiber loading based on the rule of mixtures is shown in Table 1. It is also noted that the rule of mixtures is an estimation method as it is a general rule for a weighted mean calculation of a composite which is made up of continuous and unidirectional fibers [4, 9].

1.2. The analytic hierarchy process

AHP has been used successfully by many applications such as business field, government, military, and industry [10]. It was adopted by Farag [11] and used as a decision-making process for selecting the right composite for automobile industry. The key elements of AHP described by Bodin and Gass [10] have been laid out to understand the theory and practical situations application. Few of the theories relate directly to this study are the AHP Fundamental Pairwise comparison scale, ratio scales, and ratings model. AHP fundamental aspects will accurately analyze the data in a multi-factor manner. Noted that this process follows a similar pattern of the weighted objective method, in which the decision maker (DM) assigns weights/scale ratings from 1 – 9 and estimates the unknown weights based on research, insights, or even experience and assign them relative to the multi-criteria factors [10].

The pairwise comparison question deals with assigning accurate weights to certain criterion, are based on the DM’s approximation (1 – 9) by asking whether one entity (say for example, Entity A) (i.e. criteria/alternative) is more important that the other (Entity B) in question. Bodin and Gass [10] have mentioned that the pairwise comparison must be interpreted by taking the ratio of A’s assigned weight to B’s and should be normalized, so that the denominator is always equal to 1. An example would clarify the above mentioned by using the verbal scale and associating it with the fundamental 1-9 numeric scales. Thus, by saying Entity A is “more important” than Entity B, the ratio may be written as 5/1. What this means is if the DM assigned A’s weight to be 40 and B’s to 8, the relative ratio thereby is 5/1 [10]. Thus, AHP’s resultant weights are ratio-scale numbers and consequently form a ratio scale that is units free.

Therefore, the resultant weights are normalized ratio-scale numbers. This allows the DM to compare alternatives. Subsequently, this method would allow for comparing alternative NRPCs, seeing as there are a number of combinations to select from (24 volume fraction variants; 20%, 35%, and 60% of NFPCs – with PP, with 3 combinations of PP with E-glass with respect to each volume fraction as a benchmark). Since the resulting weights are units free, it would allow easy comparisons based on numeric values alone. For example, if A acquires a resultant weight of 0.680 and B with a weight of 0.340; a ratio of 4/2, it would ultimately conclude that A is preferred twice as much as B [10]. PP has been selected as the candidate matrix due to the fact that it has been used as a polymer matrix previously [11] and it achieve higher rankings and physical properties in the final outcome [12].
For evaluation of the criteria, the eigenvector of the pairwise matrix must be calculated. This is to ensure that the DM’s scores are related to each of the other weighted scores and gives clarity to the values. Quantitative values, such as preferences, are evaluated using the eigenvector method, while quantitative values, like data on mechanical properties, need to be normalized in the matrix.

Table 1. Sample of input data of NFPC at 60% fiber loading (value based on [5, 6, 7, 8])

| Composite combos | Density (kg/m3) | Tensile strength (MPa) | Young’s modulus (GPa) | Elongation at break (%) | Mass (kg) |
|------------------|-----------------|------------------------|-----------------------|-------------------------|-----------|
| PP-Flax          | 1,364.00        | 916.00                 | 24.04                 | 161.92                  | 5.45      |
| PP-Hemp          | 1,346.00        | 556.00                 | 42.64                 | 162.40                  | 5.38      |
| PP-Jute          | 1,358.00        | 496.00                 | 16.54                 | 160.90                  | 5.43      |
| PP-Kenaf         | 1,424.00        | 574.00                 | 32.44                 | 160.96                  | 5.69      |
| PP-Sisal         | 1,334.00        | 436.00                 | 13.84                 | 164.20                  | 5.33      |
| PP-Coir          | 1,184.00        | 121.00                 | 36.64                 | 178.00                  | 4.73      |
| PP-Curaua        | 1,304.00        | 676.00                 | 18.64                 | 162.58                  | 5.21      |
| PP-Abaca         | 1,364.00        | 503.80                 | 20.80                 | 161.74                  | 5.45      |
| PP-E-glass       | 1,994.00        | 2,116.00               | 44.44                 | 162.22                  | 7.97      |

2. Methodology

2.1. Initialization of the hierarchy

The overall method to setup the AHP is in accordance to the published work by Saaty [13]. The decision hierarchy of AHP is shown in Figure 1.

![Figure 1. The decision hierarchy of AHP for the research. The values shown above correspond to the weighted scores from the pairwise comparison calculations which will be illustrated in Figure 2.](image1)

2.2. AHP parameters

![Figure 2. Pairwise comparison (top) shows the evaluated weighted scores with respective eigenvector values. Preference weights against each criterion (bottom) with legend.](image2)
The criteria were assessed according to the scaled weights set out by Bodin and Gass [10] and utilized by Farag [11]. This research explores the fuel efficiency improvement through mass (weight) reduction. The mass criterion would need to hold the highest weighting. The pairwise comparison matrix, as seen in Figure 2, shows the evaluated version of the ratio-scale numbers. Also depicted are the scores attributed to each criterion against each other, and the eigenvector evaluation.

2.3. MATLAB computation
Raw data were fed into MATLAB codes to generate the AHP results. The computation was repeated for each fibre’s weight percentile group and then again for a variant design of the car hood, to observe if any improvements were found. MATLAB coding was performed to ease the computation for large matrices of data, i.e. to obtain the eigenvectors from multiples (27x27) matrices of fiber data, necessary for the AHP.

2.4. Solid modelling proposed engine hoods
Two engine hood designs were considered in this study. Solid modelling of the proposed engine hood designs were completed using SolidWorks. The mass property of the two hood models was captured and it was used for subsequent interpretation for fuel efficiency.

The two hood dimensions are as follows: Hood 1: L = 1404.25 mm, w = 1702.27 mm, and t = 1.6677 mm, and Hood 2: L = 1410.65 mm, w = 1268.10 mm, and t = 1.2673 mm.

3. Results and discussions

3.1. Simulation output

3.1.1. Hood 1 results and Hood 2 results. Hood 1 showed promising results, and the top 5 ranks are displayed in Table 2. Majority of the values resulted from the NFPC with 60% fiber loading, while Flax at 35% ranked 5th out of the 27 candidate fibers. Hood 2 results, showed that the mass reduction achieved were greater than Hood 1, and produced similar ranking to that of the Hood 1 results with the exception of the Curaua fiber at 60% outperforming kenaf fiber at the same percentage for 3rd place, as shown in Table 2.

| Fiber | Mass (kg) | Fiber | Mass (kg) |
|-------|----------|-------|----------|
| 1 Flax 60% | 5.45 | 1 Flax 60% | 5.30 |
| 2 Hemp 60% | 5.38 | 2 Hemp 60% | 5.09 |
| 3 Kenaf 60% | 5.69 | 3 Curaua 60% | 5.96 |
| 4 Curaua 60% | 5.21 | 4 Flax 60% | 5.23 |
| 5 Flax 35% | 5.11 | 5 Flax 35% | 2.90 |

3.2. Fuel efficiency improvement
By comparing both top 5 NFPC candidates of Hood 1 and 2 and benchmarking it with the synthetic PP + E-glass (35% and 60%), the mass reduction was calculated, and consequently the fuel efficiency through the reduction was derived. The results showed that fuel efficiency can be achieved by utilizing the NFPC with kenaf fiber (60% loading), Curaua fiber (60% loading) and flax fiber (35% loading) in Hood 1, while Table 3 also shows that by using NFPC with flax fiber (60% loading) and hemp fiber (60% loading) with design Hood 2, poor fuel efficiency was resulted. NFPC with 60% flax fiber is common for both designs. However, the highest improvement of fuel efficiency was achieved in the case of PP with 35% flax loading at 0.4%.
Table 3. Fuel efficiency improvements due to mass reductions for two Hood designs.

| Fiber               | Hood 1 Mass | Hood 2 Mass | Mass reduction H1 | Mass reduction H2 | Fuel efficiency improvement |
|---------------------|-------------|-------------|-------------------|-------------------|-----------------------------|
| PP-Flax 60%         | 5.45        | 3.09        | 31.62%            | 31.64%            | 0.06%                       |
| PP-Hemp 60%         | 5.38        | 3.05        | 32.50%            | 32.52%            | 0.08%                       |
| PP-Kenaf 60%        | 5.69        | 3.23        | 28.61%            | 28.54%            | 0.24%                       |
| PP-Curaua 60%       | 5.21        | 2.96        | 34.63%            | 34.51%            | 0.34%                       |
| PP-Flax 35%         | 5.11        | 2.9         | 22.34%            | 22.25%            | 0.40%                       |
| PP-E-glass 60%      | 7.97        | 4.52        | -                 | -                 | -                           |
| PP-E-glass 35%      | 6.58        | 3.73        | -                 | -                 | -                           |

4. Conclusions

It can be concluded that fuel efficiency were achieved through mass reduction by utilizing NFPC, and statistically analyze the mechanical properties by adopting the AHP method of decision making. The results achieved by this simulation are consistent with the current findings, and show that the optimum candidate material is PP - flax at 35% fiber loading. The cost analysis shows many other fibers that come close to being optimal, which opens the path into more extensive research into other possible fibers in the chart with more criteria, focused on environmental factors and then can be compared to these findings.

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