Introduction

Material selection is one of the most important activities in the design process, and this has drawn the awareness of researchers for more than 20 years. An unsuitable selection of materials may result in the destruction or failure of an assembly and can substantially decrease its performance. It has been found that the cheapest price might not be the encouraging approach to achieve the optimum material, and this is why multi-criteria decision making (MCDM) methods have become popular in this field.

In this study, a method called Six-Sigma (6σ) had been chosen to select the best material for automotive crash box (ACB) fabrication. Currently, 6σ is practiced in production and product development, where organizations...
aim to enhance the process or product quality to be more productive and efficient.\textsuperscript{2} Higher sigma quality level specifies a process that is less likely to create defects. The $6\sigma$ method is described using a statistical thought,\textsuperscript{3} defined as having less than 3.4 defects per million opportunities or a 99.9997\% success rate. The $6\sigma$ method could benefit in improving customer satisfaction, reducing manufacturing cost, improving the product quality, increasing the processing speed, and reducing the invested capital.\textsuperscript{4,5} The $6\sigma$ method is defined as a structured and efficient system approach with an effective track record of refining the organizational performance and eliminating waste during the production process by using five basic phases which are define, measure, analyze, improve, and control (DMAIC).\textsuperscript{6} Several studies by engineering researchers have applied the DMAIC approach to improve manufacturing processes or to improve product quality. As examples, in 2004, Tong used the DMAIC approach for the improvement of printed circuit board quality;\textsuperscript{7} in 2008, Li used the DMAIC approach for the improvement of the capability of an SMT (surface-mount technology) solder printing process;\textsuperscript{8} in 2014, Sharma and Rao applied the DMAIC approach for the improvement of process capability in an engine crankshaft manufacturing process; and in 2009, Chen and Lyu used the Lean Six-Sigma approach for the improvement of touch panel quality.\textsuperscript{9} From the above review summary, it can be seen that the $6\sigma$ method is a very efficient and powerful method to enhance the continuous improvement methodology for eliminating defects in a product, process, or service. Composites offer many benefits to human being.\textsuperscript{10–19} Key among them are light weight, strength, corrosion resistance, durability, and design flexibility.\textsuperscript{20–34} However, until now, none of the researchers had carried
out materials selection of natural fibers for polymer composite ACBs using the $6\sigma$ method. Moreover, none of the researchers have used the $6\sigma$ method as a tool for material selection.\textsuperscript{35} Therefore, the author is motivated to apply the $6\sigma$ process improvement methodology (DMAIC) in material selection to enhance the capability of the $6\sigma$ method, and it could benefit industries and researchers. The DMAIC approach was an appropriate technique to carry out the decision making in material selection due to several reasons. Most importantly, the failure of engineers to perform an analysis to select appropriate materials before the manufacturing process could affect the profitability of businesses due to product failure or reduction in the quality of the product. The DMAIC approach in $6\sigma$ is a five-step systematic approach which allows engineers to effectively manage material selection before the process of manufacturing. The DMAIC approach considers the entire production process from the early stages, as opposed to only the end product, that is, it takes into account the process starting from the raw materials to the end product.\textsuperscript{36}

Description of the ACB

The crash box is a device assembled at the front end of a car side frame to absorb the kinetic energy during collisions. This device is expected to collapse with the crash energy absorbed to reduce the damage of the main cabin frame, as well as to save the occupants.\textsuperscript{37,38} Figure 1 shows the schematic diagram of a vehicle frontal structure crash management system which consists of a bumper cover at the outermost part assemble to the hood, a bumper energy absorber, a bumper rail, and a crash box connected to the longitudinal beams of the car.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.jpg}
\caption{The schematic diagram of a vehicle frontal structure.\textsuperscript{37}}
\end{figure}
Methodology of materials selection of natural fibers for the composite ACB

Figure 2 describes the $6\sigma$ process of materials selection general structure. The major tools of material selection are illustrated. In this method, the five major parameters are define, measure, analyze, improve, and control (DMAIC). The DMAIC approach was used as a platform for this current materials selection process. Each step came with a different tool to execute the process of selection. The process started with “define” to identify the problem and to determine the goal. In this stage, the mind mapping process was used to collect the information to develop a chart of essential elements regarding the selection of the material. The criteria and alternative of materials selection were then determined based on the important elements in the developed chart. In order to obtain accurate and precise results, the second step, called “measure,” used hierarchical frameworks as a tool to measure sigma performance level. In this stage, priorities criteria of material selection were set on each level of the hierarchy, based on the information obtained in the “define” stage. The third process is called “analyze.” In this stage, the properties table identified material characteristics needed to fabricate ACB as well as material properties of natural fibers which potentially could be used to reinforce polymer hybrid composite in the fabrication of ACB. The fourth stage is called “improve” where evaluation and the final solution had been completed by using the qualitative technique used to rank the multi-dimensional alternatives of an option set known as the Pugh method.39 Besides the qualitative technique, the Pugh method was chosen since it has the capability to provide a solution based on the best characteristics from several options. Therefore, it can meet the voice-of-the-customer needs for a material selection process.40 The final stage of this method, known as “control,” is to monitor and verify the accuracy of the results from the “improve” stage. Expert Choice 11.5 software was used to compute the data using pairwise comparison to execute the AHP method.41 In this phase, the AHP method had been chosen as a control tool for the results obtained in the “improve” phase due to its advantages in being able to determine the most suitable material for ACB based on the proposed material selection framework provides in the “measure” phase. Furthermore, AHP offers clear criteria and priority factors during the material selection process. In addition, the powerful AHP method could provide several sensitivity analysis scenarios to verify the final decision in the control phase.42

Step 1: define

Materials selection is one of the most important processes, which determines the quality of the design from both an engineering and an economical point of view. It is vital to know the factors affecting materials selection as shown in Figure 3 before commencing the materials selection process. Cost is a critical factor to consider when selecting

![Diagram](image-url)
materials for certain products due to economic constraints. Cost always fluctuates based on competition and availability of the material in the market. The high capability of biodegradability, recyclability, reuse capability, and the use of corrosion-free materials are other selection factors which were considered to ensure the longer life span of the product.

The crashworthiness department of the automotive industry is continuously attempting to reduce the product weight by selecting the lightest material to obtain high-performance ACBs. The most important criterion for crash box material is toughness, where higher toughness provides better energy absorption capability. Toughness properties require stability of strength and ductility. Materials with good toughness properties are required, where toughness is the energy of mechanical deformation per unit volume prior to fracture, and it can be defined as the ability to absorb kinetic energy up to the point of failure. In addition, there are several other requirements in materials selection to select the most appropriate natural fibers in ACB, as summarized in the product design specification (PDS) of Table 1. The material selection process analyzed important design parameters based on the PDS, which is a specification document on the product (ACB), prepared at the outset of the research. However, it has not been presented here for the sake of brevity. The material must demonstrate an improvement in density to acquire the lightweight part, that is, lower than 2.81 g/cm³ or below the total weight of 1.5 kg. The material must also have a high value of elongation at break to provide better toughness properties. In addition, the candidate material must be available (no shortage of resources), must have low moisture content to protect from the formation of cracks in the fiber, must have high tensile strength for durability, and must have a high percentage of hemicellulose to be able to produce an environmentally friendly product with high biodegradability.

Step 2: measure

In the “measure” stage, the hierarchical framework was divided into five levels as depicted in Figure 4; the rank criteria in this hierarchy framework was extracted from Figure 3 and Table 1 where the top level of hierarchy specified the overall goals, which was to select the best natural fiber.

Table 1. Summary of the product design specification for the selection of natural fibers.

| Requirement                  | Specification |
|------------------------------|---------------|
| Density                      | Density < 2.81 g/cm³ |
| Elongation at break (toughness): | high |
| Availability                 | high |
| Moisture content             | low |
| Tensile strength (durability): | high |
| % hemicellulose (biodegradation): | high |

Figure 4. The hierarchy framework for the selection of the materials of natural fibers for ACB.
fiber material for ACB. The second level specified the main criteria or factors influencing the goal defined, such as the high performance of the material, lightweight material, and material with high sustainability to protect health as well as being environmentally friendly, where the detailed definition for each criterion has been provided in Table 2. The third hierarchy level was sub-criteria 1, where this level narrowed down the specific criteria to achieve the goal. The fourth hierarchy level was the sub-criteria 2, which listed all natural fibers constraints based on the sub-criteria 1 and these needed to be prioritized. The fifth level was a set of alternatives which recognized possible solutions that were used to select the most appropriate natural fiber in order to achieve the desired goal.

Table 2. Summary of level 2 of criteria in hierarchy framework.41,46.

| Criteria                  | Definition                                                                                                                                                                                                 |
|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Performance of ACB        | The best performance of ACB refers to the ability of ACB to absorb maximum kinetic energy during a collision. Able to perform axial collapse prior to other parts collapsing during impact to absorb energy. The energy of a material absorbed before fracture known as toughness. Corrosion resistance and can perform well in any condition (durability). In addition, the higher the performance of the material, the higher the safety that the ACB structure could offer to protect the main cabin frame, as well as to keep the occupants safe. |
| Weight factor             | Choosing weight criteria in the design of ACB refers to the material density and the dimensions of the product. Dimensions and density are both factors directly related to how the design product can be a lightweight component while still maintaining the required performance. |
| Environment               | The scope of material criteria in this study must have good biodegradable capability, the component must be safe to use, and low emissions both during safe preparation and when in use. |

Table 3. Description of material properties represents the lowest level of hierarchy framework on best natural fiber material selection for ACB.46–48.

| No. | Material properties | Description                                                                                                                                  |
|-----|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Density             | To identify lighter natural fibers                                                                                                          |
| 2   | Elongation at break | To determine the capability of natural plant fiber to resist changes of shape without crack formation                                      |
| 3   | Tensile strength    | To determine the durability and strength of materials                                                                                       |
| 4   | Hemicellulose content | To predict biodegradation and moisture absorption                                                                                           |
| 5   | Microfibril angle   | To evaluate the modulus and durability of fibers                                                                                             |
| 6   | Young’s modulus     | To measure elastic constant to resist deformation when stress is applied                                                                     |

Step 3: analysis

The “analyze” phase identifies the capability of natural fibers material properties candidates as shown in Table 4 before conducting the process of material selection. This phase helps to spot the advantages and disadvantages of certain materials properties, as well as the problems, which could occur during the production process. Nine natural fiber materials and steel were selected as candidates for their material properties to be analyzed such as density, Young’s modulus, tensile strength, and specific energy absorption (SEA).

Step 4: improve

The “improve” stage evaluated nine natural fibers materials with aluminum as a datum. Aluminum, which is one of the existing materials currently used for ACB fabrication, was selected as a datum due to the high SEA capability, where it has 23.04 kJ/kg compared to steel, which is another common material used to fabricate ACB, which only has 15.77 kJ/kg of SEA capability.53 Final results in Table 5 by using the Pugh method qualitative technique show that oil palm should be chosen as the best material to fabricate ACB. Oil palm obtained the highest total number of 8+ when compared to other natural fiber materials such as hemp and flex, which took the second place jointly with 7+. The Pugh method depends on a series of pairwise similarities between material candidates against a reference of common ACB materials. As mentioned earlier in step 2, six material properties with additional two relevant selection criteria of low cost and availability had been listed in Table 5 to compare with datum material properties.
### Table 4. Properties of natural fibers material properties.49–54

| Properties                  | Unit | Sugar Palm | Kenaf | Oil Palm | Sisal | Jute | Hemp | Flax | Pineapple | Coir | Aluminum |
|-----------------------------|------|------------|-------|----------|-------|------|------|------|-----------|------|----------|
| Density                     | g/cm³| 1.22–1.26  | 1.2–1.4| 0.7–1.55 | 1.5   | 1.3  | 1.48 | 1.5  | 0.8–1.6   | 1.2  | 2.7      |
| Young’s modulus             | GPa  | 5.90       | 53.00 | 3.20     | 9.4–22 | 26.5 | 70   | 27.6 | 1.44      | 4–6  | 5        |
| Elongation at break         | %    | 22.30      | 1.60  | 25.00    | 2.0–2.5| 1.5–1.8| 1.6  | 2.7–3.2 | 14.5     | 30   | nil      |
| Tensile strength            | MPa  | 276.60     | 930.00| 248.00   | 511–635| 393–773| 690  | 345–1035| 400–627   | 175  | 700      |
| Hemicellulose               | %    | 13.30      | 20.30 | 14.94    | 12    | 14–20| 15   | 18.6–20.6| 9.45–18.8| 0.15–0.25| nil     |
| Microfibril angle           | n/a  | 1.00       | 2.00  | 8.00     | 7     | 4.00 | 3    | 5    | 6         | 9    | nil      |
| Specific energy absorption  | (SEA)| kJ/kg      |       |          |       |      |      |      |           |      | 23.04    |

### Table 5. Final material selection.

| Properties                                      | Al  | Sugar palm | Kenaf | Oil palm | Sisal | Jute | Hemp | Flax | Pineapple | Coir |
|------------------------------------------------|-----|------------|-------|----------|-------|------|------|------|-----------|------|
| Density                                        | Datum | +         | +     | ++       | +     | +    | +    | +    | +         | ++   |
| Young’s modulus                                | s    | +         | -     | -        | +     | +    | ++   | +    | -         | s    |
| Tensile strength                               | -    | +         | -     | -        | -     | -    | -    | -    | -         | -    |
| High availability                              | +    | +         | ++    | +        | +     | +    | +    | +    | +         | +    |
| Low cost                                       | +    | +         | ++    | +        | +     | +    | +    | +    | +         | +    |
| Hemicellulose (To predict biodegradation and moisture absorption) | -    | -         | -     | -        | -     | -    | -    | -    | -         | -    |
| Microfibril angle (To evaluate the modulus and durability of fibers) | -    | -         | -     | -        | -     | -    | -    | -    | -         | -    |
| High biodegradability                          | +    | +         | ++    | +        | +     | ++   | +    | +    | ++        | +    |
| Total (+)                                      | 5    | 6         | 8     | 5        | 6     | 7    | 7    | 5    | 5         | 5    |

(++) = much better than datum; (+) = better than datum; (s) = similar with datum, (-) = worse than datum. Al = aluminum.

Note: Final results are obtained by using the Pugh Method qualitative technique which shows that oil palm should be chosen as the best material to fabricate ACB. Oil palm obtained the highest total number (8 +), it also indicated oil palm is the most preferred material when compared to other natural fiber materials such as hemp and flex, which took the second place jointly with (7 +).
Step 5: control

Based on the result in the “improve” phase, oil palm fiber was suggested as the most suitable candidate material for ACB. The advantage of the Pugh method technique over other decision-making tools is its ability to handle many decision criteria. However, the quality of the decision using the Pugh method is basically associated with the “quality” of the selection criteria. This quality has three aspects: first, incorrect selection criteria could lead to the wrong decision. Naturally, incorrect criteria could happen from using opinions when identifying the criteria. Second, incomplete selection criteria is where the set of selection criteria is not complete. Third, inadequate selection criteria is where criteria that can have multiple interpretations are poorly defined. Therefore, the analytical hierarchy process (AHP) was used in this control phase to monitor and verify the result’s accuracy from the “improve” phase.

In this control stage, the data extracted from the measurement and analysis process had been simulated to verify the results obtained from the “improve” phase to select the most appropriate natural fiber material for the ACB. After the judgment on the pairwise comparison, all priority weightage values were presented in Figure 5, known as the hierarchy framework for natural fiber properties. Meanwhile, Figure 6 presents the priority vectors and the inconsistency ratio. Based on the graph presented in Figure 6, oil palm fiber is consistently suggested as the most suitable candidate material for ACB, with similar results obtained earlier in the “improve” phase. Oil palm fiber scored the highest priority value of 0.129% or 12.9%, followed by sugar palm (0.121), flax fiber (0.119), and then followed by other types of natural fibers. The overall inconsistency ratio value equaled to 0.00, which was less than 0.1, proving that the judgment made throughout the analysis was very consistent and the proposed analysis results were acceptable.

The process verified the results obtained from the “improve” phase beginning with the development of a pairwise comparison matrix, where the software Expert Choice 11.5 at this stage was used to judge a pairwise comparison. The software uses relative scale pairwise comparison or numerical comparison as a selection principle to perform the judgment. The value of scale intensity explains that the performance criteria were graded with an extremely strongly preferred scale intensity, followed by

Figure 5. Hierarchy framework for natural fiber properties.
quality and weight. The detailed scale intensity values are shown in Table 6.

From the numerical assessment shown in Figure 7, the performance criteria was represented by the value of 1.286 or 9/7. This value defined that the performance was strongly preferred to the weight and environmental criteria. Meanwhile, the weight and environmental criteria were equally preferred, represented by the value of 1 or 7/7 when compared to each other. The example of assigned values shown in Figure 8 was based on the comparison ratio values for sugar palm and kenaf with respect to elongation at the break. The value with red color addresses the reciprocals ratio acquired from the inverse comparison, while Table 4 shows the assigned value for the natural fiber comparison with respect to sub-criteria 2. Each natural fiber came with a range value such as jute (1.5%–1.8%), where the mean value of 1.65 was considered in the calculation (22.3 / 1.65 = 13.515).

Results

“Improve” was the fourth step in the selection of the materials of the 6σ method. In this process, the Pugh method was used to evaluate the most appropriate material selection process by reviewing the pairwise candidates based on qualitative measurements. The certain drawback from the Pugh method is that it needs additional measurements to ensure the collected results are precise and accurate. Therefore, the AHP method was performed to evaluate and verify the most appropriate material selection result. However, priority vectors of the AHP method bounded to the main criteria highly influenced the priority of the natural fiber showing that the final ranking in the material hierarchy selection can be changed by a small amendment in the factor weights. Thus, the stability of the results collected in the control process by varying the criteria weights has to be tested due to the highly subjective judgment of the priority vector. The testing process could use a certain scenario by increasing or decreasing the criteria weight. The changes in priorities and the different rankings of the alternatives can be monitored due to the adjustment of the weight for individual criteria. Hence, the stability information of the ranking in the selection of the most suitable material for ACB can be presented using sensitivity analysis. Therefore, three scenarios had been selected to vary the priority vector of sensitivity analysis, via Expert Choice v.11.5 software. Every single main criterion priority vector was increased by 20%, and the final weightages in the overall rank of the natural fibers are shown graphically in Figures 9–11. The increasing percentage of priority vector performance changes from 20% to 39.1% to 59.1% as presented in Figure 9, where oil palm fiber was still the most suitable natural fiber for ACB with the highest percentage value in the ranking of the alternatives. This value provided a consistent result with the decision ranking collected earlier.

However, flax fiber was also recommended as the most suitable material for ACB for the scenario where the weight criteria priority vector value was increased by 20%, followed by oil palm fiber and others as shown in Figure 10. Similarly, for the scenario where the environment criteria priority vector value was increased by 20% as shown

Table 6. The principal scale of judgment comparison.48,55

| AHP intensity scale | Description of scale intensity |
|--------------------|---------------------------------|
| 1                  | Equally preferred               |
| 2                  | Equally to moderately preferred |
| 3                  | Moderately preferred            |
| 4                  | Moderately to strongly preferred|
| 5                  | Strongly preferred              |
| 6                  | Moderately to very strongly preferred |
| 7                  | Very strongly preferred         |
| 8                  | Moderately to extremely strongly preferred |
| 9                  | Extremely strongly preferred    |

Figure 6. Results of the selection judgment.
in Figure 11, flax fiber was determined to be the most appropriate fiber for ACB, followed by kenaf fiber and oil palm fiber.

**Discussion**

A sensitivity analysis was conducted to study the consequences of the different factors on determining the best option. The final priorities of the material selection were highly dependent on the priority vectors attached to the main criteria. If the results from the “improve” and “control” stages were inconsistent, researchers would have to review the parameters and variables given for both stages. However, in this study, both phases of “improve” and “control” using two different methods consistently showed that oil palm was the best natural fiber material for selection to reinforce the polymer composite for ACB fabrication. The selection of oil palm as the most appropriate natural fiber is supported by several research studies. Yap et al.\(^5\) reported that the experimental results of composite reinforcement by oil palm natural fiber showed the highest improvement in toughness (energy absorption during collision) index and residual strength factor. In addition, Shinoj et al.\(^6\) had concluded that oil palm fiber reinforced with some polymeric matrices improved the strength and toughness properties whereas the strength of composite was lower in some cases. Ahmad\(^6\) did a comparison study and said that oil palm natural fiber was found to be appropriate as reinforcement because it possesses a high tensile strength of 300–600 N/mm\(^2\), which is considered high when compared with other natural fibers. The results met the study expectations where the natural fibers selected must be a balance where both ecological and economical needs can be satisfied. The selected fibers must be required to offer advantages such as high energy absorption, low cost, high availability specifically in a country such as
Malaysia, low density, high toughness, acceptable specific strength, and biodegradability.

**Conclusion**

The process of selection for the best natural fiber material through the $6\sigma$ method had proposed oil palm fiber as a particularly suitable reinforcement in composite ACB, where the decision made was based on the following three main criteria: the highest performance natural fiber, the most lightweight natural fiber, and the most environmentally friendly natural fiber. The $6\sigma$ technique provided another alternative for researchers or design engineers conducting material selection. The advantage of the $6\sigma$ material selection is that the double decision-making techniques must deliver consistent results in order to

**Figure 9.** Sensitivity graph of the main criteria with respect to goal when priority vector of performance was increased by 20% (from 39.1% to 59.1%).

**Figure 10.** Sensitivity graph of main criteria with respect to goal when priority vector of weight was increased by 20% (from 30.4% to 50.4%).
recommend oil palm natural fiber as the most appropriate material selection. Moreover, the integration of qualitative techniques in the Pugh method and statistical analysis of the pairwise comparison matrix AHP provided more realistic data during the comparison process to select the most appropriate material. The selection process, which could be viewed from the two perspectives of qualitative and quantitative, was based on a set of predefined criteria and constraints related to specifications of the desired component. For this reason, the voice of customers and the evaluation data were interpreted from a qualitative customer statement to quantitative data from pairwise evaluation results which could be acted upon.

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