

# Conceptual Design of Natural Fiber Composites as a Side-Door Impact Beam Using Hybrid Approach

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**Abstract:** This paper presents the conceptual design stage in the product development process of a natural fiber composites of the side-door impact beam, which starts from idea generation to the selection of the best design concept. This paper also demonstrates the use of the integrated Theory of Inventive Problem Solving (Function-Oriented Search) (TRIZ (FOS)) and Biomimetics method, as well as the ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method. The aim of this study was to generate design concepts that were inspired by nature and to select the best design concept for the composite side-door impact beam. Subsequently, eight design concepts were generated using the TRIZ (FOS)-Biomimetics method and finite element analysis were used to analyse their performance and weight criteria using ANSYS software. VIKOR method was used as the multiple criteria decision making tools to compare their performances, weight and cost criteria. As a result, design concepts B-03 and C-02 were ranked as the first and second best, with VIKOR value of 0.0156 and 0.1178, respectively, which satisfied the conditions in VIKOR method. This paper shows that the integrated method of TRIZ (FOS)-Biomimetics and VIKOR can assist researchers and engineers in developing designs that are inspired by nature, as well as in selecting the best design concept using a systematic strategy and justified solutions during the conceptual design stage.

**Keywords:** Theory of inventive problem solving; TRIZ (FOS); biomimetics; ViseKriterijumska Optimizacija I Kompromisno Resenje; VIKOR; side-door impact beam

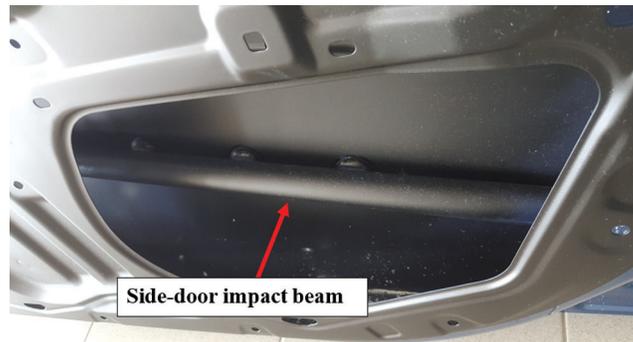
## 1 Introduction

Side-door impact beam was introduced by General Motors in late 1960's to prevent passenger compartment from door intrusion when the vehicles involve in collision [1]. This was then followed by National Highway Traffic Safety Administration (NHTSA) to set up the side impact collision standard for



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advance test dummies under the Federal Motor Vehicle Safety Standards 214 (FMVSS 214) [2]. Side-door impact beam improve the strength, stiffness and energy absorption of the vehicle's door during side collision. Shaharuzaman et al. [3] studies the cross section of the side-door impact beam through published journals and find that circular cross section was the dominant type of side-door impact beam with different design type such as usage of rib in the beam. Fig. 1 shows the side-door impact beam of a vehicle.



**Figure 1:** Side-door impact beam

Over the years, engineers and researchers have become increasingly more interested in sustainable designs and environmentally friendly products. In Europe, car manufacturers have improved the CO<sub>2</sub> discharge due to regulations that limit emission from vehicles. According to Regulation (EC) No 443/2009 [4] the targeted emission average is 95 g CO<sub>2</sub>/km by 2020 and the Regulation (EU) No 333/2014 [5] was introduced to ensure the targets are realized. Research by the Ministry of Transportation, Japan, showed that the emission of CO<sub>2</sub> can be reduced by 20 g/km by decreasing vehicle weight by 100 kg [6] and this can be achieved by replacing the metal base part to polymer composites as it is more lightweight.

The main objective of using polymer composites material is to reduce vehicle weight, which results in lower emission levels. With increasing awareness among manufacturers and consumers, coupled with rules and regulations on reducing emissions, improving fuel efficiency, the end of life vehicles (ELV) process, and biodegradability, manufacturers have slowly migrated from using synthetic fiber composites to natural fiber composites (NFCs) [7]. There are many reports on natural fiber composites being used to replace synthetic fibers due to their low cost, low density, and high specific properties [8,9].

Currently, natural fiber composites (NFC) are the subject of immense interest to researchers for its use in the automotive industry, due to attributes such as low cost, lightweightness, being environmentally friendly, their excellent specific strength and stiffness, recyclability, and their image as a natural product [9]. NFC has been used as interior and exterior components to reduce the usage of expensive carbon, aramid, and glass fibers. For example, DaimlerChrysler (biggest carmaker) has developed up to 50 car parts using bio-based materials [10,11]. They reported that the most suitable reinforcement type of NFC for structural application include flax, kenaf, and hemp, due to their higher strengths [10]. The selection of the reinforcement is not dependent only on their strength, but it is considered as one of the top criteria. The reasons why automotive industries are taking a big step on using natural fiber composites is because their lightweight properties can improve vehicle fuel consumption and are environmentally friendly for recycling and safe disposal [12]. In the context of having plenty of natural fibers available sporting different mechanical and material properties, the selection of the material needs to be analyzed prior to product design and development. The flexibility afforded by changing materials at this stage is evident, as it would be more difficult to swap materials at later stages [13].

In concurrent engineering, the composite product development process needs to be studied in the early stage such as materials selection, design concept selection, manufacturing process selection, and life cycles analysis where it is considered as conceptual design stage of the product [14]. Conceptual design is an important stage in the product development process, where decisions are made to determine the later stages in the development process [15,16]. For the side-door impact beam, the composite materials of the product have been chosen using *ViseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR) method where the results show that kenaf/polypropylene composites as the highest rank to be the natural fiber side-door impact beam [17,18].

Conceptual design consists of pre-concept generation, concept design generation, and concept design evaluation [19]. In this stage, idea generation techniques are utilised by designers and engineers to come up with the design idea that can be used in the later stage. Various tools are available to generate ideas, such as brainstorming, biomimetic/biomimicry, blue ocean strategies, and the theory of inventive problem solving (TRIZ) [19]. In the early 2000, researchers have begun to use TRIZ tools that were integrated with other methods, such as the Quality Function Deployment (QFD) [20,21], the Theory of Constraints (TOC) [22], and the Axiomatic Design (AD) [23] to generate design ideas [24].

TRIZ is the acronym of a Russian method, *Teoriya Resheniya Izobretatelskikh Zadach*, developed by Genrich Asthuller, a scientist and engineer, who has studied more than 400,000 patents from which TRIZ was born [25]. TRIZ helps scientists, engineers, and various industries to solve problems using their initial problem description, problem identification, problem-solving techniques, and specific solutions [26,27]. In the conceptual design phase, TRIZ can be used as a standalone, or integrated with other methods to generate design ideas for solving scientific, engineering, and technological problems. Mansor et al. [28] improved the design of a water dispenser tap, while Mawale et al. [29] designed the new alarm device for medical infusion bags using TRIZ method. Integrating TRIZ with Analytic Network Process (ANP) in conceptual design has also been widely used. For example, Hambali et al. [30] determined the best design concept for the wheelchair, while Noor Azammi et al. [31] used the same method to select the best conceptual design for automobile engine rubber mounting.

In recent years, the integration of TRIZ with biomimetics has raised the interest of researchers for solving engineering problems. Scientists believe that the integration of nature into engineering technology will provide eco-friendly results during the product development process. Vincent suggested that TRIZ could be the best method to develop better relationships between nature and technology [32]. Lim et al. [33] created the biomimicry contradiction matrix of TRIZ using text-mining and latent dirichlet allocation (LDA) for usage of biomimicry functions and TRIZ principles. In another work, Abdala et al. [34] compared the usage of TRIZ and BioTRIZ inventive principles and showed that the latter was able to effectively stimulate creativity in problem solving. Liu et al. [35] developed new inventive principles that were integrated into biomimetics based on biological functions, while Chen et al. [36] developed an eco-innovative TRIZ and biomimetics for product service system (PSS) using the same TRIZ inventive principles.

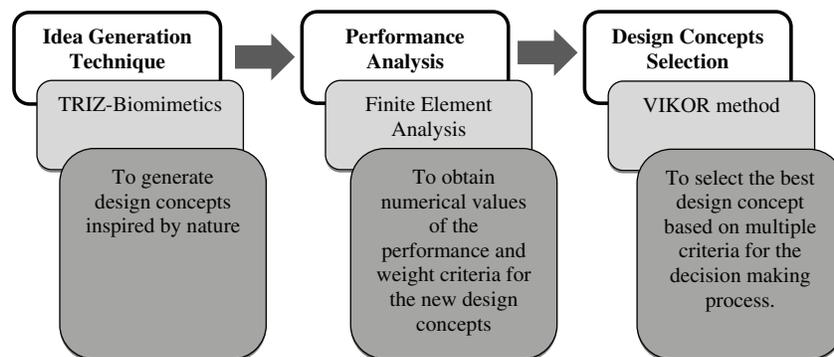
This paper discusses the conceptual design process of developing natural fibre composite as a side-door impact beam using the integrated method of TRIZ and biomimetics. Then, the best design concept was selected using *ViseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR), which is a multi-criteria decision making (MCDM) method. This paper will describe the three phases used in this study, namely, the idea generation phase using the TRIZ-biomimetics method, the finite element analysis (FEA) phase consisting of the drop impact test for the side-door impact beam using ANSYS software, and the design concept selection phase using VIKOR. In the first phase, the TRIZ Function-Oriented Search (TRIZ-FOS) method that reflects biomimetic design ideas was used. Biomimicry Taxonomy was the function search used to develop the design concepts based on biological strategies and ideas inspired by

nature. In the second phase, the FEA of the impact test on the composites was conducted. The performances and weight data of the impact beam were collected to use in the third phase. Finally, VIKOR method was used to select the best design concept from the concepts generated in the first phase.

## 2 Research Methodology

### 2.1 Research Framework

The proposed framework for this research is shown in Fig. 2. The conceptual design stage for the side-door impact beam started with idea generation using the TRIZ-Biomimetics method. Then, the finite element analysis (FEA) of the performances (impact test) and the weight criteria of the generated design concepts were analysed using ANSYS software. The collected data were used for selecting the best design concept for the composite side-door impact beam using VIKOR method. The framework proposed in this paper was able to narrow down the gap between nature and engineering to produce eco-friendly results for the initial engineering problems.



**Figure 2:** Research framework based on the TRIZ-Biomimetics and VIKOR methods

TRIZ tools are widely used for inventive problem solving solutions for science and engineering problems. The structured TRIZ tools have helped researchers and engineers to generate ideas and develop solutions for the initial problems. TRIZ (FOS) was proposed in this paper to find a solution to the initial problem, which consisted of four steps: (1) identifying the target problem, (2) generalising the problem, (3) finding existing solutions, and (4) applying existing solutions [37]. TRIZ (FOS) tools would find an existing technology to solve the initial problem, known as technology transfer [38]. To get some ideas for identifying and generalising the problem, the keywords for the initial problem can be referred to in Biomimicry Taxonomy [39]. In this paper, the existing technology refers to biomimetics, where information for biological strategies can be gathered from the AskNature.org website [40]. These biological strategies can be implemented to generate ideas for solving the initial problem.

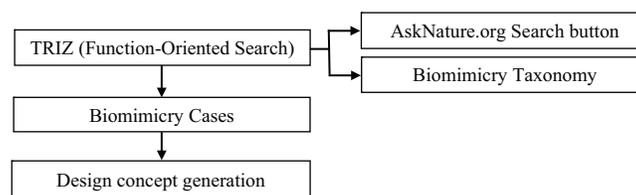
Ideas that were generated using the TRIZ (FOS)-Biomimetics method were then analysed through the finite element analysis (FEA) using ANSYS software to determine the performance and weight data of the generated designs. The FEA of the composite side-door impact beam simulated the impact analysis from the experimental setup by Cheon et al. [41]. Data from the FEA were recorded to compare the design concepts. The performances of the design concepts were predicted and estimated to obtain the concrete values of each sub-criterion using the MCDM method, namely, VIKOR. The performance data included the maximum stress, maximum deformation, and impact energy absorption, while the weight data included the volume and mass of the composite side-door impact beam. Finally, the collected data were compared using VIKOR, with six sub-criteria and eight design concepts as alternatives. The details of each step are explained in the next section.

## 2.2 Idea Generation Using TRIZ (FOS)-Biomimetics

The TRIZ Function-Oriented Search (TRIZ (FOS)) is one of the tools in the TRIZ method that can find existing technologies to be transferred to the initial problem as a solution [38]. In other words, TRIZ (FOS) would borrow ideas from existing functions and implement them in the initial problem. This method can generate ideas where there are successful solutions deployed elsewhere. Montecchi et al. [42] called it as the technology transfer from any domain based on analogical thinking to the same application context. This method can reduce the duration of the conceptual design stage by identifying engineering problems and searching for the technology that has been solved in a different domain, which is nature in the context of this study.

Technology development that adapts from nature to solve engineering problems is called biomimicry or biomimetics [32]. Scientists and researchers believe that nature has the solutions to the problems faced by human, which have become guidelines for solving engineering problems. Some examples of successful biomimetic products include the Shinkansen bullet train that mimics the Kingfisher's beak for the nose cone by Eiji Nakatsu [43], the Fastskin swimsuit based on shark scales that was developed by Speedo, and the Velcro zip for minimal force of zipping and unzipping by Mestral [44]. Successful technology transfer from nature into engineering shows that integrated methods in idea generation techniques can be developed to solve engineering problems.

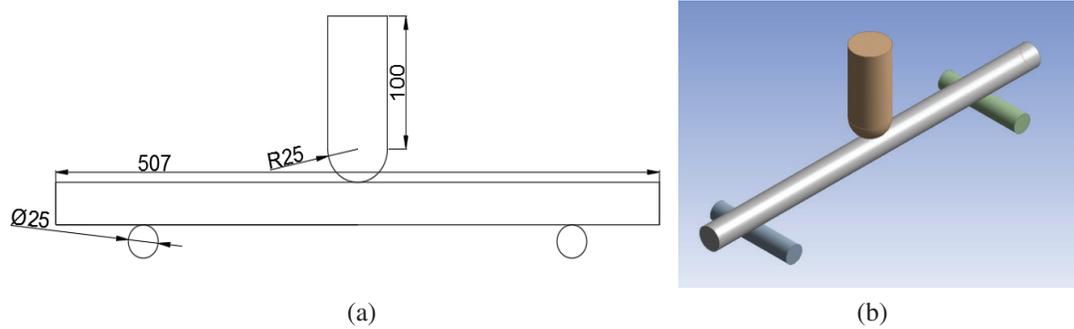
The integrated TRIZ (FOS)-Biomimetics method can help designers and engineers to develop nature-engineering frameworks that could systematically solve problems. This method was proposed in this study to generate ideas in the conceptual design stage for the product development process of the automotive side-door impact beam. This method was used to develop new designs of a cylindrical beam that can reduce fracture and intrusion to the passenger side in a vehicle. The framework of this method is shown in Fig. 3, where the keywords of the FOS were needed to identify the biomimicry cases. The keywords can be typed into the search button of the asknature.org website or using the function keywords of the Biomimicry Taxonomy developed by Biomimicry Institute [40]. A total of 160 function keywords are available to identify the engineering problems that need to be solved. From the biomimicry cases, users need to read, understand, and filter the cases listed in the website to solve the current engineering problem and generate relevant concepts of nature to be turned into engineering technology.



**Figure 3:** Framework of TRIZ (FOS)-Biomimetic method

## 2.3 Impact Test

This is the second phase of the conceptual design framework of this study. The performances of the design concepts generated from the first phase were analysed, which included the stress, stiffness, and impact energy absorption using ANSYS software. The 2D drawing of the experimental setup for the impact test is shown in Fig. 4(a), and the measurement unit is in mm [41]. Fig. 4(b) shows how the stainless steel impactor (nose of 25 mm in diameter and 125 mm in height), is impacting the 507 mm side-door impact beam. The beam is supported by two stainless steels of 25 mm in diameter, with a span of 360 mm. The performance data of the impact analysis for different design concepts were recorded and used during the design concept selection phase. This step is important to obtain the numerical values for the performance analysis and weight calculation for the comparison data required by the MCDM approach.



**Figure 4:** (a) 2D drawing of the experimental setup (in mm), (b) 3D drawing of the impact test setup

#### 2.4 Design Concept Selection Using VIKOR Method

The final phase for the conceptual design of the side-door impact beam was to select the best design concept using VIKOR. VIKOR method is one of the MCDM methods used to compare, analyse, and rank multiple alternatives with multiple criteria using numerical method. VIKOR analyses and ranks the multiple criteria based on established criteria, which compromises the closest to the ideal solutions [45]. VIKOR was developed by Opricovic et al. [46] from the  $L_p$ -metric used in compromised programming method. Eq. (1) shows the  $L_p$ -metric that was used to calculate the compromised criteria in VIKOR for the following Eqs. (4) and (5):

$$L_{pi} = \left\{ \sum_{j=1}^n \left[ w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right]^p \right\}^{1/p}, \quad 1 \leq p \leq +\infty; i = 1, 2, \dots, I \quad (1)$$

where  $L_{pi}$  is the  $L_p$ -metric used to formulate ranking measures for alternatives of  $i$ ,  $w_j$  is the weight of importance for the  $j$ th criterion,  $f_j^*$  is the best value, and  $f_j^-$  is the worst value for all criterion functions.

**Step 1:** The normalised values for the matrix of the  $i$  alternatives and  $j$  criteria were calculated for the design concepts and criteria, respectively. Eq. (2) shows the normalised matrix values:

$$D = \begin{matrix} & C_1 & C_2 & \dots & C_j \\ A_1 & x_{11} & x_{12} & \dots & x_{1j} \\ A_2 & x_{21} & x_{22} & \dots & x_{2j} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_i & x_{i1} & x_{i2} & \dots & x_{ij} \end{matrix} \quad (2)$$

where matrix  $D$  shows alternatives of  $A_1, A_2, \dots, A_i$  and criteria of  $C_1, C_2, \dots, C_j$ .

The following Eq. (3) was used for the normalised calculation:

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^n x_{ij}^2}} \quad (3)$$

where  $x_{ij}$  denotes the value of the  $i$ th alternative and the  $j$ th criterion.

**Step 2:** The best  $f_j^*$  and worst  $f_j^-$  values of all criterion functions were determined during this step. Next, two different types of criteria were determined whether as a benefit criterion or as a cost criterion. If the criterion needs to be at maximum, then it is considered as a benefit criterion and vice versa.  $f_j^* = \max f_{ij}$  and  $f_j^- = \min f_{ij}$  were used to determine the benefit criterion, while,  $f_j^* = \min f_{ij}$  and  $f_j^- = \max f_{ij}$  were used

for the cost criterion. The  $f_j^*$  is the positive and  $f_j^-$  is the negative ideal solution for the  $j$ th criterion in this step. A positive ideal solution is the best alternative, while a negative ideal solution consists of the worst alternatives, with respect to each evaluation criterion.

**Step 3:** The distance between the alternative to the ideal solution was computed and summed to obtain the final value using Eqs. (4) and (5):

$$S_i = \sum_{j=1}^n w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \quad (4)$$

$$R_i = \max w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \quad (5)$$

where  $S_i$  is the weighted summation of the distance to the best evaluation value for the  $i$ th alternative, with respect to all criteria.  $R_i$  is the maximum weighted distance to the best evaluation value for the  $i$ th alternative, with respect to the  $j$ th criterion. The best ranking for a positive ideal solution is based on  $S_i$  values, while the worst ranking for a negative ideal solution is based on  $R_i$  values. In other words,  $S_i$  and  $R_i$  are indicative of the  $L_{1i}$  and  $L_{\infty i}$  values, respectively, from the  $L_p$ -metric in Eq. (1).

**Step 4:** The VIKOR values,  $Q_i$  for  $i = 1, 2, \dots, m$  were calculated using Eq. (6):

$$Q_i = v \left[ \frac{S_i - S^+}{S^- - S^+} \right] + (1 - v) \left[ \frac{R_i - R^+}{R^- - R^+} \right] \quad (6)$$

where  $S^-$  refers to  $\max S_i$ ,  $S^+$  refers to  $\min S_i$ ,  $R^-$  refers to  $\max R_i$ ,  $R^+$  refers to  $\min R_i$ , and  $v$  is the weight of the strategy of the majority criteria or the maximum group utility.

**Step 5:** The alternatives were ranked using the values of  $S_i$ ,  $R_i$ , and  $Q_i$  in descending order. Based on the  $Q_i$  values calculated in Step 4, the alternatives were ranked to make a decision. The compromised solution was then proposed by the  $Q$  value, with minimum remarks as an alternative  $A^{(1)}$ , as the best ranked if the following two conditions were satisfied:

Condition 1: Acceptable advantage.  $Q(A^{(2)}) - Q(A^{(1)}) \geq DQ$ , where  $DQ = 1/(J - 1)$ , where  $J$  is the number of alternatives and  $A^{(2)}$  is the alternative with the second position on the ranking list by  $Q$ .

Condition 2: Acceptable stability in decision-making. The alternative  $A^{(1)}$  must also be the best ranked by  $S$  or/and  $R$ . This compromised solution is stable within a decision-making process, where the value of  $v$  lies in the range of 0–1. The strategy of voting could be by consensus when  $v \approx 0.5$ , by majority rule when  $v > 0.5$ , or with a veto when  $v < 0.5$ . In this paper, these strategies were compromised by  $v = 0.5$ .

If one of the previous conditions is not satisfied, then a set of compromised solutions is proposed, which consists of:

Condition 3: Alternatives  $A^{(1)}$  and  $A^{(2)}$ , only if Condition 2 is not satisfied; or

Condition 4: Alternatives  $A^{(1)}, A^{(2)}, \dots, A^{(M)}$  if Condition 1 is not satisfied.  $A^{(M)}$  is determined from  $Q(A^{(M)}) - Q(A^{(1)}) < DQ$  for maximum  $m$ , which means that the positions of these alternatives are close to the ideal solution.

In the VIKOR method, the conditions that must be satisfied by the alternatives using the VIKOR values of  $Q$  and  $DQ$  are known as the self-validation technique. The values and rankings of the alternatives must be satisfied by acceptable advantage and acceptable stability. However, if these conditions are not satisfied, the ranking and best selection must follow Condition 3 or Condition 4 to confirm that it is the best alternative ranked by VIKOR.

### 3 Results and Discussion

Based on the TRIZ (FOS)-Biomimetics framework shown in Fig. 3, the asknature.org search button or the Biomimicry Taxonomy table can be used to search for biomimicry cases. Tab. 1 shows the results of the biological strategies and inspired ideas from the TRIZ (FOS)-Biomimetic method using the Biomimicry Taxonomy table. The Biomimicry Taxonomy table features eight groups, 30 sub-groups, and 160 functions for a design idea adapted from nature. In this study, two groups were chosen, with three sub-groups and four functions, as listed in Tab. 1. The results show that under the “Get, Store, or Distribute resources” group, sub-group of “Capture, Absorb, or Filter” and function of energy, 48 biological strategies and one inspired idea are available in the database. The total numbers of biological strategies and inspired ideas for the four functions were 217 and 12, respectively. Nonetheless, there will be similar biological strategies and inspired ideas between these functions. Researchers need to read and understand all of the biological strategies and inspired ideas to relate with the current engineering problems to adapt nature as the solution to generate conceptual designs, which in this case, the new side-door impact beam.

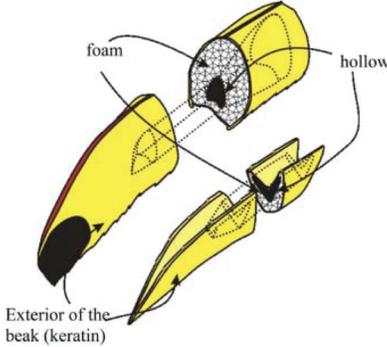
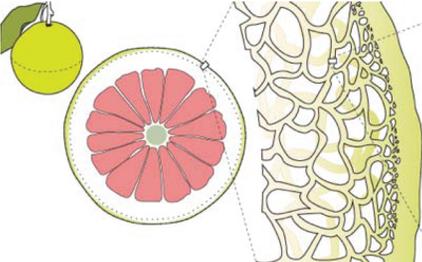
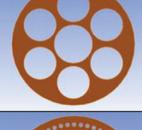
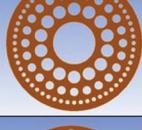
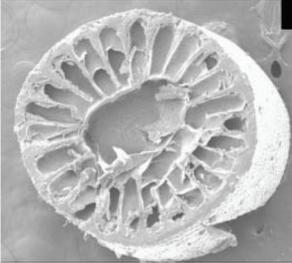
**Table 1:** Numbers of biomimicry cases searched by function using Biomimicry Taxonomy

Group	Get, store, or distribute resources	Protect from physical harm		
Sub-group	Capture, absorb or filter	Manage structural forces	Prevent structural failure	
Function	Energy	Compression	Impact	Fracture/ Rupture
Biological strategies	48	65	57	47
Inspired ideas	1	3	4	4

The biological strategies and inspired ideas from asknature were used to design the concept of the new automotive side-door impact beam, as shown in Tab. 2. The conceptual design ideas were generated from a toucan beak, pomelo peel, and hedgehog spine. The cross-sections of the beam generated using the TRIZ (FOS)-Biomimetics method are shown in the table, where the structures were basically adapted from the biological strategies of nature. Inspired from the toucan beak, three different design concepts were generated. Design A-01 and Design A-02 consisted of four ribs, while Design A-03 has eight ribs with a hollow design. Design concepts B-01, B-02, and B-03 were adapted from the pomelo peel, where they feature hierarchical structures. Meanwhile, the hedgehog spine inspired the design concepts of C-01 and C-02, differentiated by 24 and 12 holes, respectively. A total of eight design concepts were generated using the TRIZ (FOS)-Biomimetics method for the side-door impact beam in this study.

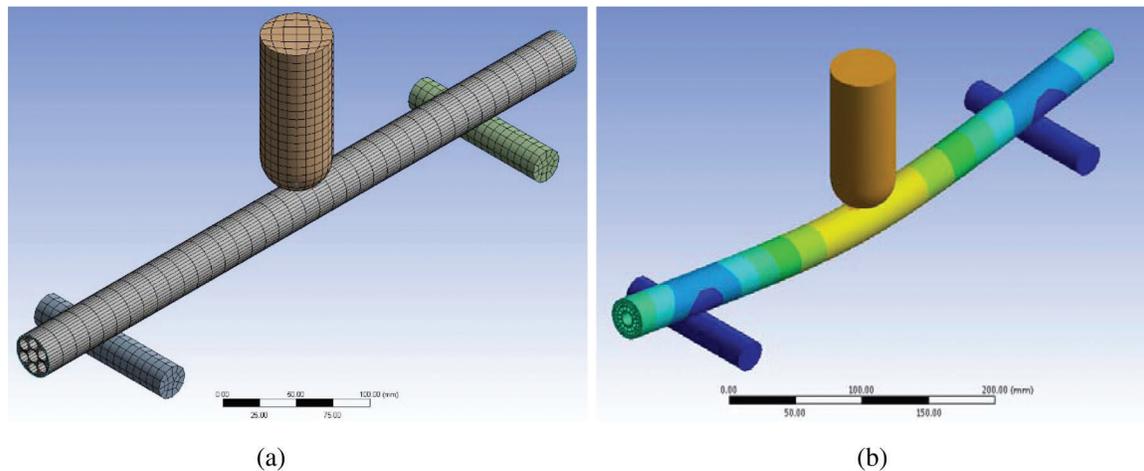
These design concepts were then analysed based on the performance of the composite side-door impact beam. The FEA results of the composite side-door impact beam were further analysed using ANSYS software, where the performance criteria included the maximum stress, maximum deformation, and energy absorption, while mass and volume were recorded for the weight criteria. The costs of the raw materials were taken from previous researches [50–52]. Fig. 5(a) shows the mesh model for the FEA of the impact analysis for Design B-02, with 9,491 nodes and 6,362 elements. The numbers of nodes and elements for all design concepts ranged from 9,491 to 46,171 and 6,362 to 37,367, respectively. Fig. 5(b) shows the stainless steel impactor, which is impacting the 507 mm composite side-door impact beam for the FEA. The data recorded for the FEA are listed in Tab. 3. These results were used to find the best design concept for the composite side-door impact beam using VIKOR.

**Table 2:** Idea generation using the TRIZ (FOS)-Biomimetics method

	Biomimetic Strategies	Design	Name
A	 <p>Toucan beak [47]</p>		A-01
			A-02
			A-03
		B	 <p>Pomelo peel [48]</p>
	B-02		
	B-03		
C	 <p>Hedgehog spine [49]</p>		C-01
			C-02

Tab. 4 shows the results of the normalisation matrix from Tab. 3 using Eq. (3) in Step 1, and the best and worst values for each criterion obtained in Step 2. The benefit criteria in this study were maximum stress and energy absorption, while the cost criteria were deformation, mass, volume, and cost. The following Tab. 5 lists the weighted normalised matrix of Tab. 3, which combined the results that were obtained using Eqs. (4) and (5). The weights of these criteria were recalculated from the previous study [53] of the product design specification for the side-door impact beam. In this study, three criteria were involved out of six criteria. The VIKOR method was applied for Step 3 and Step 4 using Eqs. (4) and (5) to determine the distance between the design concepts and the ideal solution.

The results of VIKOR values,  $Q_i$ , calculated using Eq. (6) are shown in Tab. 6, with the positive and negative ideal solutions ( $S$  and  $R$ ). As explained in the methodology, two conditions must be satisfied



**Figure 5:** (a) Mesh model for Design concept B-02; (b) FEA of the side-door impact beam for data collection

**Table 3:** Properties of the natural fibre composite side-door impact beam design concepts based on criteria

Criteria	Max. stress (MPa)	Max. deformation (mm)	Energy absorption (J)	Mass (kg)	Volume (mm <sup>3</sup> )	Cost (USD/part)	
Design concepts	A-01	298.42	29.390	47.381	0.37989	3.3918	0.9984
	A-02	472.11	24.258	30.161	0.37989	3.3918	0.9984
	A-03	231.94	24.188	39.655	0.40436	3.6103	1.0627
	B-01	328.06	24.813	89.525	0.47068	4.2025	1.2369
	B-02	175.29	24.996	41.368	0.39263	3.5057	1.0318
	B-03	499.27	27.855	91.215	0.51711	4.6170	1.3590
	C-01	1156.6	24.609	53.195	0.34400	3.0714	0.9040
	C-02	270.66	30.529	80.363	0.52383	4.6771	1.3766

before the alternatives can be suggested as the best design concept for the side-door impact beam. The first condition was the acceptable advantage, where the VIKOR value of the second ranked alternative minus the first alternative must be larger than the DQ value, which was 0.1429 in this study. Thus,  $Q(A^{(2)}) - Q(A^{(1)}) \geq DQ$ ,  $0.1178 - 0.0156 = 0.1022$  did not satisfy the acceptable advantage condition. The second condition was the acceptable stability, where the alternative ranked first must also be the best ranked in S and/or R. The results showed that Design concept B-03 fulfilled this condition. Based on both conditions, the first ranking in VIKOR value did not satisfy the first condition, yet satisfied the second condition. Therefore, the fourth condition was referred to since Condition 1 was not satisfied. The fourth condition stipulates that Q value minus Q value in the first ranking should be less than DQ value,  $Q_3 - Q_1 = 0.3143 - 0.0156 = 0.2987$ , which was bigger than DQ. Meanwhile,  $Q_2 - Q_1 = 0.1022$ , which was less than DQ. These results showed that both  $Q_1$  and  $Q_2$  alternatives were close to the ideal solution. Thus, it was concluded that Design concepts B-03 and C-02 were the best designs for the side-door impact beam since these design concepts were close to the ideal solution based on the VIKOR method.

**Table 4:** Normalised matrix, as well as the best and worst values for  $f_{ij}$  (Step 2)

Criteria	Max. stress (MPa)	Max. deformation (mm)	Energy absorption (J)	Mass (kg)	Volume (mm <sup>3</sup> )	Cost (USD/part)
Design concepts	A-01	0.2028	0.3930	0.2646	0.3114	0.3114
	A-02	0.3209	0.3244	0.1684	0.3114	0.3114
	A-03	0.1577	0.3235	0.2215	0.3315	0.3315
	B-01	0.2230	0.3318	0.5000	0.3859	0.3859
	B-02	0.1192	0.3343	0.2310	0.3219	0.3219
	B-03	0.3394	0.3725	0.5094	0.4239	0.4239
	C-01	0.7862	0.3291	0.2971	0.2820	0.2820
	C-02	0.1840	0.4083	0.4488	0.4294	0.4294
$f_j^*$	0.7862	0.3235	0.5094	0.2820	0.2820	0.2820
$f_j^-$	0.1192	0.4083	0.1684	0.4294	0.4294	0.4294

**Table 5:** Weighted normalised matrix (Step 3)

Criteria	Max. stress (MPa)	Max. deformation (mm)	Energy absorption (J)	Mass (kg)	Volume (mm <sup>3</sup> )	Cost (USD/part)
Weights	0.1645	0.1645	0.1645	0.1169	0.1169	0.2727
Design concepts	A-01	0.1439	0.0297	0.1181	0.0936	0.2183
	A-02	0.1148	0.1628	0.1645	0.0936	0.2183
	A-03	0.1550	0.1645	0.1389	0.0776	0.1811
	B-01	0.1389	0.1484	0.0045	0.0345	0.0805
	B-02	0.1645	0.1435	0.1343	0.0853	0.1989
	B-03	0.1102	0.0694	0.0000	0.0044	0.0102
	C-01	0.0000	0.1536	0.1024	0.1169	0.2727
	C-02	0.1485	0.0000	0.0292	0.0000	0.0000

**Table 6:** The positive ideal solution, S, negative ideal solution, R, and VIKOR values, Q

Rank	S	S value	R	R value	Q ( $v = 0.5$ )	Q value
1	C-02	0.1777	B-03	0.1102	B-03	0.0156
2	B-03	0.1986	B-01	0.1484	C-02	0.1178
3	B-01	0.4413	C-02	0.1485	B-01	0.3143
4	A-01	0.6972	A-03	0.1811	A-03	0.6787
5	C-01	0.7625	B-02	0.1989	A-01	0.7204
6	A-03	0.7947	A-01	0.2183	B-02	0.7462
7	B-02	0.8118	A-02	0.2183	A-02	0.8326
8	A-02	0.8476	C-01	0.2727	C-01	0.9365

#### 4 Conclusion

In conclusion, three criteria with six sub-criteria were taken into consideration in determining the best design concept for the biomimetic-inspired composite side-door impact beam. This paper demonstrates how the integrated TRIZ (FOS)-Biomimetics method and the VIKOR method were used to generate eight design concepts. FEA was used to evaluate the sub-criteria and VIKOR method was used to analyse and select the best design concept for the composites side-door impact beam. The TRIZ (FOS)-Biomimetics method generated eight design concept ideas inspired by nature. These methods can be used to solve engineering problems using the problem identification feature in TRIZ and the technology transfer using biological strategies in the AskNature database. FEA evaluated the design concepts and generated the values for the performance and weight criteria. These values offered accurate assessment for the comparison of the design concepts to make quantitative judgement in the final phase using VIKOR method. VIKOR showed that Design concepts B-03 and C-02 were the best design concepts in this study. Design concept B-03 gave the least VIKOR value of 0.0152 in the first rank, while Design concept C-02 came in second with 0.1178. The integrated method of TRIZ (FOS)-Biomimetics-VIKOR can be used as a tool to generate design concepts that are inspired by nature and rank them to select the best design concepts. The strategy proposed in this paper can help engineers to generate ideas that are inspired by nature and then select them using a systematic strategy and justified solutions using MCDM in the conceptual design stage.

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