

Manufacturing Process Selection of Composite Bicycle's Crank Arm using Analytical Hierarchy Process (AHP)

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Abstract. Crank arm is one of the important parts in a bicycle that is an expensive product due to the high cost of material and production process. This research is aimed to investigate the potential type of manufacturing process to fabricate composite bicycle crank arm and to describe an approach based on analytical hierarchy process (AHP) that assists decision makers or manufacturing engineers in determining the most suitable process to be employed in manufacturing of composite bicycle crank arm at the early stage of the product development process to reduce the production cost. There are four types of processes were considered, namely resin transfer molding (RTM), compression molding (CM), vacuum bag molding and filament winding (FW). The analysis ranks these four types of process for its suitability in the manufacturing of bicycle crank arm based on five main selection factors and 10 sub factors. Determining the right manufacturing process was performed based on AHP process steps. Consistency test was performed to make sure the judgements are consistent during the comparison. The results indicated that the compression molding was the most appropriate manufacturing process because it has the highest value (33.6%) among the other manufacturing processes.

1. Introduction

Manufacturing process selection is a method to determine the most suitable process to fabricate a product. Many researchers have addressed in the literature on the importance of selection of an appropriate manufacturing process at the early stage of the product development process. Determining the most suitable process in the early stage can avoid the cost-penalty of making changes become large but it is a difficult task and a crucial decision because various factors has to be considered during the process selection [1].

Analytic Hierarchy Process (AHP) is a tool that employs at the conceptual design stage in the product development process [2, 3]. AHP is widely implanted on applications based on decision-making usually in the area of engineering, personal and social categories for the theme of selection and evaluation. AHP has been used to solve multi-criteria decision making in academic research and industrial training. Generally, the use of AHP is based on experience and skill of the users or experts to determine the factors that affecting the decision process. Furthermore, AHP can be integrated with



other techniques such as quality function deployment (QFD) and data envelopment analysis (DEA) but in this research AHP will be used alone [4].

The automotive component is generally made from an expensive material such as aluminium alloy, titanium, chrome steel and carbon fibre [5, 6, 7]. In the manufacturing process, there are many processes with different amounts of cost and fabricating time. The manufacturing process also gives the manufacturers different types of problems. By doing this research, the problem faced by the manufacturers can be solved by using Analytical Hierarchy Process (AHP) to determine the most appropriate manufacturing process to fabricate a bicycle crank arm that will cut the unwanted cost [8].

Composite material exists in human technology for thousands of years, natural composite exist in animal and plant. The composite material is a mixture of two or more materials with different properties that produce unique composite properties. Nowadays, there are many types of composite material which can manipulate the cost and the properties such as polymer composites.

2. Analytical Hierarchy Process (AHP)

One of the multi-criteria decision-making support tools is the Analytic Hierarchy Process (AHP) and it was introduced by Saaty [9-10]. Many researchers getting interested in AHP mainly due to the nice mathematical properties of the method and it is easy to obtain the fact that required the input data. AHP can be used to solve the complex decision problem because it uses a multi-level of objectives, criteria, sub-criteria and alternatives. The related data are obtained by using a set of pairwise comparison. The comparisons are used to get the weights of the importance of the decision criteria and the relative performance measures of the alternatives in term of each individual decision criterion.

Many researchers applied AHP in their research, especially in task selection. Hambali employed AHP to select the most appropriate polymeric composite automotive bumper beam. The result revealed that the glass fibre epoxy is the most appropriate material because it has the highest value (25.7%, mass fraction) compared with other materials [2]. M.R Mansor integrated AHP, TRIZ and Morphological chart to select the best conceptual design of Kenaf fiber polymer composite automotive parking brake lever [11]. M.U Rosli applied AHP for Natural Fiber Composites Automotive Armrest Thermoset Matrix Selection [3].

However, there are some problems with the way pairwise comparisons are used and the way the AHP evaluates alternatives. Belton observed that AHP may reverse the ranking of the alternatives when an alternative identical to one of the already existing alternatives is introduced [12]. Belton and Gear proposed that each column of the AHP decision matrix to be divided by the maximum entry of that column in order to overcome the deficiency in AHP. Then, they introduced a variant of the original AHP, called the revised-AHP. Later, Saaty accepted the previous variant AHP and now called Ideal Mode AHP [9]. Besides the revised-AHP, other authors also introduced other variants of the original AHP. However AHP is the most widely accepted methods and is considered by many as the most reliable MCDM method.

3. Carbon Fiber Manufacturing Process

Composite manufacturing has been used for over 10,000 years ago when a composite material which is mud and straw used in the building, it is an early man-made manufactured composite [12]. There are many types of manufacturing process for polymer product but in this study only carbon fiber will be considered as a material to make bicycle crank arm. The suitable manufacturing processes for making carbon fiber bicycle crank arm are called hollow molding technology and these processes will be discussed.

3.1. Resin Transfer Molding (RTM)

RTM is a closed-mold, vacuum-assisted process that employs a flexible solid counter tool used for the B-side surface compression. This process yields excellent strength-to-weight characteristics, high glass-to-resin ratio and increased laminate compression. In this process, reinforcement mat or woven roving is placed in the mold cavity that has the shape of the desired part which is then closed and

clamped [13]. Catalysed, low-viscosity resin is pumped in under pressure, displacing the air and venting it at the edges, until the mold is filled. After the filling cycle, the cure cycle starts during which the mold is heated, and the resin polymerizes to become rigid plastic. Gel coats may be used to provide a high-quality, durable finished product.

3.2. *Compression Molding (CM)*

Compression molding is a closed-mold composite manufacturing process that uses matched metal molds with the application of external pressure [14]. The mold is closed with a top force or plug member, pressure is applied to force the material into contact with all mold areas, while heat and pressure are maintained until the molding material has cured.

3.3. *Vacuum Bag Molding (VBM)*

Vacuum bagging is a process that uses a clamping method using atmospheric pressure to hold the adhesive or resin coated components of a lamination in place until the adhesive is cured. Vacuum bagging uses atmospheric pressure as clamps to hold together laminated plies that is sealed in an airtight envelope [15]. The pressure on the outside and inside of the envelope is equal to atmospheric pressure when the bag is sealed to the mold. As a vacuum pump evacuates air from the inside of the envelope, air pressure inside is reduced but air pressure outside remains at 14.7 psi [16]. Atmospheric pressure forces the side of the envelope and everything within it together putting equal pressure over the surface of the envelope. Pressurizing a composite lamination serves several functions. First, it removes trapped air between layers. Second, it compacts the fiber layers for efficient force transmission among fiber bundles and prevents shifting of fiber orientation during cure. Third, it reduces humidity. Finally, and most important, the vacuum bagging technique optimizes the fiber-to-resin ratio in the composite part.

3.4. *Filament Winding (FW)*

Filament winding is an automated method for creating composite structures by winding the filaments under tension over a rotating mandrel (tool). The fiber placement is guided by a machine with two or more axes of motion. This process is primarily used for hollow shapes of design [17]. There are two primary components involved in filament winding, first a stationary steel mandrel rotates, while a carriage arm travels horizontally up and down the length of the mandrel, second traveling arm includes a winding eye, which groups the roving and dispenses them to the mandrel. As the mandrel turns, the roving wrap around it to form a composite layer over the mandrel surface. The precise orientation of the composite matrix is determined by the rate of travel of the carriage and by the rotational speed of the mandrel, both of which are automated. Before encountering the mandrel, the fibers are impregnated with a resin, which later solidifies with the fiber to create the final composite material. After the filament winding lay-up pattern has been executed, the entire assembly (mandrel plus a layer of composite material) is cured in an oven.

4. Methodology

The methodologies of this research for an appropriate manufacturing process of composite bicycle's crank arm, according to the AHP selection method are as follows:

1. Define the objective of selection.
2. Develop a hierarchical framework.
3. Construct set of pairwise comparison matrix.
4. Perform judgement of pairwise comparison
5. Perform the consistency analysis. The consistency ratio (CR) must be less than 10% or 0.1.
6. Perform step 2-5 at all level of hierarchy.
7. Develop overall priority ranking.
8. Select the best alternatives.

5. Selection of manufacturing process by AHP method

Figure 1 shows the hierarchical framework of the research. The main goal is selecting the most suitable manufacturing process for bicycle's crank arm in order to produce a good quality product. The factors that considered in selection are structured in hierarchy form. The selected main criteria in level 2 are Production characteristic (PC), geometry of design (GD), cost consideration (CS), material (MT) and ease of maintenance (EM). The sub-criteria in level 3 are production quantity (PQ), rate of production (RP), processing time (PT), shape of design (SH), size (SZ), weight (WG), complex of design (CD), tolerance and surface finish (TS), tooling cost (TC) and equipment cost (EC).

Based on the gathered data from literature review as shown in Table 1, the pairwise comparison between each criteria and manufacturing process will be performed. Consistency analysis is performed in order to check the consistency of the pairwise comparison performed earlier. The pairwise comparison is accepted since that the result is 0.03 as shown is Table 2.

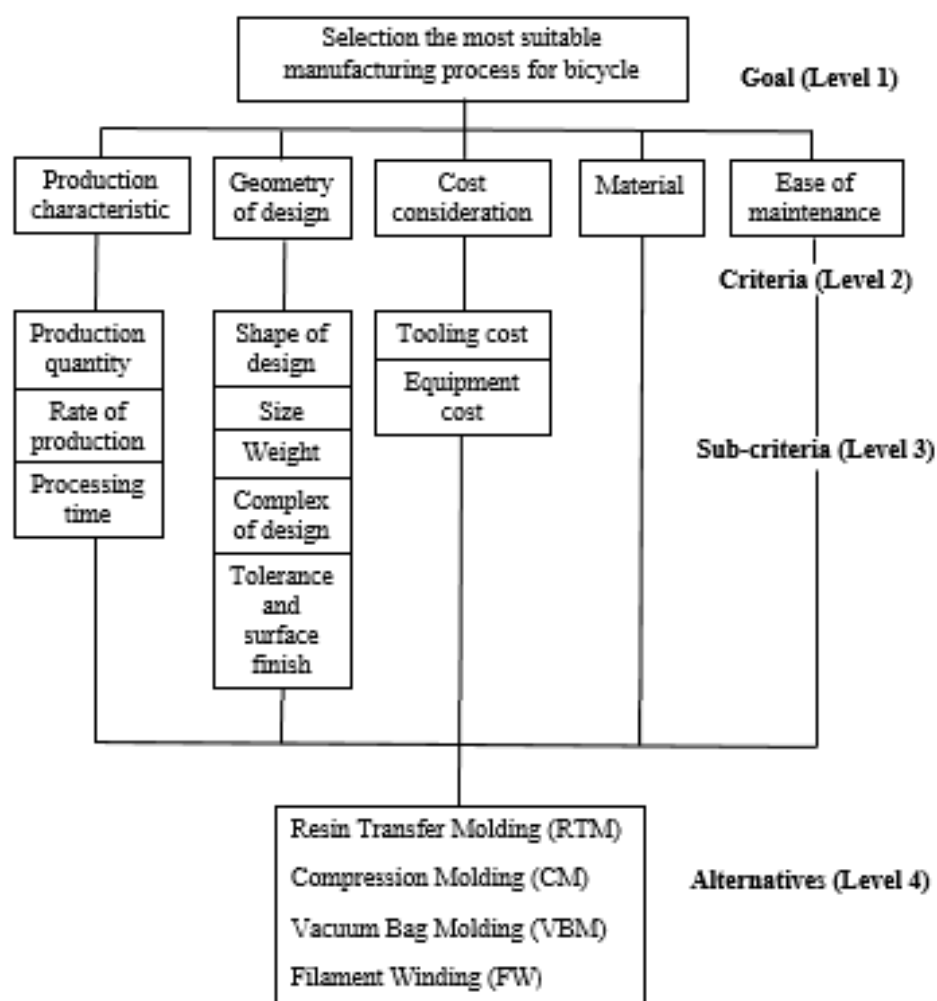


Figure 1. Hierarchical structure of AHP.

Table 1. Data used to perform pairwise comparison.

Process Criteria	RTM	CM	VBM	FW
PQ	Medium	High	Medium	High
RP	Medium	High	Low	High
PT	Average	Fast	Slow	Fast
SH	Highly possible	Highly possible	Possible	Least Possible
CD	Complex-simple	Complex-simple	Simple	Simple
SZ	Small-large	Small-large	Small-large	Small-large
WG	Light	Medium	Medium	Medium
TS	Good-excellent	Good-excellent	Good	Good
TC	Low-high	Medium-High	Low	Low-High
EC	Medium	High	Low	Low-High
MT	Carbon fiber, resin, polyester, epoxy	Carbon fiber, resin, polyester, epoxy, vinylester	Carbon fiber, resin	Carbon fiber, resin
EM	Easy	Hard	Easy	Easy

Table 2. Consistency test for criteria.

Goal	PC	GD	CS	MT	EM	Priority vector (PV)	New Vector (NV)	NV/PV	
PC	1	3	3	3	5	0.430	2.267	5.272	CI = 0.031
GD	1/3	1	1	1	3	0.161	0.838	5.204	
CS	1/3	1	1	3	3	0.210	1.114	5.305	
MT	1/3	1	1/3	1	3	0.138	0.698	5.058	CR = 0.03 (acceptable)
EM	1/5	1/5	1/3	1/3	1	0.062	0.296	4.774	
						Total		25.613	
						Maximum eighenvalue (λ_{\max})		5.123	

Next, all the pairwise comparison and consistency analysis for main criteria, sub-criteria and alternatives are performed as partly shown in Table 3. Consistency verification test is one of the most crucial steps and this is where the AHP method has the advantages. This step measures the degree of consistency among the pairwise comparisons by calculating the consistency ratio. Consistency ratio (CR) is the ratio of consistency index (CI) to random index (RI).

Table 3. Consistency test for alternatives.

	Priority vector											
	GOAL											
	PC			GD					CS		MT	EM
	PQ	RP	PT	SH	CD	SZ	WG	TS	TC	EC		
RTM	0.125	0.173	0.153	0.558	0.411	0.250	0.484	0.555	0.122	0.138	0.269	0.228
CM	0.375	0.372	0.389	0.263	0.380	0.250	0.224	0.252	0.057	0.058	0.564	0.097
VBM	0.125	0.092	0.068	0.122	0.147	0.250	0.161	0.097	0.558	0.385	0.091	0.384
FW	0.375	0.426	0.389	0.057	0.061	0.250	0.130	0.097	0.263	0.420	0.075	0.291
Consistency test												
λ_{max}	4.000	4.134	4.043	4.118	4.033	4.000	4.156	4.043	4.118	4.171	4.082	4.153
CI	0.000	0.045	0.043	0.039	0.011	0.000	0.052	0.014	0.039	0.057	0.027	0.051
RI	0.900											
CR	0.000	0.049	0.047	0.043	0.012	0.000	0.058	0.016	0.044	0.063	0.030	0.057

Table 4. Priority vectors.

	Priority vector											
	GOAL											
Criteria	PC			GD					CS		MT	EM
	0.430			0.161					0.210		0.191	0.062
Sub-criteria	PQ	RP	PT	SH	CD	SZ	WG	TS	TC	EC		
	0.287	0.140	0.574	0.415	0.251	0.056	0.127	0.151	0.750	0.250		
Alternatives												
RTM	0.125	0.173	0.153	0.558	0.411	0.250	0.484	0.555	0.122	0.138	0.269	0.228
CM	0.375	0.372	0.389	0.263	0.380	0.250	0.224	0.252	0.057	0.058	0.564	0.097
VBM	0.125	0.092	0.068	0.122	0.147	0.250	0.161	0.097	0.558	0.385	0.091	0.384
FW	0.375	0.426	0.389	0.057	0.061	0.250	0.130	0.097	0.263	0.420	0.075	0.291

Table 5. Overall priority vectors for sub-criteria with respect to criteria.

	Overall priority vector				
RTM	0.148	0.494	0.126	0.269	0.228
CM	0.383	0.285	0.057	0.564	0.097
VBM	0.088	0.137	0.515	0.091	0.384
FW	0.391	0.084	0.302	0.075	0.291

Table 5 summarizes the overall priority vector for four alternatives with respect to the sub-criteria. By multiplying the priority vector for process alternatives to the vector of sub-criteria, the overall priority criteria can be obtained. Table 6 shows the overall priority vector of the alternatives with respect to the criteria.

Table 6. Overall priority vectors for alternatives with respect to criteria.

	Priority vector					Overall priority vector
	PC	GD	CS	MT	EM	
	0.430	0.161	0.210	0.191	0.062	
RTM	0.148	0.494	0.126	0.269	0.228	0.235
CM	0.383	0.285	0.057	0.564	0.097	0.336
VBM	0.088	0.137	0.515	0.091	0.384	0.209
FW	0.391	0.084	0.302	0.075	0.291	0.227

Table 7 shows the compression molding process that has the highest value (0.336) among the other alternatives. The lowest value is the vacuum bag molding process with a value of 0.209.

Table 7. Result of selection.

No.	Best Selection	
1	Compression molding	0.336
2	Resin transfer molding	0.235
3	Filament winding	0.227
4	Vacuum bag molding	0.209

6. Conclusion

Nowadays, consumers are looking for vehicles more environmental friendly and lighter in weight. For this reason, the engineers are now focusing to substitute the metal parts on utilizing the natural fiber composites. Selecting the effective manufacturing process in product development is a crucial decision. The use of analytical hierarchy process (AHP) can assist manufacturers to evaluate and select the best manufacturing process based on the criteria and sub-criteria aspects of a decision. The analysis reveals that compression molding is the most suitable process for manufacturing carbon fiber bicycle crank arm as it has the highest value (0.336 or 33.6%) among the other manufacturing processes. It is proved that the analytical hierarchy process (AHP) is a useful method in solving the manufacturing process selection problem for the bicycle composite components during the conceptual design stage. Imprecise decision can cause the product to be remanufactured and not in optimized condition.

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