

Manufacturing Process Selection of "Green" Oil Palm Natural Fiber Reinforced Polyurethane Composites Using Hybrid TEA Criteria Requirement and AHP Method for Automotive Crash Box

N. S. B. Yusof^{1,2}, S. M. Sapuan^{1,3,*}, M. T. H. Sultan^{1,4} and M. Jawaid¹

¹Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, Selangor, Malaysia

²Faculty of Information Sciences and Engineering Management Science & University, Selangor, Malaysia

³Advanced Engineering Materials and Composites Research Centre Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, Selangor, Malaysia

⁴Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor, Malaysia

*Corresponding Author: S. M. Sapuan. Email: sapuan@upm.edu.my

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Abstract: In this study, the best manufacturing process will be selected to build an automotive crash box using green oil palm natural fibre-reinforced polyurethane composite materials. This paper introduces an approach consist of technical aspects (T), the economic point of view (E) and availability (A), and it's also called as TEA requirement. This approach was developed with the goal of assisting the design engineer in the selection of the best manufacturing process during the design phase at the criteria selection stage. In this study, the TEA requirement will integrate with the analytical hierarchy process (AHP) to assist decision makers or manufacturing engineers in determining the most appropriate manufacturing process to be employed in the manufacture of a composite automotive crash box (ACB) at the early stage of the product development process. It is obvious that a major challenge in the manufacturing selection process is lack of information regarding manufacturing of ACB using natural fibre composite (NFC). There have been no previous studies that examined ranking manufacturability processes in terms of their suitability. Therefore, the TEA-AHP hybrid method was introduced to provide unprejudiced criteria-ranking selection prior to evaluation of pairwise comparisons. At the end of this study, the pulforming process was selected as the best manufacturing process for fabrication of the ACB structural component.

Keywords: Manufacturing process selection; automotive crash box; natural fibre composites; TEA requirement

1 Introduction

The aim of this study is to select the best manufacturing process for fabricating automotive crash box ACB by using green natural fibres in a polymer composite material. The design of composites for ACB requires a balance among different attributes such as light weight, high performance, and low material



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and fabrication cost. There has been a growing awareness that selection of the manufacturing process also needs to be made earlier in the design process, a practice also known as the concurrent engineering field of study. The correct selection of the manufacturing process will improve the existing excellent properties of composites, such as high strength and stiffness, good fatigue properties, good impact properties, good damping properties and low density, which make them attractive and suitable for numerous industries [1]. In addition, Natural fiber composites NFC offering better solutions to improved environmental sustainability at lower cost at the same time replacing synthetics composite [2,3]. An unprejudiced approach to evaluating the manufacturing process options must be used to obtain the expected excellent results from the manufacturing waste. Based on these reasons, the TEA requirement has the capability of providing unbiased criteria selection prior to evaluation of pairwise comparisons.

The results of comparing processes must go through sensitivity analysis before a final selection of the manufacturing process. Several constraints had been identified in considering the issues involved in the selection process. Five general assumptions have been made in the scope of this study, which are 1) only mechanical design issues will be considered, 2) the concept of the product has been translated into detailed technical drawings, 3) the design requirements of the product design specification (PDS) will be fulfilled to minimize the manufacturing cost, 4) attention will be paid only to the engineering aspect of the manufacturing process without considering non-functional attributes such as user-friendliness and aesthetic value, 5) and the final consideration is that the manufacturing process must be relevant and realistic. Another selection criterion for the manufacturing solution processes in this study must be able to produce the component using natural fibre-reinforced composite materials.

Within these constraints, the manufacturing process selection criteria can be considered to fall into three wide groups. This is an ordinary occurrence when grouping technical aspects that refer to constraints number 1 and 2. The primary requirements of the technical aspects that are determined often relate to the specified performance of the item, such as its toughness. Another technical thought is the processability of a specification, such as a chamfer or fillet at a certain angle. Moreover, technical aspects also consider whether the information in the technical drawings is sufficient for translating a design idea into to an actual product. Likewise, to attain the ultimate point of limiting fetching, a practical course of material handling must be evaluated for financial practicality as determined in constraint number 3. In the selection of the manufacturing process, a further complication arises because some of the costs involved will be global to all producers. Thus, many of these costs will depend on local conditions. The final selection of the manufacturing process continuously depends to some degree on the physical setting of the process. For a designer, these circuitous impacts may incorporate such broadly changing viewpoints as company approach and the availability of manufacturing facilities as mentioned in constraints number 4 & 5.

2 Methodology

A flow chart showing the proposed methodology for the selection of the most suitable manufacturing process for ACB natural fibre composite is depicted in Fig. 1. There are two core design activities (two stages) involved, namely, the product design specification (PDS) and conceptual design stage. The goal of this proposed selection process is to assist the manufacturing engineers in choosing the most appropriate process that best suits the design requirements.

Fig. 2 describes the general structure for the selection of a manufacturing process for green oil palm natural fibre-reinforced polyurethane composites using hybrid TEA requirement criteria and AHP method for ACB. The relationship between the major tools, i.e., the AHP and TEA criteria requirements is illustrated in Fig. 4. The system was developed using Expert Choice software.



Figure 1: Flow chart for the manufacturing process selection for an automotive crash box (ACB)



Figure 2: Conceptual design of ACB



Figure 3: Sequences of manufacturing requirements



Figure 4: The hierarchical frameworks of manufacturing process selection for ACB

2.1 Product Design Specification

The preliminary stage of this proposed selection system is a product design specification (PDS). The PDS is a document set up prior to the product development process that controls the design and manufacture of a product [4]. The PDS is very important to the product development process because it has great influence in explaining the requirements of the finished product [5,6]. In considering the most appropriate manufacturing process for the ACB, only 10 elements of the PDS were considered in the design. The shape of the ACB as designed is shown in Fig. 2. The details of PDS and geometry design are not discussed in this paper. The outer shape of the ACB is hexagonal with a maximum size of this structure of 140 mm \times 140 mm, a diagonal length of 90 mm, a length that must be between 120 mm and 300 mm and a wall thickness that must be between 1.8 mm and 3 mm. The density of the product is expected to be less than 95 kg/m³ by using a natural fibre composite material compared with the existing ACB minimum density of 95 kg/m³ using aluminium as a core structure material. However, the energy absorption capacity for this product is still expected to reach 5700 J or more. Therefore, long fibre is used in this study with composite thermosetting as a type of matrix and tempering as a manufacturing treatment chosen to increase toughness for structural properties. The material requirements and the product design specification indicated in Tab. 1.

2.2 Selection Process at the Conceptual Design Stage

The second stage of this suggested selection method is called the conceptual design stage. The conceptual design of a product manufacturing process is the initial stage of design activities because several decisions are addressed at this stage, such as materials selection, design concept selection and manufacturing process selection [4,24]. Thus, selection using the most suitable decisions at this stage is critically important. This is because the majority of the success of the product has been predict and the cost and method of manufacturing has been decided prior to the completion of the conceptual design process [25,26]. At this stage, various selection process activities have been applied in order to determine the most suitable manufacturing process for a given design as illustrated in Fig. 2.

Specifications	Descriptions	References
Square/Rectangle/Hexagonal	$140 \times 140 \text{ mm}$	[10-12]
Length	$120 \le L \le 300 \text{ mm}$	
Thickness	$1.8 \le t \le 3 \text{ mm}$	
Diagonal	90 mm	[12]
Density	$ ho \le 95 \text{ kg/m}^3$	[8,12–16]
Energy absorption capacity	$E \approx 5700 J$	[15,16]
Type of Fibre	Oil Palm Natural Fibre:	
Composite	1. Long Fibre: For better toughness properties	[17-21]
Requirement	2. Type of Matrix: Polyurethane Composite	
	Thermosetting (Thermoset)	
	3. Tempering Treatment	
Economic	Select the most economical cost of manufacturing operation and material	[21–23]
Availability	High Availability of the manufacturing process and skilled workers.	[21–23]

Table 1: Product design specification PDS for the conceptual design of ACB using oil palm natural fibre reinforced polyurethane composite [6-23]

2.2.1 Introduction of TEA Criteria

Based on the constraint set, TEA criteria requirement which refer to technical aspects (T), the economic point of view (E) and availability (A) are introduced. TEA criteria requirements have been developed to provide solutions for criteria selection of the manufacturing process for automotive crash box design. These happened in a sequence based on priority as illustrated in Fig. 3. A TEA requirement is a set of filters developed for manufacturing processes based on their priority. All the possible processes will be listed in a large data pool and the AHP method is then used to perform evaluation of pairwise comparisons.

Hierarchical frameworks were divided into five stages as depicted in Fig. 4 with the top level of the hierarchy specifying the goal of the study which was to select the best manufacturing process. The second level specified the factors influencing the goal, taken from TEA criteria requirements. The criteria were then translated to numerical values base on the description of the best manufacturing process for ACB. In the third level of hierarchy, sub-criteria 1 narrowed down the specific factor to achieve the goal, and sub-criteria 2 clearly describe the elements of sub-criteria 1. The bottom level is the pool of set manufacturing process solutions to fabricate ACB design. This level grouped all possible manufacturing processes using composite materials.

The data addressed by Sapuan [27] had been used for the options of manufacturing process solutions at the bottom level of the hierarchy frameworks. The summary of the manufacturing process base on TEA requirements is described in Tab. 2. The first of the TEA requirements is the technical aspect, which is the main factor in the manufacturing process selection. It defines how the performances of the final product fulfil the expected design outcome. The technical aspect is then divided into two categories, which follow: 1) production characteristics (the ability of the process to perform tempering treatment on the product and the ability of the manufacturing process to mass produce the product). ACB design is expected to have high toughness properties to absorb a high amount of impact energy during collision. The toughness of the material increases by performing the heat-treatment process called tempering [28,29]. 2) Product geometry is a technical aspect that will consider whether the geometry and shape

Manufacturing Process	Technical ability (Geometry and ACB Composite Requirements)	Economic Point of View (Operational Cost and Material Cost)	Availability (Facility and Skilled Workers)
Pultrusion	 Resins: Generally, epoxy, polyester, vinyl ester and phenolic Fibres: Any Cores: Not generally used The process pulls the materials through the die for impregnation, and then clamps them in a mould for curing. This makes the process non-continuous but accommodating of small changes in crosssection components. Mass production volume 	 This can be a very fast, and therefore economic, way of impregnating and curing materials. Fibre cost is minimized since the majority is taken from a creel. Limited to constant or near constant cross-section components. Heated die costs can be high. 	• Generally used in industry
Filament winding	 Resins: most types of resin. Fibres: Any. The fibres are used straight from a creel and not woven or stitched into a fabric form. Cores: Any The process is limited to convex shaped components. Structural properties of laminates can be very good since straight fibres can be laid in a complex pattern to match the applied loads. This process is primarily used for hollow, generally circular or oval sectioned components, such as pipes and tanks. Mass production volume. 	 Mandrel (a permanent part of the finished product) costs for large components can be high. Capital investment is relatively high. Fibre cost is low since there is no secondary process to convert fibre into fabric prior to use. Low-cost and very fast process of laying material down. 	 Very precise control over the mechanism is required for uniform distribution and orientation of fibre. Low availability
Hand lay-up	 Resin: most types of resin. Fibres: all types included heavy aramid fabric, simple principle, higher fibre content and longer fibre than spray up. Core: any High Technical ability Low Volume Process 	• Low-cost process, low-cost tooling.	 Widely used for many years. Wide choice of suppliers and material types. High availability

 Table 2: Data used to perform pairwise comparison of ACB [17,18,27–35]

Manufacturing Process	Technical ability (Geometry and ACB Composite Requirements)	Economic Point of View (Operational Cost and Material Cost)	Availability (Facility and Skilled Workers)
Spray up	 Resin: primarily polyester, Fibres: glass roving only, Cores: none Laminates tend to be very resin-rich and therefore excessively heavy. Only short fibres are incorporated which severely limits the mechanical properties of the laminate. Limiting airborne styrene concentrations to legislated levels is becoming increasingly difficult. Low volume process 	 Low-cost way of quickly depositing fibre and resin, low cost of tooling Low-cost process 	Widely used for many years.High availability
Pulforming	 Extends the capability of pultrusion. High capability to produce both solid and hollow sections with a quite complex cross-sectional shape. Mass production volume 	• Cheaper labour cost, high operation cost with machine automated operation.	• Generally used in industry
Resin transfer moulding (RTM)	 Resins: Generally, epoxy, polyester, vinyl ester and phenolic, although high temperature resins such as bismaleimides can be used at elevated process temperatures. Fibres: Any. Stitched materials work well in this process since the gaps allow rapid resin transport. Some specially developed fabrics can assist with resin flow. Cores: Not honeycombs, since cells would fill with resin, and pressures involved can crush some foams. Generally limited to smaller components. Mass production volume 	 Possible labour reductions Matched tooling is expensive and heavy in order to withstand pressures. Un-impregnated areas can occur resulting in very expensive scrap parts. High-cost process 	Commonly used in industry

Table 2 (con	tinued	I).
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Manufacturing Process	Technical ability (Geometry and ACB Composite Requirements)	Economic Point of View (Operational Cost and Material Cost)	Availability (Facility and Skilled Workers)
Vacuum Bagging	 Resins: Primarily epoxy and phenolic. Polyesters and vinyl esters may have problems due to excessive extraction of styrene from the resin by the vacuum pump, Fibres: The consolidation pressures mean that a variety of heavy fabrics can be wet-out. Cores: Any The mould only has to be strong enough to hold the laminate in its desired shape until the epoxy has cured. Therefore, most moulds can be relatively light weight and easy to build. Custom shape: variety and simplicity the mould use Mass production volume 	 The extra process adds cost both in labour and in disposable bagging materials. High-cost process 	• A higher level of skill is required by the operators. Low availability
Out of autoclave processing (OOA)	 Resins: Generally, epoxy, polyester, phenolic and high-temperature resins such as polyimides, cyanate esters and bismaleimides. Fibres: Any. Used either direct from a creel or as any type of fabric. Cores: Any, although special types of foam need to be used due to the elevated temperatures involved in the process. Longer, higher temperature tool life Ability to produce more complex tools Mass production volume 	 Fibre cost is minimized in unidirectional tapes since there is no secondary process to convert fibre into fabric prior to use. The extended working times (of up to several months at room temperatures) means that structurally optimized, complex lay-ups can be readily achieved. Material cost is higher for pre-impregnated fabrics. Autoclaves are usually required to cure the component. These are expensive, slow to operate and limited in size. High-cost process 	• Highly skilled workers for handling quickstep machine and curing chamber.

d).		
Technical ability (Geometry and ACB Composite Requirements)	Economic Point of View (Operational Cost and Material Cost)	Availability (Facility and Skilled Workers)
• Automated tape laying (ATL) and automated fibre placement (AFP) are processes that use	 Reduced labour costs Reduced material scrap Reduced manufacturing time 	 User-friendly proprietary off-line and on-line software Highly skilled workers

Table 2 (continued).

Manufacturing

Process

Automated tape layering

·	 computer-guided robotics to lay one or several layers of carbon fibre tape or tows onto a mould to create a part or structure. Precise, repeatable, tension independent process and enables placement at any angle Mass production volume 	• High-cost processing	needed
	Mass production volume		

shown in the technical drawings as shown in Fig. 2 are possible or impossible to fabricate using that manufacturing process. In addition, a few elements of geometry are also considered in this selection process, which are design complexity, product size, shape of the design, product wall thickness, product weight, tolerances and surface. The second requirements are from the economic point of view which is to minimize the cost of the operational process and the fibre cost without compromising the performance of the product. The solutions of this requirement are very much more complex to achieve since the cost is based on the chain of supply and demand which always fluctuates. Sometimes the cost is also related to the global price trend, which also affects the local producer. The final requirement is availability, this requirement will focus on selection issues such as the availability of facilities and skilled workers [30].

3 Results and Discussion

This process begins with the development of a pairwise comparison matrix, where the software Expert Choice 11.5 at this stage was used to evaluate pairwise comparisons. The software uses relative scale pairwise comparison or numerical comparison as a selection principle to perform the judgement as shown in Tab. 3.

According to the AHP workflow, Expert Choice software was used to determine the most appropriate manufacturing process for the ACB. The results shown in Fig. 5 represent the relative weights for the main factors, sub-factors 1, sub-factors 2 and alternatives. The judgements for all levels are acceptable if the consistency ratio (CR) is less than 0.1 [38,39].

Pairwise comparison starts with comparing the relative importance of two selected items. The manufacturing engineers must perform pairwise comparison for all factors and alternatives that are under consideration in the selection process. Fig. 6 shows the process of pairwise comparison for technical ability criteria and how to perform the calculation of pairwise comparison to choose the best manufacturing process. The entire comparison process is described in Tab. 2 and TEA requirements help the designers to set the priorities. In this case, the pultrusion process and hand lay-up process have similar technical ability requirements to fabricate the ACB structure. Therefore, both processes were

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

Table 3: The principal scale of judgement comparison [35–37]



Figure 5: All priority vectors for criteria, sub-criteria and alternatives

given a 1, equally preferred for both processes on an intensity scale. In contrast, the pultrusion process provides better technical ability compared with the resin transfer molding process and had been given a 3 as the intensity scale. Meanwhile, intensity scale 3, which has a red color, indicated out of autoclave process found to have better technical ability compare with pultrusion manufacturing process. The judgements for all levels are acceptable since the consistency ratio (CR) is less than 0.1. Some cases found that when the consistency ratio exceeds the limit, the designers should review and revise the pairwise comparisons.

Fig. 7 shows the Pulforming process with a weight of 0.147 (14.7%) as the most suitable manufacturing process; the second choice is the Out of autoclave processing (OOA) with a weight of 0.142 (14.2%); and the last decision option is resin transfer moulding (RTM) with a weight of only 0.057 (5.7%). If the results of the selection are not satisfactory for some reasons such as lack of evidence and insufficient details structure, the engineers or any person in charge who can make a decision can perform the selection process again to ensure the results obtained can produce a high quality product at minimal cost.

3.1 Sensitivity Analysis

The major advantage of using the AHP method by operating the selection through Expert Choice software is a sensitivity analysis. A sensitivity analysis is performed to consider the impacts of the various factors on choosing the best-choice alternative. The final priorities of the manufacturing process are extremely dependent on the priority vectors attached to the main criteria. Fig. 8 illustrated the dynamic sensitivity graph of the main criteria with respect to the goal. It demonstrates that pulforming is

Pultrusion											
Compare the relative importa	ance with rea	spect to: \ \ S	hape of	The De	sign						
Filament Winding	Pultrusion	Filament Wi	Hand I	a Snrav	110	Pulformin	Recin Tran	Vacuum	Bag	Out of Auto	Automated
Pultrusion	1 diadaton	3.0			3.0	3.0	3.0	Sacaan	3.0	3.0	3.0
Filament Winding			3.	0	1.0	7.0	1.0		5.0	7.0	7.0
Hand Lay out					3.0	3.0	3.0		3.0	3.0	3.0
Spray up						7.0	1.0		7.0	7.0	7.0
Pulforming							7.0		1.0	1.0	1.0
Resin Transfer Molding	[5.0	7.0	7.0
Vacuum Bagging										1.0	1.0
Out of Auto Clave Processing											1.0
Automated Tape Layering		Incon: 0.00)			1					





Figure 7: Results of judgement selection process

the most suitable process, and at the same time, it also shows how sensitive the result is. For instance, if the priority vector of the economic point of view is increased by 20% (from 23% to 43%), the ranking of the priorities will consequently change with the hand lay-up process with a weight of 0.14 (14%) as a first choice, a second choice of Filament Winding with a weight of 0.125 (12.5%), and the last choice of resin transfer moulding with a weight remaining at 0.057 (5.7%) as shown in Fig. 9.



Figure 8: The dynamic sensitivity graph of the main criteria with respect to the goal



Figure 9: The dynamic sensitivity graph of the main criteria with respect to the goal when the score of the economic point of view is increased by 20% (from 23% to 43%)

4 Conclusions

Selection of the most appropriate manufacturing process for ACB in a concurrent engineering environment was studied in this paper. The proposed framework for the methodology of selecting the most suitable manufacturing process for ACB offers a systematic process to consider. A selection process to determine the optimum manufacturing process at the conceptual design stage will be a decision tool used to assist the manufacturing engineer in the selection process. The practice of integrating the concurrent engineering tool, which is called an analytical hierarchical process (AHP), with the TEA criteria requirements in solving decision-making issues at the initial stage of product development process was discussed in this paper. This study also describes the methodology for selecting the most suitable manufacturing process for ACB. The AHP-TEA requirement method can help manufacturing engineers to assess and select the best manufacturing process based on three main criteria and sub-criteria of a decision. The analysis reveals that pulforming is the most appropriate process. A sensitivity analysis was performed to study the effect of the changed factors on deciding the best manufacturing process. It is evident using Expert Choice software that the AHP-TEA criteria requirement is a beneficial method for determining the manufacturing process selection for ACB components during the conceptual design stage.

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