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Conceptual Design and Materials Selection of the FDM Composites for Passenger Vehicle's Spoiler

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ABSTRACT

One of the additive manufacturing techniques available is Fused Deposition Modeling (FDM), which offers advantages in design flexibility, cost-effectiveness, and the ability to produce intricate designs. Therefore, FDM for the 3D-printed vehicle's car spoiler is a subject that can be explored. The FDM technology can significantly reduce time and cost before mass production, and the vehicle's car spoiler was used as the case study in this research. The research investigates the mechanical properties of various commercial PLA composite filaments, addressing the lack of specifications provided by manufacturers. Testing four types of filaments—PLA/bamboo, PLA/coconut, PLA/wood, and PLA/metal. This research also emphasizes the conceptual design generation and selection for the passenger vehicle's spoiler. Five design concepts were generated using the morphological chart for the passenger vehicle's spoiler. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was used as the decision-making tool. As a result, PLA/metal, with 53.65 MPa and 70.23 MPa, showed the highest tensile and flexural strength values, respectively. Design concept 5 with the infill pattern of rib + I was the best from the

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finite element analysis (FEA) using SolidWorks simulation software. Finally, the TOPSIS technique revealed PLA/metal as the best PLA composite filament for car spoilers, scoring first in performance score with a value of 0.5774. This study demonstrates that by using a systematic approach, researchers may choose the best design concept and material choice by combining the conceptual design, experimental, simulation, and TOPSIS methods.

Keywords: 3D printing, fused deposition modeling, mechanical properties, pla composite filament, TOPSIS

INTRODUCTION

According to Rae and Binder (2023), the automotive industry involves the manufacturers of motorized vehicles, including major components like engines and bodies, but excluding items such as tires, batteries, and fuel. This industry originated in Europe during the late 19th century, initially with steam-powered vehicles, and later in the 1860s, gasoline engines were introduced, especially in France and Germany.

The automotive industry plays a very important role in the global economy, serving as a crucial catalyst for macroeconomic growth, stability, and technological advancements in both developed and developing nations (Klink et al., 2014). It encompasses a wide range of interconnected industries, upstream and downstream, supporting the core automotive sector of vehicle and parts manufacturers, as illustrated in Figure 1.

As in Figure 1, various parts and components are needed for a vehicle in the core automotive industry, such as an engine, gearbox transmission, chassis, steering wheel, brake system, dashboard, and side mirror. Some of the vehicles have spoilers. The purpose of a spoiler is to 'spoil' adverse air passage across a moving vehicle's body. Johnston (2015) stated that a spoiler is a feature on the back of a car that reduces drag or turbulence caused by the vehicle. The spoiler improves the driving grip and is a decorative element

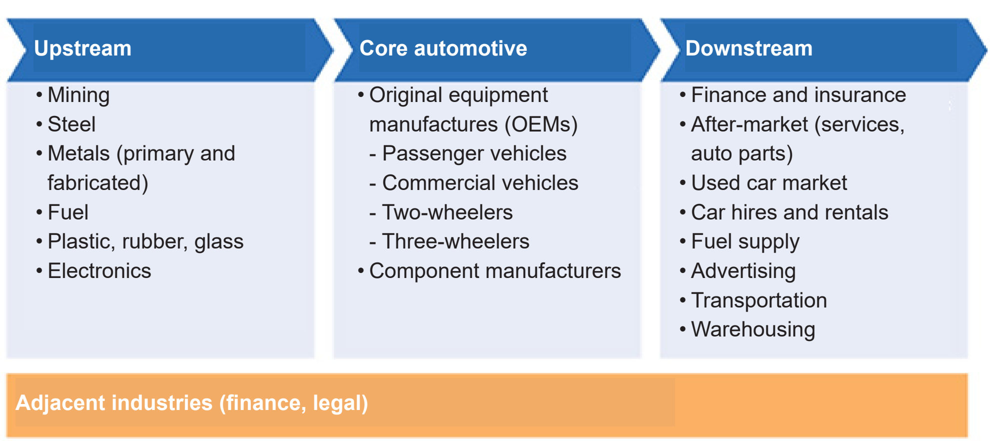

Figure 1. Automotive industries: Upstream, core automotive and downstream (Klink et al., 2014)

that makes the car look sportier (Suwanda, 2015). Figure 2 shows the type of spoiler chosen to be studied in this research (Idros, 2022).

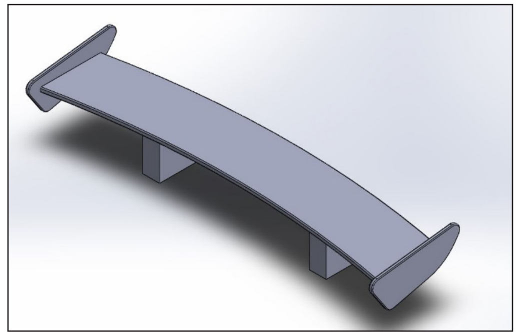

Figure 2. GT wing spoiler (Idros, 2022)

In a study conducted by Irawan et al. (2020), the manufacturing process of woven rattan fiber composites was described as having dimensions of 220 cm in length and 70 cm in width. Prior to drying, the material underwent a 30-minute soaking in 90 % alcoholic liquid. The spoiler generated two positive mold pieces: one for the top and one for the bottom. These pieces were put together to create the finished product, which had the design on it. The mirror coating comprises the first layer of the spoiler, followed by the continuous layer of rattan fiber. After that, it was firmly sealed and laminated with a resin matrix until it dried. Subsequently, the positive molds were opened, the spoiler was removed, and the final touches were applied before it was ready to be used, as shown in Figure 2.

It can be seen from Figure 3 that the natural fiber composite spoiler was made manually using mold and human experts. Human experts depend on individual skills that differ from one another. Therefore, implementing additive manufacturing (AM) technology in this area is significant. AM can be referred to as the technologies that construct 3D objects by depositing the material layers one after another (Mahale et al., 2021). Pelz et al. (2021) stated that AM has ushered in a new era of digital manufacturing by revolutionizing engineering procedures. Metal, ceramic, and plastic components were easily produced using AM processes for prototypes and finished products. According to Bandyopadhyay and Heer (2018), the manufacturing industry is continually changing, and 3D printers can now produce multi-material systems with increased performance in user-defined places. The AM revolution has stimulated broad innovation using a single material.

The key principle of AM is forming three-dimensional parts by incrementally adding material, according to the ISO/ASTM standard 52900:2015(E). The method applies to most industrial fields. It makes use of a wide variety of substances, such as metallic, ceramic, and polymers, as well as mixtures in the form of composites, hybrid, and graded functional substances, and hydrogels, in a variety of physical states, such as solid, liquid, viscoelastic, and gels (Alghamdi et al., 2021).

Figure 4 shows the classification of AM processes from different perspectives. According to the ASTM, more than 50 technologies are based on the above processes (Alghamdi et al., 2021). As a result, ASTM has created a set of standards (ISO/ASTM 52900:2015) that divides the various AM processes into seven broad groups. AM methods were developed with seven families based on the product creation approach. These

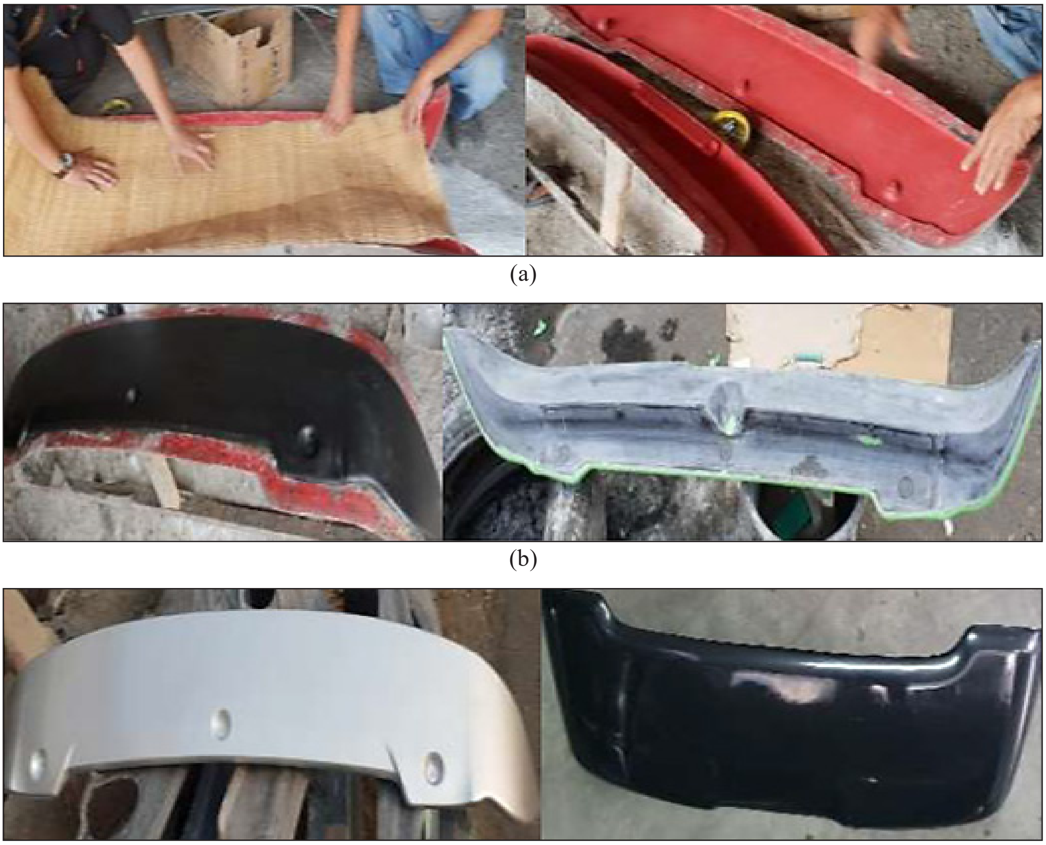

Figure 3. Methodology of car spoiler production using rattan fiber composite (Irawan et al., 2020): (a) Preparation of rattan fibers and positive mold; (b) Manufacturing process of car spoiler; and (c) Product prototype of spoiler

include vat photopolymerization, powder bed fusion, binder jetting, material jetting, sheet lamination, material extrusion, and directed energy deposition (Pelz et al., 2021). Material requirements, process parameters, development speed, performance and cost, dimensional precision, final product utilization, and applications all impact the material choice for AM (Sood et al., 2010).

One of the AM methods is Fused Deposition Modelling (FDM), which converts a CAD or digital three-dimensional (3D) model into a 3D object. FDM, also known as 3D printing, is a technique considered suitable for producing functional and aesthetic prototypes, also known as rapid prototyping. It is the most popular because of the simple concept that it does not require health-conscious solvents or glues. Besides that, all printing apparatus setups are cheap and require less space. The FDM or 3D printing technique can create parts or objects with large thicknesses or intricate shapes that are typically impossible to produce using conventional manufacturing techniques (Mazzanti et al., 2019). The material

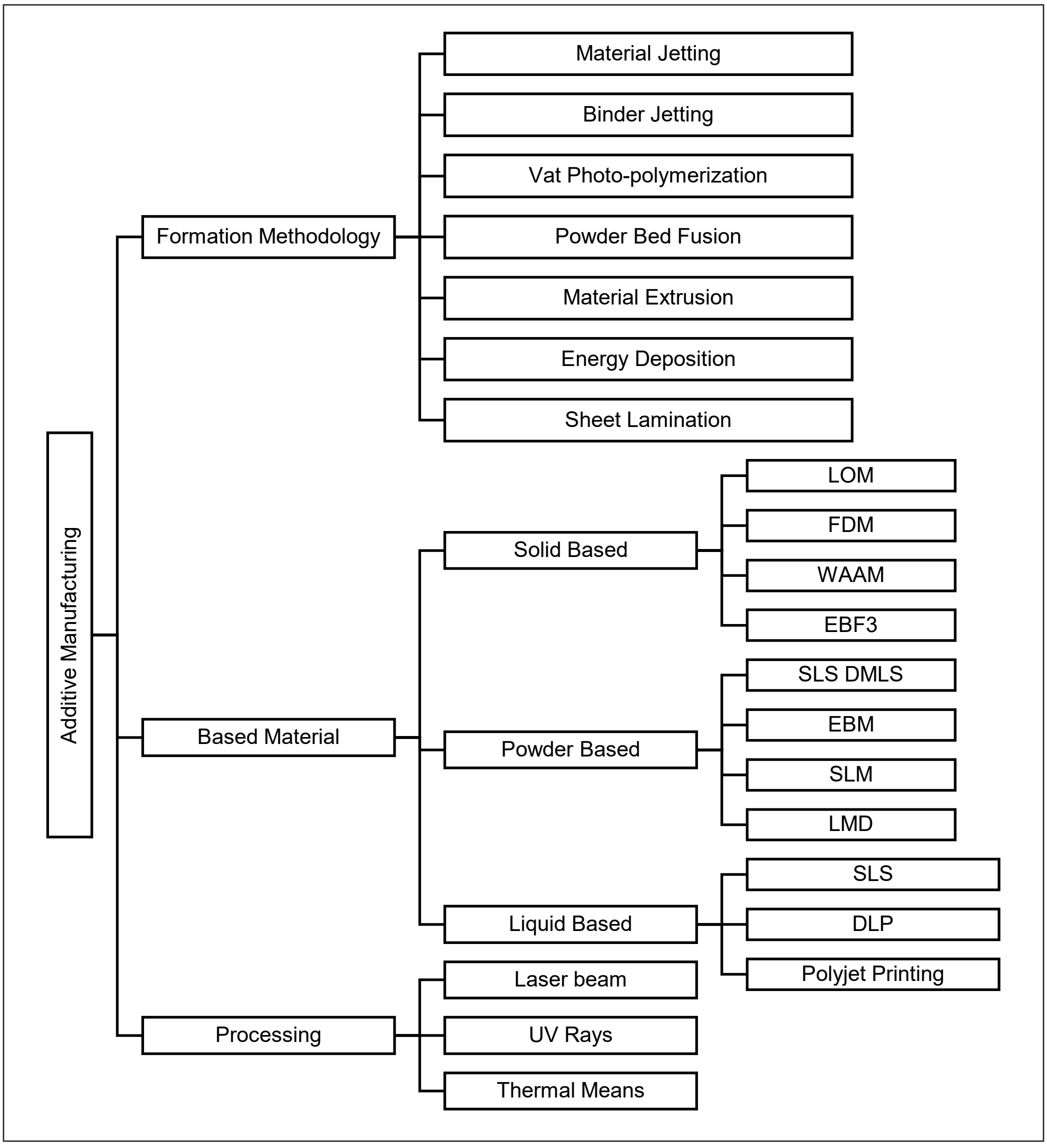

Figure 4. AM processes classification (Alghamdi et al., 2021)

starts to melt when the extruder of an FDM 3D printer is heated to a working temperature. The component is created by melting the filament over its glass transition temperature and forcing it through a narrow opening known as a heat break. This step is done on the printer bed, as shown in Figure 5 (Babagowda et al., 2018).

There are commercially available PLA composite filaments without information on their mechanical properties. This study provides mechanical testing of the available filaments for the users. Therefore, it is significant to this study to create car spoiler structures using natural composite material depending on their mechanical properties,

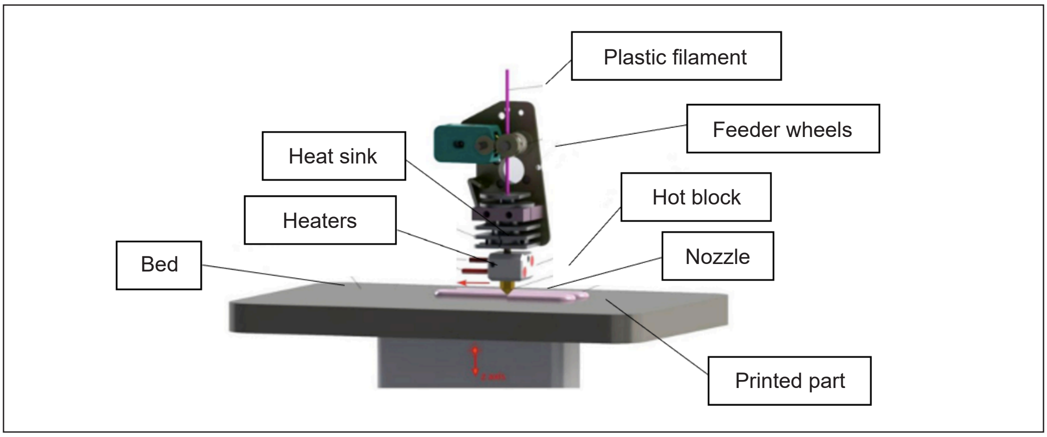

Figure 5. Schematic of 3D printer (Heidari-rarani et al., 2019)

physical properties, and hybridization of the conceptual design stages. This paper aims to analyze the mechanical properties of commercial PLA composite filaments using the Fused Deposition Modelling (FDM) technique to generate the conceptual design of a passenger vehicle's spoiler and select the best conceptual design and best PLA composite filaments by Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method.

MATERIALS AND METHODS

Figure 6 shows the research methodology, which can be divided into two sections: mechanical properties and conceptual design. The mechanical properties section analyzed the tensile and flexural strengths of the PLA composite filaments printed using the FDM technique. The conceptual design section generated the design concepts of the passenger vehicle's spoiler using the morphological chart, performed analysis through the finite element analysis (FEA) method, and selected the best conceptual design by Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Finally, the TOPSIS method was utilized to determine the best material of PLA composite filaments for the best design of a car spoiler.

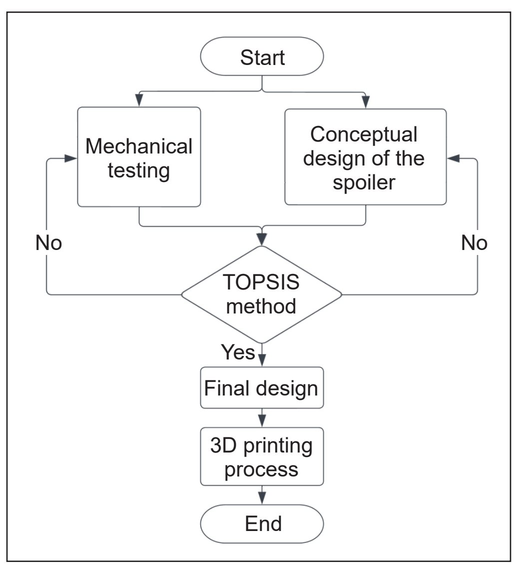

Figure 6. Methodology of the research

The samples or specimens for the tensile and flexural strength analyses were printed using the Creality Ender 6 printer (Figure 7). The printing process started by setting the nozzle temperature at 205, 210, and 215°C with the printer nozzle diameter of 0.6 mm and 1.75 mm filament diameter. The setting of bed temperature was from 50 to 60ºC with the specimen's infill percent of 50%. The adhesive was added during the printing to support the specimen using a brim. The specimens were printed within 1 hour and 30 minutes. The infill pattern layer setup during the printing was lined, and the additional support of the plate adhesion for the specimens, such as brims, helped to improve bed adhesion and prevent warping. Also, 3D glue and 3D blue tape were used to support the bed adhesion. The setup parameters for Creality Ender 6 are shown in Table 1. Four types of PLA composite filaments (FDM) were printed in 3D, including polylactic acid (PLA)/bamboo, PLA/coconut, PLA/wood, and PLA/metal. The printed specimens followed ASTM D638 Type IV for tensile and ASTM D790 for flexural specimens (Ahmad et al., 2020).

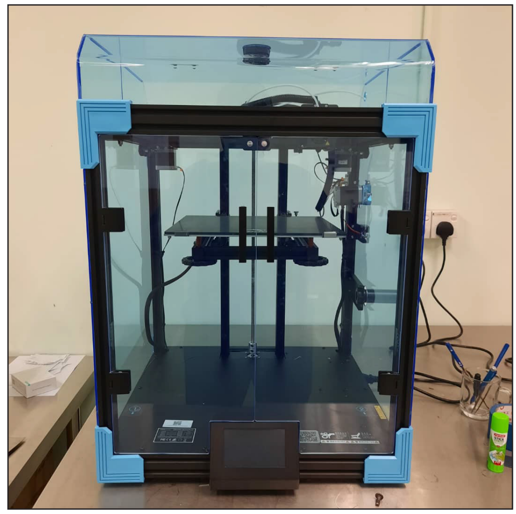

Figure 7. Creality Ender 6 3D printer

Table 1
Printing parameters

Parameter	Value
Nozzle temperature (°C)	205–240
Bed temperature (°C)	50–100
Percent infill (%)	100, 80, 50
Printing speed (mm/s)	100
Raster angle (°)	45
Layer height (mm)	0.2
Nozzle size (mm)	0.8 & 0.4
Adhesive	Glue, blue tape, and brim
Material type	Hybrid PLA/bamboo PLA/wood PLA/coconut PLA/metal

The morphological chart method was applied at the beginning of the idea generation of the conceptual vehicle's car spoiler. The conceptual design was selected based on the morphological chart results (Asyraf et al., 2019), which focused on the five designs (Table 2). The design feature was divided into four main parts for the car spoiler: the spoiler frame type, end plate, frame body, and infill pattern structure. Kumar et al. (2017) inspired these rear spoiler design concepts including the spoiler frame, end plate and frame body. Additionally, in FDM, the infill pattern can be chosen by the designer from the slicer software to reduce the filament usage, simultaneously reduce the printing cost and improve the mechanical properties of the products (Kadhum et al., 2023).

The morphological chart method in Table 2 was applied in this study, and the proposed design concepts shown in Table 3 indicate that five design concepts were generated. Table 3 simplified the design generated using the morphological chart in Table 2.

Table 2
Morphological chart for conceptual design generation

Design features	Solution				
	1	2	3	4	5
Spoiler frame type	Curve	Straight	Pedestal		
End plates type	Type A	Type B	Type C	Type D	None
					
Spoiler frame body	Unibody	Separate parts			
Infill pattern	Rib + V	Honeycomb	Square lattice	Rib + square	Rib + I

Table 3
Conceptual design generation from the morphological chart (Table 2)

Design concept	Solution			
	Spoiler frame type	End plates type	Spoiler frame body	Infill pattern
1	Straight	Type D 	Separate parts	Square lattice
2	Curve	Type C 	Separate parts	Honeycomb
3	Pedestal	Type A 	Separate parts	Rib + square
4	Straight	Type C 	Separate parts	Rib + V
5	Curve	Type D 	Separate parts	Rib + I

The mechanical properties data from the mechanical testing and the performance data from finite element analysis (FEA) were used in the TOPSIS method to determine the score rank of the best material for the best passenger vehicle's spoiler. The basic steps of the TOPSIS method formula and calculation (Mansor et al., 2014) are described below:

Step one: Construct standardized decision matrix A. For the comprehensive assessment questions with *n* evaluation units and m evaluation indexes, its decision matrix A is:

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

Step two: Construct weighted and standardized decision matrix V, weight vector W= (W_1, W_2, ……., W_n):

$$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \quad (2)$$

Step three: Determine the ideal solution X^+ and minus ideal solution X^-:

$$x^+ = \{\max v_{ij} \mid j \in J), (\min v_{ij} \mid j \in J')| i = 1,2,\dots,n\} = \{x_1^+, x_2^+, \dots x_m^+\}$$

$$x^- = \{\min v_{ij} \mid j \in J), (\max v_{ij} \mid j \in J')| i = 1,2,\dots,n\} = \{x_1^-, x_2^-, \dots x_m^-\}$$

Step four: Calculate distance. The distance of each project to the ideal solution X^+ is:

$$s_i^+ = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - x_j^+\right)^2} \quad (3)$$

The distance of each project to the minus ideal solution X^- is:

$$s_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - x_j^*\right)^2} \quad (4)$$

Step five: Calculate the relative proximity index of each project to the ideal solution C_i:

$$C_i = {s_i^-}\Big/\left(s_i^- + s_i^+\right) \quad (5)$$

Step six: Rank the priority of the projects in descending order of C_i.

RESULTS AND DISCUSSION

Five design concepts were generated from the morphological chart (Table 3). All the design concepts were modeled using 3D software, SolidWorks (Figure 8). Design Concept 1 selected the straight spoiler frame with type D of the end plate, frame of a separate body, and infill pattern as a square lattice structure. Design Concept 2 chose the curved spoiler frame and the end plate of type C with a separate body of the frame. Design Concept 3 selected the pedestal frame type and Type A end plate of the car spoiler, which featured a separate spoiler body. In contrast, Design Concept 4 selected the spoiler's straight frame type and Type C end plate, featuring a separate spoiler body. Design Concept 5 chose the curved frame type with a Type D end plate and a separate body for the spoiler. Figure 9 shows the rib + I pattern for the infill in Design Concept 5.

Figure 10 shows the fixed fixtures, external loads applied on the spoiler, and meshing of the car spoiler in Solidworks software. Figure 11 shows the results obtained from the simulation software and data for the Von-Mises stress, displacement, and strain,

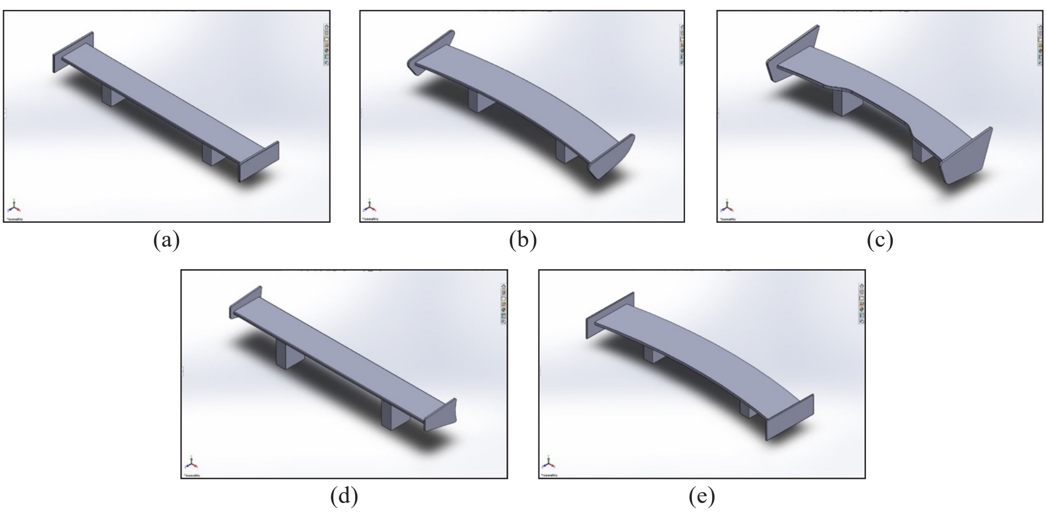

Figure 8. Five design concepts generated from the morphological chart: (a) Design concept 1; (b) Design concept 2; (c) Design concept 3; (d) Design concept 4; and (e) Design concept 5

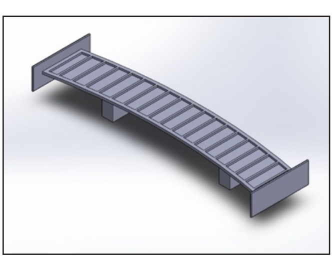

Figure 9. Design concept 5 with infill pattern rib + I

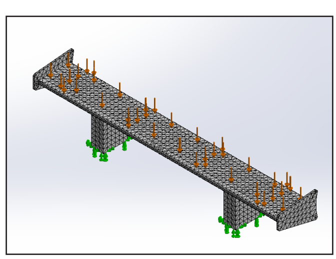

Figure 10. Boundary condition, external loads applied, and meshing for the spoiler

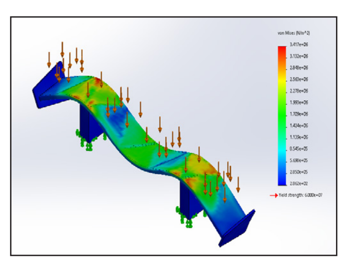

Figure 11. Simulation path coefficients and significance

which were recorded for the different material properties gained for the PLA composite filaments.

Figures 12 and 13 show the tensile and flexural test results, respectively, for the mechanical properties of the PLA composite filaments. Three specimens following the ASTM D638 standard were used for tensile testing, and the other three specimens following the ASTM D790 standard were used for flexural testing for each type of natural fiber filament. In the graph, the mechanical properties data of PLA composite were compared. As in Figure 8, the PLA/metal was the highest, with 53.65 MPa, followed by PLA/wood (36.62 MPa), PLA/bamboo (32.83 MPa), and PLA/coconut (30.70 MPa). The highest value for flexural stress shown in Figure 13 is PLA/metal with 70.23 MPa, followed by PLA/bamboo with 41.04 MPa, PLA/coconut with 39.36 MPa, and the lowest is PLA/ wood with 37.18 MPa.

The mechanical property of the composite filament is important in utilizing the FDM method in 3D printing to ensure the materials the designer uses are the best for their product. Therefore, the data on mechanical properties helps designers and engineers select the appropriate materials for 3D printing based on the required mechanical performance. Besides that, it can be the early performance prediction for the engineers to analyze whether the printed part can withstand the required load without fail. This study used the TOPSIS method to select the best materials to help engineers and researchers.

From the finite element analysis (FEA) analysis of five design concepts of a passenger vehicle's spoiler (Table 4), Design Concept 5 had the lowest value of Von Mises stress. Design Concept 5, showing the lowest displacement and strain, was selected for FEA simulation by replacing the mechanical properties with the PLA composite filaments analyzed in the experimental analysis. The data from the FEA simulation of Design Concept 5 were combined with the data on mechanical properties from the first section, as illustrated

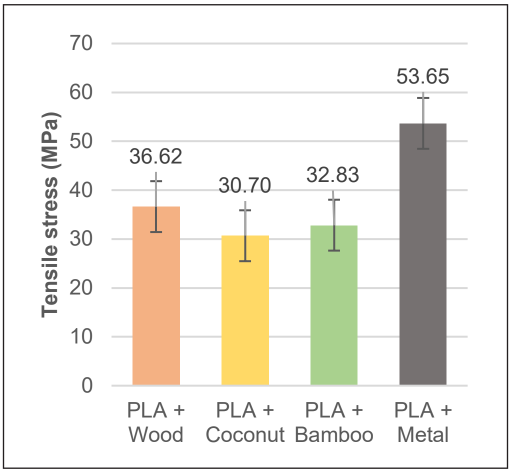

Figure 12. Tensile stress for PLA composite filaments

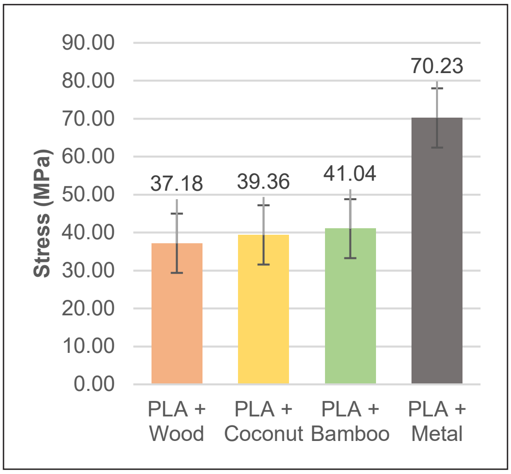

Figure 13. Flexural stress for PLA composite filaments

in Figures 12 and 13. From the findings, the best concept design and best material for the passenger vehicle's spoiler were generated and ranked by using the TOPSIS method.

Table 4
Simulation results for five design concepts

Design concept	Von Mises stress (Max) (N/m^2)	Displacement (Max) (mm)	Strain (Max)
Design concept 1	2.439	1.212	3.320
Design concept 2	2.381	1.418	3.455
Design concept 3	2.822	1.717	3.968
Design concept 4	3.417	1.639	4.882
Design concept 5	2.114	1.123	2.613

Table 5 compiles the data from the mechanical properties and data on the performance of Design Concept 5 from the FEA analysis for all PLA composite filaments. Data from Table 4 were used for the TOPSIS method and calculated using Equations 1 to 5. Through the TOPSIS method, the value of C_1 can be obtained, and the results are shown in Table 6.

Table 5
Data of PLA composite filaments

Material	*TS (MPa)	YM (GPa)	FS (MPa)	FM (GPa)	Cost (RM/kg)	VMS (N/m^2)	DP (mm)
PLA/ Bamboo	32.83	4.88	41.04	1.07	156.90	2.114	1.333
PLA/ Coconut	30.70	5.20	39.36	1.46	152.94	2.114	1.25
PLA/ Wood	36.62	5.34	37.18	1.18	79.00	2.114	1.218
PLA/ Metal	53.65	6.26	70.23	2.71	245.96	2.114	1.039

*TS: Tensile Strength, YM: Young Modulus, FS: Flexural Strength, FM: Flexural Modulus, VMS: Von Mises stress, DP: Displacement

(i) Decision matrix A was determined using Equation 1 and was shown in Table 5

$$A = \sqrt{\sum_{j=1}^{n} x_{ij}^2}$$

(ii) The weighted vector and standardized matrix were calculated using Equation 2 and tabulated in Table 7.

$$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}}$$

(iii) the standardized matrix V was calculated, and the ideal solution X+ and minus ideal solution X- were determined, as shown in Table 8.

(iv) The distance of each material to the ideal solution, S_i^+, and minus the ideal solution, S_i^-, were calculated using Equations 3 and 4.

(v) Finally, the relative proximity index of each material to the ideal solution was computed using Equation 5 and tabulated in Table 9.

Table 6
Decision matrix for the criteria and composite filaments

Material	TS	YM	FS	FM	Cost	VMS	DP
PLA/ Bamboo	36.62	5341.53	37.18	1182.4	79.00	2.114	1.218
PLA/ Coconut	30.7	5203.03	39.36	1461.77	152.94	2.114	1.25
PLA/ Wood	32.83	4879.13	41.04	1071.33	156.90	2.114	1.333
PLA/ Metal	53.65	6261.77	70.23	2714.267	245.96	2.114	1.039
A	78.991	10891.241	97.714	3471.287	338.741	4.228	2.429

Table 7
Weighted vector and standardized matrix for the criteria and composite filaments

Material	TS	YM	FS	FM	Cost	VMS	DP
PLA/ Bamboo	0.46359	0.49044	0.38050	0.34062	0.23322	0.50	0.50134
PLA/ Coconut	0.38865	0.47773	0.40281	0.42110	0.45150	0.50	0.51451
PLA/ Wood	0.41561	0.44799	0.42000	0.30863	0.46319	0.50	0.54867
PLA/ Metal	0.67919	0.57494	0.71873	0.78192	0.72610	0.50	0.42766
Weightage	0.143	0.143	0.143	0.143	0.143	0.143	0.143

Table 8
Data of PLA composite filaments

Material	TS	YM	FS	FM	Cost	VMS	DP
PLA + Wood	0.06629	0.07013	0.05441	0.04871	0.03335	0.07150	0.07169
PLA + Coconut	0.05558	0.06831	0.05760	0.06022	0.06456	0.07150	0.07358
PLA + Bamboo	0.05943	0.06406	0.06006	0.04413	0.06624	0.07150	0.07846
PLA + Metal	0.09712	0.08222	0.10278	0.11181	0.10383	0.07150	0.06116
X+ (best)	0.09712	0.0822	0.10278	0.11181	0.03335	0.0715	0.06116
X- (worst)	0.05558	0.06406	0.05441	0.04413	0.10244	0.0715	0.07846

Table 9
Results of the TOPSIS method analysis

Material	S_i^+	S_i^-	Performance score		Rank
			$S_i^+ + S_i^-$	C_i	
PLA/bamboo	0.09765	0.03684	0.1345	0.2740	4
PLA/coconut	0.08803	0.04178	0.1298	0.3218	3
PLA/wood	0.08676	0.07065	0.1574	0.4488	2
PLA/metal	0.07048	0.09632	0.1668	0.5775	1

Figure 14 shows the best concept design of a car spoiler, which is Design Concept 5 fabricated via FDM 3D printing, and the PLA composite material of PLA/metal was determined to be the best material for the passenger vehicle's spoiler. As proposed in the morphological chart of Design Concept 5, the infill pattern inside the car spoiler has a rib + I structure pattern.

Figure 14. 3D printed spoiler for Design Concept 5 using PLA/metal composite filament

CONCLUSION

In conclusion, four types of PLA composite filaments were printed using the FDM 3D printing technique to determine their mechanical properties. The specimens were characterized via a tensile test (ASTM D638) and a flexural test (ASTM D790) to generate data on the material properties of the PLA composite filaments. The morphological chart approach enabled the solution in the conceptual design stage, and the idea developed was further refined to include particular design characteristics. For the simulation data of the von Mises stress value of 2.114, Design Concept 5 was chosen as the ultimate design concept for developing the product. The best design and material selection was finalized using the TOPSIS method based on the highest priority rank value. TOPSIS method validated that Design Concept 5 with PLA/metal filament was at the highest rank among all four materials with a value of 0.5775. This study used only four composite filaments to analyze their mechanical properties and select the best materials for the vehicle's spoiler. If there are databases for all commercially available filaments, it can help researchers and engineers select the filament for their products. It can be concluded that the hybrid morphological chart-TOPSIS method is proven to be able to be applied in performing the idea refinement, idea generation, conceptual design development, and conceptual design selection process approaches to achieving the desired solution in developing the conceptual design of the PLA composite filament of a passenger vehicle's car spoiler. This study proposes the hybrid method of producing the products using 3D printing to realize the conceptual design stage and assist the engineers in reducing the cost and choosing the best product materials.

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