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Full Length Research Paper

Application of analytical hierarchy process in the design concept selection of automotive composite bumper beam during the conceptual design stage

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Selection of design concepts is an area of design research that has been under considerable interest over the years. The level of success of product designs achieved depends significantly on the initial concept at the conceptual design stage. Inappropriate decision making during design concepts selection at the conceptual design stage can cause the product to be redesigned or remanufactured. To overcome such problem, this paper proposed a concept selection model called concurrent design concept selection and materials selection (CDCSMS) to assist designers in selecting the most appropriate design concepts and materials for automotive composite components at the conceptual design stage using analytical hierarchy process (AHP). To illustrate the proposed model, 8 design concepts of automotive composite bumper beam are considered and the most appropriate one is determined by using the analytical hierarchy process (AHP). The final decision was carried out by performing the sensitivity analysis in order to study the effect of the different factors on deciding the best decision option.

Key words: Analytical hierarchy process (AHP), design concept selection, conceptual design stage, automotive bumper beam.

INTRODUCTION

Design concepts selection (DCS) is an area of design research that has been under considerable interest over the years (Salonen and Perttula, 2005). Design concept selection or selection of design concepts is one of the important activities for a product development process. DCS is the decision making phase of concept design, where designers evaluate concepts with respect to customer needs and the designers' intention (Xiao et al., 2007). The determination of the best design concepts at the conceptual design stage is a crucial decision. The selection of the most appropriate design concepts is important because a poor design concept can never be compensated for by a good detailed design and will incur great expense of redesign cost (Hsu and Woon, 1998) and (Zhang et al., 2006). A poor product concept could lead to high redesign costs and a delay in product realization as well as jeopardizing the chances of successful commercialization (Fung et al., 2007). Thus, the level of success of product design achieved depends significantly on the initial concept at the early stage of product development process. DCS is also considered as a multi-criteria decision making (MCDM) problem due to many factors affecting the selection process that has to be considered. Therefore, selecting the best design concepts is not the easy task and the most critical stage in product design development due to many factors influencing the selection need to be considered.

The right decision at the early stage of product development is very important. One of the early stages of pro-

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duct development process is called conceptual design stage (Pugh, 1991) and (Pahl et al., 2007). Conceptual design is an early stage of the product development process which involves the generation of solution concepts to satisfy the functional or design requirements of a design problem. The conceptual design stage plays a critical part in the overall success of the product as once the conceptual design process has been completed, the majority of product cost and quality has been fixed by selecting particular concepts (Rehman and Yan, 2003). Thus, the conceptual design stage is more important and critical stage compare to the other design stages in product development process because at this stage, it forms the background work and involve many complex evaluation and decision making tasks such as materials selection process, selection of design concepts and manufacturing process selection (Sapuan, 2005; Xu et al., 2007). Generally, the main goal of conceptual design stage is to select the most suitable concept from a number of possible options. The main concern of conceptual design is the generation of physical solutions to meet the design specification (Hsu and Woon, 1998). Almost 70% of total product cost is considered at the conceptual design stage (Huthwaite, 1989; Kota and Lee, 1993). However, Lin et al. (2004) presented that 85% of lifecycle costs are determined during the conceptual design stage in the development of a product. Majority of the product cost is allocated prior to the end of the conceptual design stage (Ullman, 1992). Therefore, conceptual design stage has become one of the most important activities in the development of a new product. It is also indicated that the importance of the correct decisions made at the conceptual design stage. In order to support the efficiency in selecting the optimum design concepts at conceptual design stage, an appropriate evaluation and decision tools need to be considered.

There are many design concept selection methods that have been developed to assist designers to make the right decision of design concepts in the literature. The simple decision method is the Pugh concept selection method (Pugh, 1991). This method involves qualitative comparison of each alternative to a reference or datum alternative, criterion by criterion. It is useful in conceptual design because it requires the least amount of detailed information. However, no measure is given of the importance of each of the criteria and it does not allow for coupled decisions. Therefore, there is a danger that the final concept can be imprecise (Ayag, 2005). Hsiao (1998) proposed a fuzzy decision making method for selecting an optimum design from various design alternatives. Ozer (2005) developed an integrated framework for understanding how various factors affect decision making in new product evaluation and provided guidelines for reducing their negative impacts on new product decisions. A recent study published by Ayag and Ozdemir (2009) proposed a fuzzy ANP-based approach to evaluate a set of conceptual design alternatives developed in a new product development environment in order to reach the best one satisfying both the needs and expectations of customers and the engineering specifications of companies. Analytical hierarchy process (AHP) (Saaty, 1980) is the most commonly used technique for solving decision problems and can also be implemented in solving design concept selection problem. Zavbi and Duhovnik (1996) discussed the use of AHP in making the right decision and stressed the importance of the determination of criteria influencing the selection process. Calantone et al. (1999) illustrated the use of the analytic hierarchy process (AHP) as a decision support model to aid managers in selecting new product ideas to pursue. Hambali et al. (2007) used AHP to determine the most appropriate design concepts in wheelchair development at the conceptual design stage.

Despite that some works have been carried out on the implementation of AHP in product development process, very limited studies were carried out in the past on the selection of design concepts at the conceptual design stage. The main focus of this paper is to propose a model that can provide specific steps to assist designers to evaluate and determine the most optimum decision of design concept by using analytical hierarchy process. In this paper, 8 new conceptual design of automotive front bumper beam for passenger cars have been considered to test the proposed model.

A NEW SELECTION MODEL AT THE CONCEPTUAL DESIGN STAGE

The proposed framework of the selection process at the conceptual design stage is depicted in Figure 1. Generally, conceptual design stage comprises 3 main design activities namely concept generation, concept selection and concept development. At the concept selection stage, the decision tasks can be divided into 2 main parts. The first part is called the design concept selection and the second part is called the materials selection. Both of these parts are simultaneously performed by implementing analytical hierarchy process (AHP). This simultaneous system is called concurrent design concept selection and material selection or CDCSMS model. CDCSMS model is a model that assists designers to evaluate and determine the best design concepts and materials simultaneously during concept selection process at the conceptual design stage. After the ranking of decisions have been determined (called design selected), then various scenarios of sensitivity analysis are performed to see how sensitive the decision options which will change with the importance of the criteria. Thus, the proposed CDCSMS model provides a systematic approach for designers to determine the most optimum decision during concept selection at the conceptual design stage.

However, in this paper, a CDCSMS model is only employed to determine the most optimum design concepts for

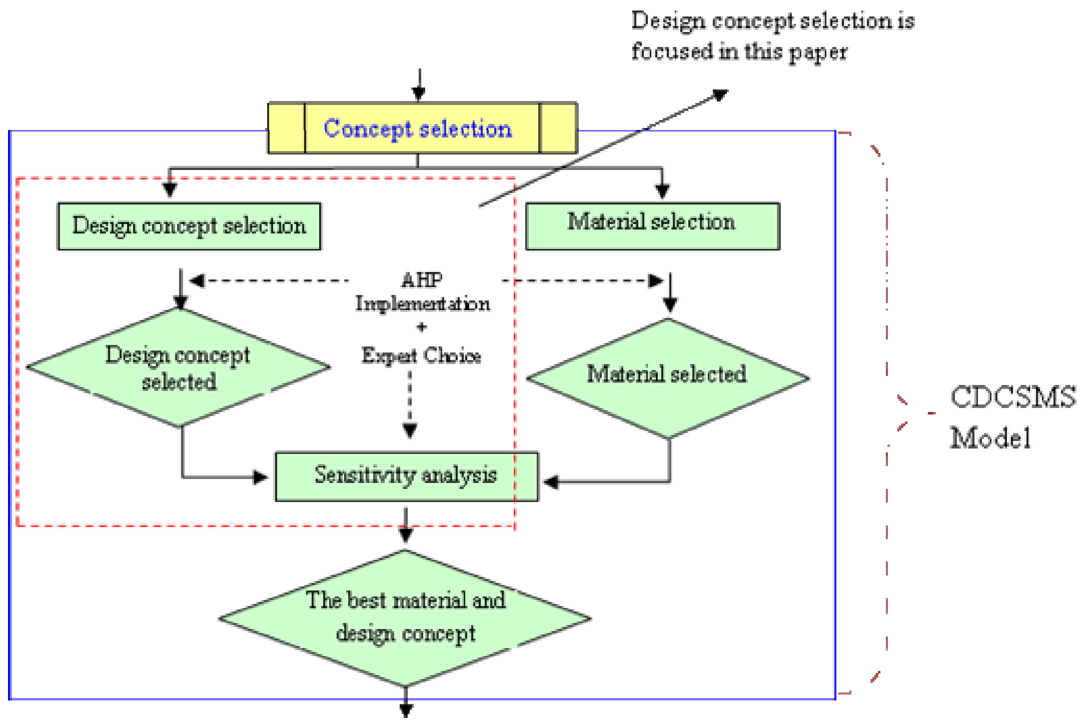

Figure 1. A framework of selection process at the conceptual stage.

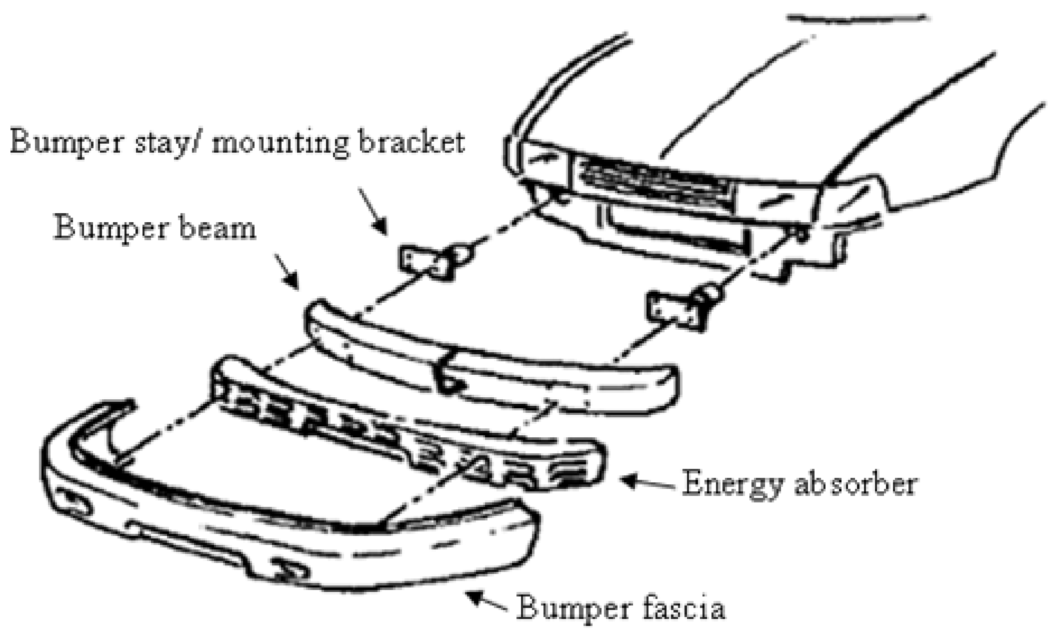

Figure 2. Bumper systems (Rush, 1990).

automotive composite bumper beam. The objective is to illustrate how AHP can be integrated in this framework in order to determine the best design concept for the auto-automotive front bumper beam for passenger cars during concept selection at the conceptual design stage.

SELECTION OF DESIGN CONCEPTS FOR THE AUTOMOTIVE BUMPER BEAM

The automotive industry has always been known to be very competitive as far as its design and material usage

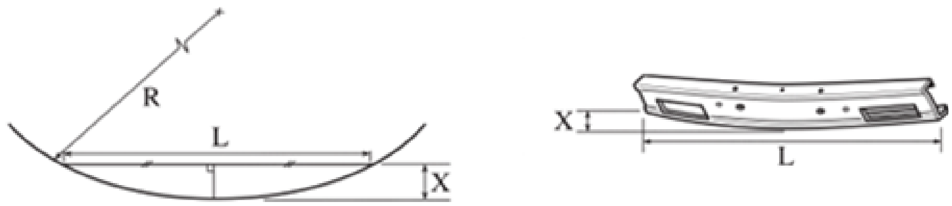

Figure 3. Definition of sweep.

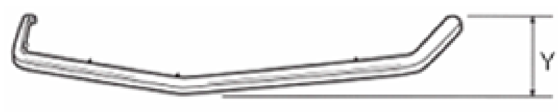

Figure 4. Definition of the depth of draw

are concerned. The automotive industry was selected due to its facing greater market pressure to develop high quality products more quickly at lower cost, reduce weight in order to improve fuel efficiency and cost. Automotive bumper system was selected as a case study of this research. Automobile bumper is a structural component of an automotive vehicle which contributes to vehicle crashworthiness or occupant protection during front or rear collisions. The bumper system also protects the hood, trunk, fuel, exhaust and cooling system as well as safety related equipments (Suddin et al., 2007). The bumper system is generally recognized as being composed of 4 basic components namely bumper fascia, energy absorber, bumper beam and bumper stay as shown in Figure 2 (Yim et al., 2005) and (Lee and Bang, 2006). Bumper beam was selected due to it playing the important role of absorbing the bulk of energy and provide protection to the rest of the vehicle (Bernert et al., 2006). Bumper beams are also the backbone of the energy absorbing systems located both front and rear on automobiles. Thus, it is important to determine the most appropriate design concept and material for the automotive bumper beam at the early stage of product development process.

Design requirements of automotive bumper beam

Bumper beam is one of the main parts of the bumper system that protects a vehicle from front and rear collisions. Thus, it is important to design and manufacture bumper beam which can contribute to have good impact behaviour. The most important consideration in designing bumper system is the ability of the bumper system to absorb enough energy to meet the original equipment manufacturers (OEM's) internal bumper standard (Bernert et al., 2006). A recent work published by Suddin et al. (2007) cited that the ability to stay intact at high speed impact, weight, manufacturing process ability, cost, formability and recyclability of materials are the major factors needed to be considered in designing bumper beam during the design phase. The other factors such as strength, shape, impact condition, thickness, cross section and ribbing pattern also need to be considered in designing automotive bumper beam (Bernert et al., 2006; Sapuan et al., 2002; Hosseinzadeh et al., 2005). However, bumper beam designs have to satisfy and meet safety standards requirement by local regulation and international organizations such as CFR (Code of Federal Regulations) Part 581 of the National highway traffic safety administration (NHTSA) in the United States, CMVSS (Canada Motor Vehicle Safety Standard) 215 in Canada and ECE regulation 42 in Europe (Bernert et al., 2006).

Conceptual design of automotive bumper beam

Bumper beam is a complex shape, thus, all the proposed design concepts are assumed curve flat-faced. To design automotive bumper beam, generally, a convenient way of defining the degree of roundness is to use the concept of sweep. Sweep expresses the degree of curvature of the outer bumper face or the face farthest removed from the inside of the vehicle. Sweep is defined in Figure 3 and its standard dimension. Depth of draw is often used to describe the amount of rounding and wrap a round on a bumper section as shown in Figure 4. Depth of draw is the distance, Y, between the extreme forward point on a bumper and the extreme after point on a bumper (Bernert et al., 2006). The dimension of each proposed conceptual design is assumed as same as standard dimension as shown in Table 1. After implementing various design techniques such as brain storming at the concept generation stage, there are 8 design concepts of automotive bumper beams which were carried out as depicted in Figure 5.

DESIGN CONCEPT SELECTION USING ANALYTICAL HIERARCHY PROCESS

There are 8 design concepts of automotive front bumper beam that have been evaluated in order to determine the most appropriate one to be carried forward to a final conceptual design. AHP is used to determine the most appropriate design concept. Generally, AHP consists of 3 basic steps namely decomposition, comparative judge-

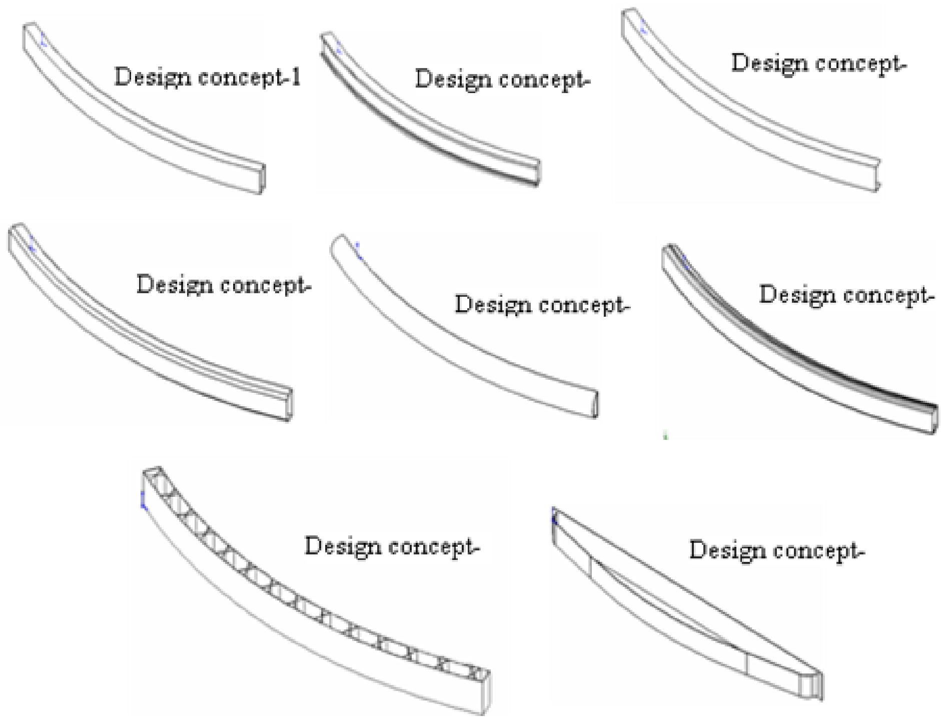

Figure 5. Design options.

Table 1. Dimension of bumper beam [26].

Dimension	Unit (mm)
Circle of radius (R)	1908
Chord length (L)	1524
Sweep in the camber (X)	159
Depth of draw (Y)	210
Width	120
Thickness	2

ment and the synthesis (Saaty and Vargas, 2001; Adhikari et al., 2006; Cheng et al., 2007. These steps can be elaborated by structuring them in a more encompassing 9-step process as shown in Figure 6.

Factors influencing the selection of a design concept

The selection of the best design concept for the automotive front bumper beam for passenger cars depends upon the variety of factors which include:

Energy absorption (EA): The most important factor in designing bumper beam is the ability to absorb enough energy to meet the original equipment manufacturers (OEM's) internal bumper standard (Bernert et al., 2006). However, in order to achieve good energy absorption characteristics, the structure of bumper beam need to be determine at the early stage of product development process.

a. Structure of bumper beam (SC): Structure of bumper beam is important in determining the capability of the beam to absorb kinetic energy when it collides. To provide excellent energy absorption, there are 4 factors that have to be considered in designing bumper beam as follows:

i. Curvature structure (CST): Curvature structure of bumper beam determines the level of energy to be absorbed. According to Sharpe et al. (2001), the bumper beam is curved in plan so as to keep a constant offset to the front bumper skin providing a consistent level of pro-protection to vulnerable road users across the vehicle front. The bumper beam straightens and as a consequence the beam mounts are pushed outwards. This outward motion puts the energy absorbing structure into bending and so energy may not be absorbed efficiently. The bumper beam is curved or bent for several reasons. Firstly, the space behind the central portion of the bumper beam permits deflection of the bumper beam in the event of impacting another car without damaging structure behind the bumper beam. Secondly, this curvature of the bumper beam provides room behind the bumper beam for vehicle components such as the radiator. Finally, the curvature of the bumper beam is desirable for aesthetic purposes (Steward et al., 1992; 1994). Thus, it is important to design bumper beam which can contribute to excellent energy absorption.

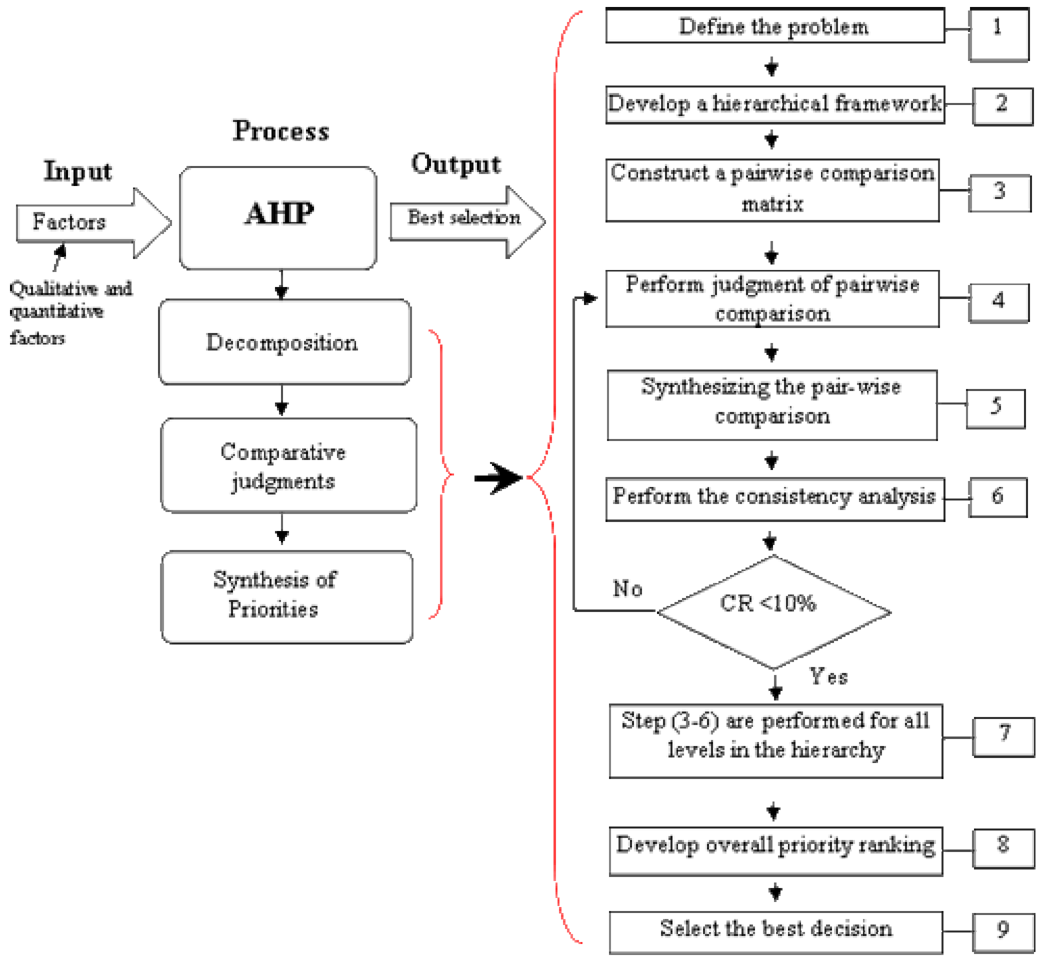

Figure 6. AHP principles and its steps.

ii. Ribbing pattern (RP): Ribs are commonly used to give strength and rigidity to the product. At the same time, ribs help to have thinner walls and therefore reduce the amount of material and later the cooling time (Ashaab et al., 2003). The structure of bumper beam can be strengthened by ribs in specific places in order to form a more rigid and stabilized structure. The ribs are strengthening plates mainly placed along the vertical direction for preventing deflection of lateral surfaces and thus creating a rigid structure and reduce deflect-tion (Hosseinzadeh et al., 2005). According to Haque et al. (2001), ribs provide the needed rigidity for off-centre impacts.

iii Cross section (CS): The cross sectional shape of the bumper beam is important that it influences the energy absorption rate (Jacob et al., 2002; Cheon et al., 1997). Various cross sectional shape of the bumper beam have been developed in order to provide effective deformation resistance such as circular type, square, square + rib, C-section, I-section, B-section, D-section, etc. The right cross section can increase the strength of the bumper beam and provides dimensional stability. Increased strength permits absorption of energy with consequent reduce-tion in distortion of the bumper beam when it is impacted (Steward et al., 1994). Therefore, it is very important to determine the bumper beam cross section during the initial stage of design process.

iv. Thickness (TH): By increasing the material thickness of bumper beam, it will greatly improve the bumper beam strength. According to Anderson et al. (1998), the strength to weight rations improvement by adding material thickness. The bumper beam part which has thinner material such as central portion provides effective energy absorbing characteristics (Baccouche et al., 2007). However, it is well known when the thickness of a product is increased, the weight of a product increased proportionally. Thus, it is important to determine the right thickness of bumper beam.

Cost (CT): It is about 70% of the cost of a product that is determined before production activity (Clark and Wheelwright, 1993). Therefore, it is very important to design and develop composite bumper beam which con-tributes to the cost reduction without sacrificing its safety and impact performance characteristics. There are 3 most important costs required to be considered in design-ing bumper beam as follows:

a. Material cost (MC): Cost of materials plays a very significant role in assisting designers to evaluate and determine the best design at the early stage of product development process. The cost of the material for bumper beam is based on its weight and the price of material per unit weight.

b. Manufacturing cost (MFC): Manufacturing cost is the most important factor in determining the best design concept at the early stage of product development process. According to Yang and Lin (1997), if the product manufacturing cost can be estimated during the design stage, designers can modify a design to achieve proper performance as well as a reasonable cost at an early stage of the product development process. Generally, manufacturing cost is based on the size and complexity of the product, the manufacturing process employed for making the shape and finish, the material used to make the product, e.t.c. The cost of manufacturing is estimated based on the material-manufacturing-selling (1-3-9) rule (Ullman, 2002).

c. Repair cost (RC): Repair cost is also an important consideration in designing automotive bumper beam (Bernert et al., 2006). The repair cost is roughly estimated assuming when bumper beam involved in low speed impact. Avery and Weekes (2006) investigated the repair cost of bumper system by conducting a crash test series in order to investigate the occurrence of override in low speed impact. It was revealed that the bumper beam was a key feature in determining the severity of the damage to the vehicle in the low speed impacts. Therefore, it is important to consider cost of repair in determining the best design concept of automotive bumper beam in ensuring that vehicle damage repair costs are minimized.

Manufacturing process (MP): Manufacturing process is also needed to be considered when designing bumper beam at the early stage of the product development process. There is only one sub factor that designers really need to consider when considering manufacturing process factor and it is of how easy product would be fabricated.

a. Easy to fabricate (EF): The selection of the best design concept is also determined by considering of how easy product to be produced or fabricated by a given machine without increasing cost of manufacturing. Easy to fabricate by simplifying the shape is important when designing bumper beam. It has been desired the bumper beam can be fabricated easily which is made of composite materials.

Weight consideration (WE): It is about 75% of fuel consumption relating directly to vehicle weight; the automotive industry can expect an impressive 6 - 7% improvement in fuel usage with 10% reduction in weight (Basavaraju, 2005). Reducing the weight of the structure without sacrificing performance of the bumper can provide manufacturing cost savings. Thus, it is important to consider weight factor when determining the best design cost at the early stage of product development process.

Strength (ST): It is important to produce high stiffness bumper beam which is capable of protecting car body and its components during high speed impact. Stronger bumper beam hold up better in crashes and need replacement less often. This saves consumers money both on replacement bumpers cost. Strength is defined as an ability of bumper beam to stay intact or rigid at the high speed impact, provide dimensional stability and prevent damage to the other components. The strength of the bumper beam is determined by its deflection.

a. Deflection (DF): During this, impact bumper beam absorb all kinetic energy through deflection. Low deflections during impact shows bumper beam is not easy to bent and absorb impact. High deflections can cause bumper beam breakage allowing damage to the vehicle (Kelman and Nelson, 1998).

Styling (SL): Styling of bumper beam is also needed to be considered when evaluating the best design concept. The current styling trend for vehicles is towards rounded and aerodynamic shapes. This trend has impacted bumper design and challenged bumper manufacturers to provide the highly rounded shapes desired by vehicle stylists (Bernert et al., 2006). Therefore, it is essential to consider roundness and aerodynamic shape of bumper beam at the early stage of product development process.

a. Roundness (RN): Roundness on bumper beam surface is also needed to consider in designing bumper beam. Bumper beam which is having a good roundness formed can improved impact-absorbing performance. According to Katsutoshi and Mitsutoshi (2007), having a good roundness of the corner portion of bumper beam can improve impact-absorbing performance.

b. Aerodynamic shape (AD): Generally, an aerodynamic shape helps direct air flow to the engine compartment. Creating an excellent aerodynamic shape for bumper beam that can cut fuel consumption and emissions. Therefore, it is important to select the best design concept depends on it aerodynamic shape.

Material (MT): Bumper beam design is greatly influenced by the material selected. There are 2 factors that must be considered by designers in determining the best design concept at the early stage of product development process, namely, recyclability of materials and formability of materials.

a. Formability of materials (FM): The formability of materials is an important factor to determine the best design concept under the material criterion (Bernert et al., 2006). Formability is defined as the easy or difficulty level of materials involved in a forming process. A material with good formability requires less applied force, consumes less energy and can be formed into required shapes without failure (Cai et al., 1994).

b. Recyclability of materials (RM): The recyclability of materials is also an important consideration to determine the best design concept under the material criterion (Suddin et al., 2007; Bernert et al., 2006). The recyclability in automotive industry is very important. For example, the European Union (EU) has a requirement that by 2015, more than 95% of all vehicles by weight must be recycled (Sullivan, 2006). Concern for the environment has led to increasing pressure to recycle materials at the end of their useful life. Thus, it is important to consider the material which is easily recycled at the end of their useful life.

Maintenance (MTN): There are 3 main factors influencing the selection of the composite bumper beam related to maintenance consideration as follows:

a. Easy to repair (ER): Repairability measures how easily, quickly and cost-effectively the damaged structure and components can be repaired or replaced (Bernert et al., 2006). One of the most frequently replaced and repaired automobile part is the bumper. Because a bumper is designed to protect other parts of a car including safety systems such as steering, brakes and lights. The customer and the insurance industry desire systems that are easily repairable and that protect others. Thus, it is important to determine the best concept based on how easy bumper beam to be replaced when damaged.

b. Easy to dismantle (ED): How easy component can be separated or removed for maintenance or repairing purposes is also needed to be considered in determining the best design concept.

c. Easy to install (EI): Easy to install is also another factor influencing the selection of the best design concept at the early stage of product development process. Easy to install means that how easy component can be assembled and integrated to the other components such as bumper stay, energy absorber, e.t.c. during installation or maintenance purposes.

Determination of the best design concept during concept selection

Based on CDCSMS model, AHP is integrated to the model. Based on the AHP steps, expert choice software was used to determine the most optimum design concept. The software was developed by Forman et al. (2000), a multi-attribute decision support software tool based on the AHP methodology. The first step is to identify the problem and determine its goal. The problem should be clearly stated and decision makers have to identify factors or criteria affecting the selection process. The factors that are influencing the selection process factors are then translated to the hierarchy structure as shown in Figure 7.

Pair wise comparison begins with comparing the relative importance of two selected items. Using pair wise numerical comparisons provided by Expert Choice 11 software or relative scale pair wise comparison as shown in Table 2, to perform the judgement of pair wise comparison. The characteristics of various design con-cepts of the automotive front bumper beam for a passenger car is depicted in Table 3. The judgements or assigned values as shown in Figure 8 are based on the authors' experience, knowledge, through journals, pat-ents and handbooks.

The results of priority vector and consistency test for the main criteria with respect to the goal are shown in Figure 9. The energy absorption (EA) contributes the highest to the goal with a priority vector of 43.4% (0.434) while the maintenance (MTN) and styling (SL) contribute the lowest with a priority vector of 2.5% (0.025) only. As the value of consistency ratio (CR=0.04) is less than 0.1, the judgments are acceptable. If CR > 0.1, the judgement judgment matrix is inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved by repeating the process.

The pair wise comparisons for all levels in the hierarchy are performed. The results in Figure 10 represent all the priority vectors for criteria (for instance, energy absorption, L: 0.434 or 43.4%) and sub-criteria [for instance, material cost (MC) L: 0.258 or 25.8%]. The priority vectors also show how important between among the criteria. For instance, cross section (CS) shows the highest to the structure with a priority vector of 56.0% (L: 0.560). It is meant that cross section is the most important consideration with respect to the structure criterion compared to the other sub-criteria. The judgment for all levels are acceptable due to CR is less than 0.1. The ranking of the design concept decisions are shown in Figure 11. It shows that the design concept 6 (DC-6) with a weight of 0.191 (19.1%) as a first choice, the second choice is the design concept 5 (DC-5) with a weight of 0.182 (18.2%), and the last choice is the design concept 2 (DC-2) with a weight of only 0.064 (6.4%).

VERIFICATION OF THE DECISIONS THROUGH SENSITIVITY ANALYSIS

The purpose of performing the sensitivity analysis is to study the effect of the different factors on deciding the best decision option. The final selection of the design concept is highly dependent on the priority vectors attached to the main criteria. The minor changes in the priority vectors might contribute to the major changes in the final ranking. The stability of the ranking under varying

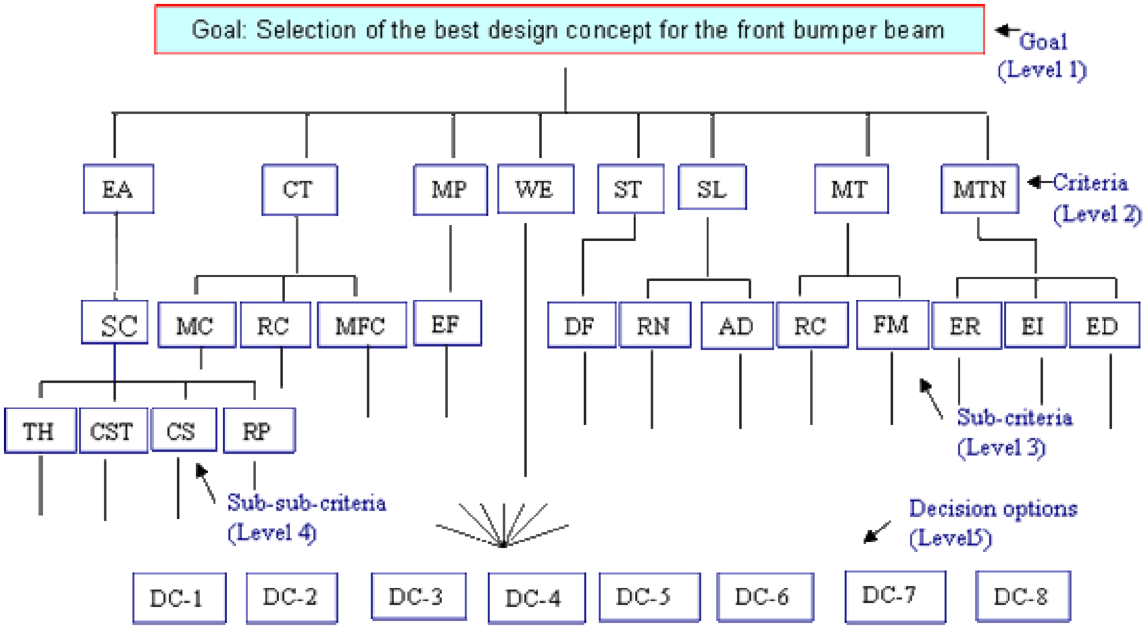

Figure 7. The hierarchy model (4 levels) represents the criteria and sub-criteria affecting the selection of design concepts for automotive bumper beam.

Table 2. Scale for pair wise comparisons (Saaty, 1980).

Relative intensity	Definition	Explanation
1	Equal value	Two requirements are of equal value
3	Slightly more value	Experience slightly favours one requirement over another
5	Essential or strong value	Experience strongly favours one requirement over another
7	Very strong value	A requirement is strongly favoured and its dominance is demonstrated in practice
9	Extreme value	The evidence favouring one over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between two adjacent judgments	When compromise is needed
Reciprocals	Reciprocals for inverse comparison	

Table 3. The characteristics of various design concepts of the automotive bumper beam.

Characteristics	DC-1	DC-2	DC-3	DC-4	DC-5	DC-6	DC-7	DC-8
TH(mm)	2	2	2	2	2	2	2+3 (Ribs)	2
CST	Good	Good	Good	Good	Good	Good	Good	Poor
CS	Rectangle	Rectangle+ Fillet	'C'	Rectangle + Taper	'D'	Hat-Box	Rectangle + Ribs	Rectangle+ Gap
RP	Nil	Nil	Nil	Nil	Nil	Nil	X-Ribs	Nil
MC (RM)	21.1	21.9	17.1	20.3	19.0	21.2	28.4	13.7
MFC (RM)	63.3	65.7	51.3	60.9	57.0	63.6	85.2	41.1
RC	Low	Low	Low	Low	Low	Low	Low	Low
EF	Low	Medium	Low	Medium	Low	Medium	High	Medium
WE (KG)	2.73	2.83	2.21	2.63	2.45	2.74	3.02	1.77
DF (mm)	57.5	170.0	124.8	147.0	53.5	41.1	147.9	331.4 m
RN	Moderate	Poor	Moderate	Good	Good	Poor	Moderate	Good
AD	Poor	Poor	Poor	Good	Good	Poor	Poor	Poor
FM	Low	Medium	Low	Medium	Low	Medium	High	Medium
RM	Low	Low	Low	Low	Low	Low	Low	Low
ER	Low	Low	Low	Low	Low	Low	Low	Low
ED	Low	Low	Low	Low	Low	Low	Low	Low
EI	Low	Low	Low	Low	Low	Low	Low	Low

criteria weights has to be tested as these priority vectors are usually based on highly subjective judgements. The sensitivity analysis is performed by increasing or decree-sing the priority vector of individual criterion, the resulting changes of the priorities and the ranking of the decision can be observed. There-fore, sensitivity analysis provides information on the stability of the ranking. Figure 12 shows the sensitivity graph of the main criteria with respect to the goal. Sensitivity analysis is not only demonstrated that the design concept 6 (DC-6) is the best choice but also shows how sensitive the decision is. For instance, if the priority vectors of manufacturing process (MP) is increased by 10% (from 6.2 – 16.2%), consequently, the ranking of the priorities will change which the design concept 5 (DC-5) with a weight of 0.186 (18.6%) as a first choice, the second choice is the design concept 6 (DC-6) with a weight of 0.179 (17.9%) and the last choice is the design concept 2 (DC-2) with a weight of only 0.066 (6.6%) as depicted in Figure 13.

The final decision was verified by simulated several scenarios with increasing or decreasing the values of the priorities vector of the main criteria (energy absorption, strength, material, cost). The ranking of the early decisions (Figure 11) was compared with the results obtained after performing 4 simulated scenarios as depicted in Table 4.

If the priority vectors of energy absorption (EA) is decreased by 15% (from 43.4 - 28.4%) and priority vector of strength (ST) is increased by 15% (from 13.1 - 28.1%), the ranking results of the best design concept will not change which is same as the previous one. But if the priority vector of material (MT) and cost (CT) are increased by 15% (from 13.1 - 28.1% for the material and 6.2 - 21.2% for the cost) as a result, the ranking of the priorities will change which the design concept 5 (DC-5) as a first choice. It can be concluded from the sensitivity analysis; the final result is mainly based on increasing or decreasing the values of the priorities vector of the main criteria. In this study, final decision of the most appropriate design concept was design concept 6 (DC-6) after various scenarios of the sensitivity analysis have been conducted.

Conclusion

The proposed model called concurrent design concept selection and material selection (CDCSMS) is a model that provides systematic approach to assist designer to effectively evaluate and

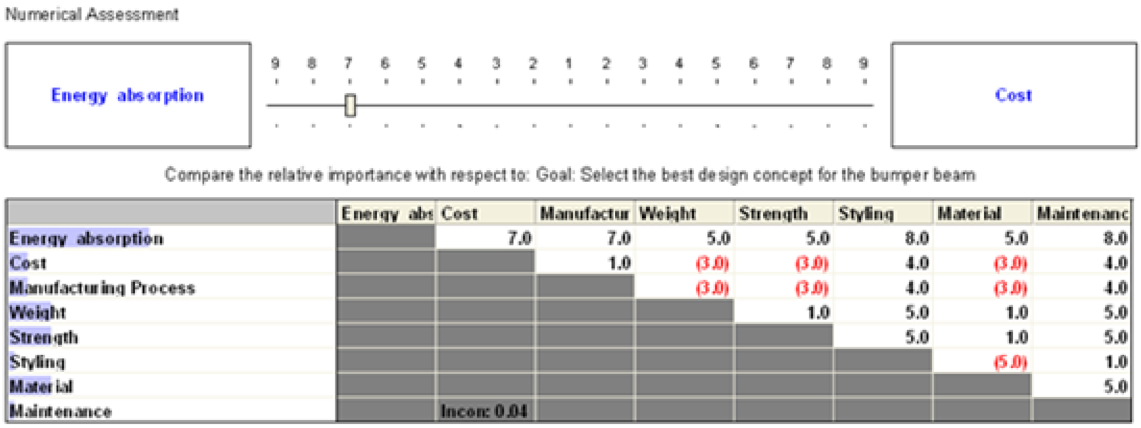

Figure 8. Pair-wise comparison of the main criteria with respect to the goal in a matrix format as a result of using Expert Choice software.

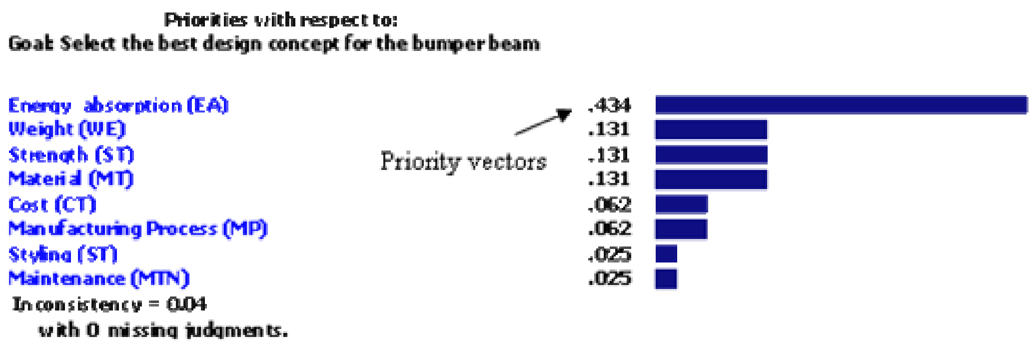

Figure 9. The priority vectors and consistency test for the main criteria with respect to the goal.

Table 4. The results obtained by simulated four scenarios.

Main criteria	Energy absorption	Strength	Material	Cost
Rank	**Decrease (15%)**	**Increase (15%)**	**Increase (15%)**	**Increase (15%)**
1	DC-6	DC-6	DC-5	DC-5
2	DC-5	DC-5	DC-6	DC-6
3	DC-3	DC-3	DC-3	DC-8
4	DC-1	DC-1	DC-1	DC-3
5	DC-8	DC-8	DC-8	DC-1
6	DC-4	DC-4	DC-4	DC-4
7	DC-7	DC-7	DC-7	DC-7
8	DC-2	DC-2	DC-2	DC-2

determine the most suitable design concept for the automotive components. The use of AHP method to integrate to the CDCSMS model proved that the selection of design concept at the conceptual stage can be performed in a more systematic approach. It is clear that AHP is a useful method method in decision-making process as it provides clear criteria and priority in design concept selection. AHP concept can help the designers to evaluate and select the best design concept based on the criteria and sub-criteria aspects of a decision. The analysis reveals that the design concept-6 is the most appropriate for further development because it has the highest value (19.1%) among the other design concepts. Various scenarios of the sensitivity analysis were performed to verify the decision in order to carry out the final decision. Therefore, this work illustrated how the

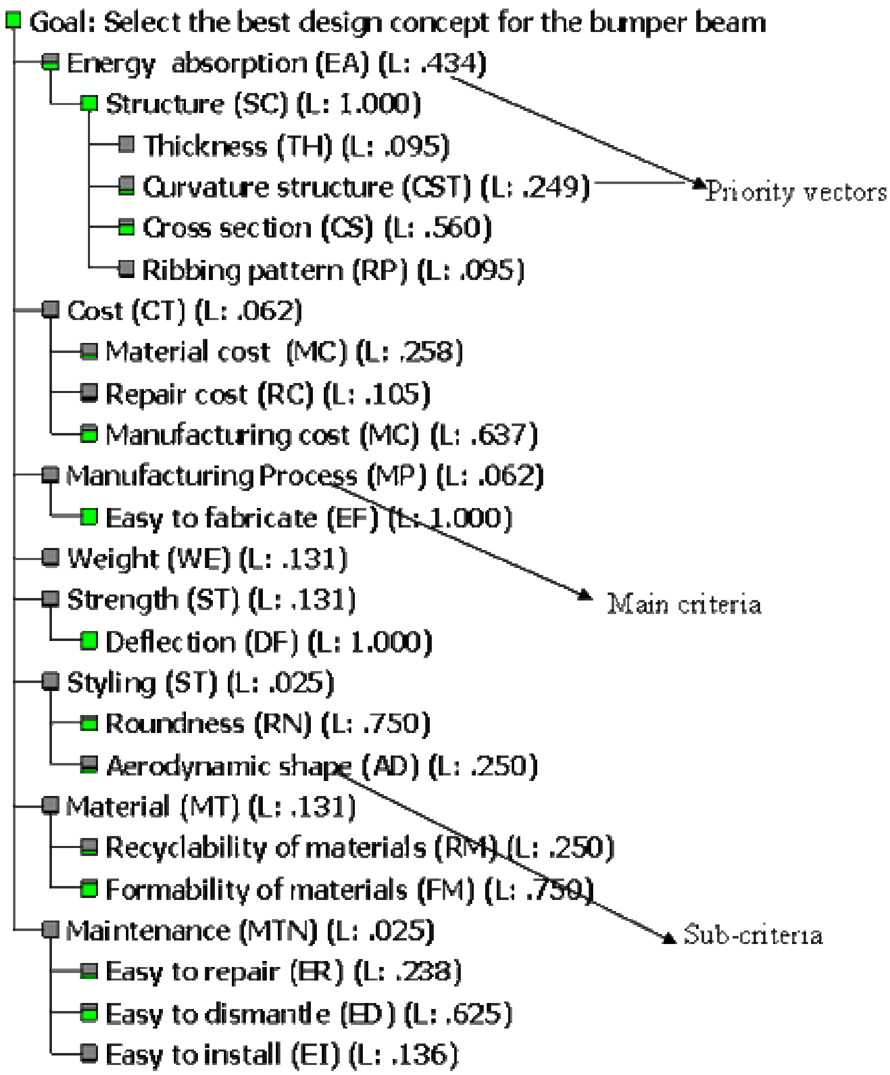

Figure 10. All priority vectors for criteria and sub-criteria.

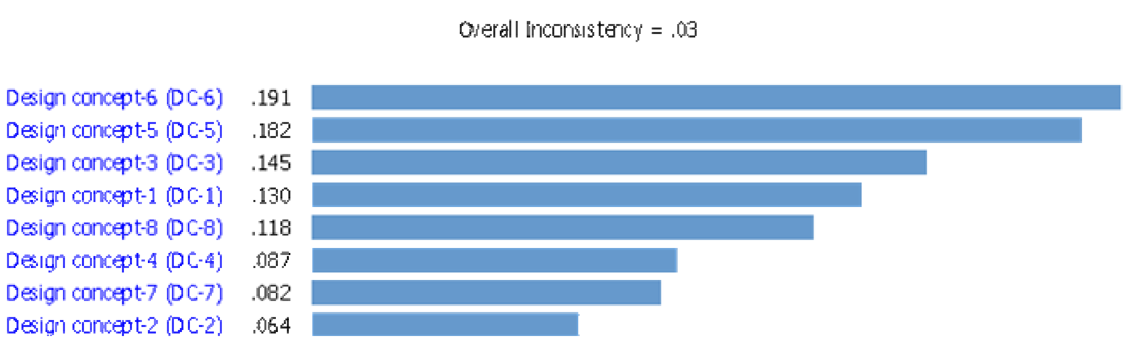

Figure 11. Result of selection.

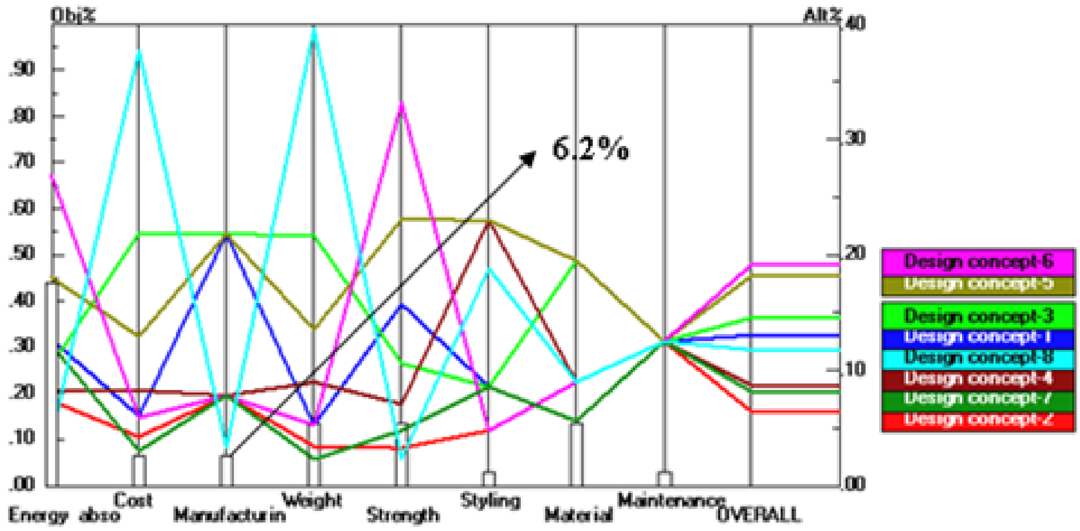

Figure 12. The sensitivity graph of the main criteria with respect to the goal.

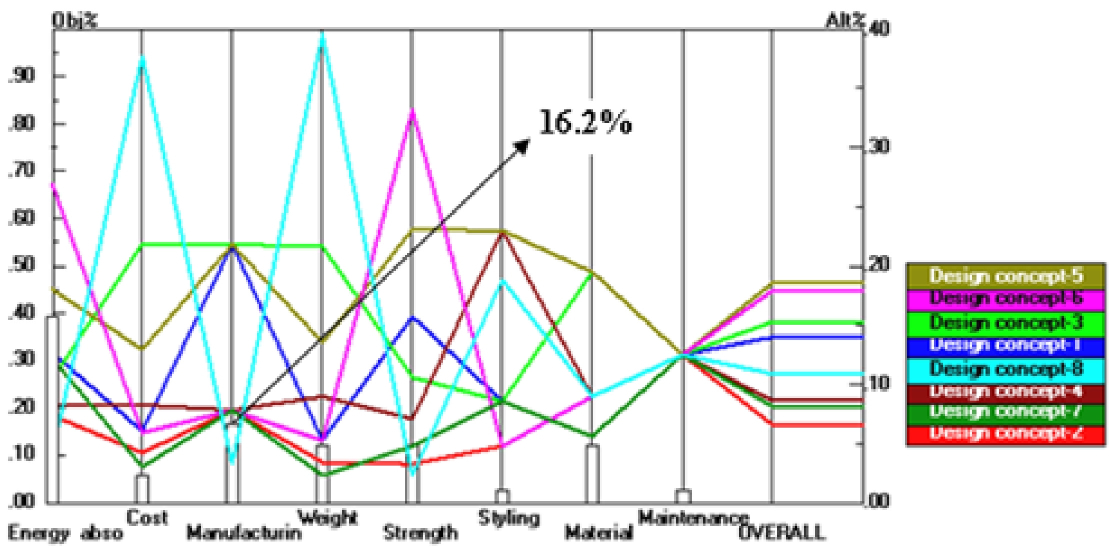

Figure 13. The sensitivity graph of the main criteria with respect to the goal when score or weight of 'manufacturing process' is increased by 10%.

AHP model is linked to the pro-posed CDCSMS model which would be implemented to help designers determine the most appropriate design concept at the early stage of product development process.

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REFERENCES

Adhikari I, Kim SY, Lee YD (2006). Selection of appropriate schedule delay analysis method: Analytical Hierarchy Process (AHP). In Proceedings on PICMET. Istanbul, Turkey.

Anderson J, Senior RB, Fillipek GL (1998). D-Section bumper. US Patent: US 5725266.

Ashaab A, Rodriguez K, Molina A, Cardenas M, Aca J, Saeed M, Abdalla H (2003). Internet-Based Collaborative Design for an Injection-moulding Syst. Concurr. Eng. 4: 289-299

Avery M, Weekes AM (2006). The development of a new low-speed impact test to improve bumper performance and compatibility. Crashworthiness 11: 573-581.

Ayag Z (2005). An integrated approach to evaluating conceptual

design alternatives in a new product development environment. Prod. Res. 43: 687-713.
Ayag Z, Özdemir RG (2009). A hybrid approach to concept t selection Through fuzzy analytic network process, Computers & Industrial Engineering. 56: 3133-3146.
Baccouche R, Mahmood H, Madasamy C, Wagner D (2007). Lightweight bumper for automobiles. US Patent: US 7210717 B1.
Basavaraju DH (2005). Design and analysis of composite beam for side impact protection of a sedan, Master Thesis, University of Mysore, India.
Bernert W, Bulych S, Cran J, Egle D, Henseleit K, Hersberger T, Kantner C, Koch M, Kudelko C, Mihelich M, Mohan R, Stokfisz S, Tang M, Vikstrom T, Welte E, Zabik B (2006). American Iron and Steel Institute: Steel Bumper Systems for Passenger Cars and Light Trucks, Revision number three, June 30, 2006. http://www.bumper.autosteel.org.
Cai Z, Yu JZ, Ko FK (1994). Experimental study on formability of textile performs for composite processing. Proceeding of the American Society For composite. September, 20-22, 1994. University of Delaware, Newark. Delaware. pp. 126-132.
Calantone RJ, Benedetto AD, Schmidt J (1999). Using the analytic hierarchy process in new product screening. Prod. Innov. Manage. 16: 65-76.
Cheng SC, Chen MY, Chang HY, Chou TZ (2007). Semantic-based facial expression recognition using analytical hierarchy process. Journal of Expert Systems with Applications 33: 86-95.
Cheon SS, Lee DG, Jeong KS (1997). Composite side door impact beam for passenger cars. Composite Structures. 38: 229-239.
Clark K, Wheelwright S (1993). Managing New Product and Process Development, New York. The free Press
Forman EH, Saaty TL, Selly MA, Waldron R (2000). Expert Choice 1982–2000 McLean, VA, Decision Support Software Inc., Pittsburgh, USA.
Forman EH, Saaty TL, Selly MA,Waldron R (2000) Expert Choice 1982–2000 McLean, VA, Decision Support Software Inc., Pittsburgh, USA.
Fung RYK, Chen Y, Tang J (2007). A quality-engineering-based approach for conceptual product design. Advanced Manufacturing Technol. 32: 1064-1073.
Hambali A, Sapuan SM, Ismail N (2007). Evaluation of design concepts at conceptual Design stage using Analytical Hierarchy Process, Product & Design 2007 Conference on Design, Simulation, Product Development and Optimization. Penang, Malaysia.
Haque E, Bassett W, Lewis TF (2001). -section automotive bumper formal from mineral-filled gas mat thermoplastic (GMT). US Patent: US 6286879 B1.
Hosseinzadeh R, Shokrieh MM, Lessard LB (2005). Parametric study of automotive composite bumper beams subjected to low-velocity impacts. Composite Structures. 68: 419-427.
Hsiao SW (1998). Fuzzy logic based decision model for product design. Industrial Ergonomics 21: 103-116.
Hsu W, Woon IMY (1998). Current research in the conceptual design of mechanical products. Computer-Aided Design. 30: 377-389.
Huthwaite B (1989). Manufacturing competitiveness and quality by design. In: Proceeding of the 4th International Conference Product Design for Manufacture and assembly. 5-6 June, Stockholm, Sweden.
Jacob GC, Fellers JF, Simunovic S, Stabuck JM (2002). Energy absorption in polymer composites for automotive crashworthiness. Composite Materials. 36: 813-850.
Katsutoshi T, Mitsutoshi K (2007). Vehicle bumper beam and process of manufacturing the bumper beam.http://www.freepatentsonline.com-/EP1749702.html.
Kelman J, Nelson GV (1998). Composite motor vehicle bumper beam. United States Patent: Patent No. 5804511.
Kota S, Lee CL (1993). General framework for configuration design: Part 1– methodology. Engineering Design 4: 277-294.
Lee KH, Bang KI (2006). Robust design of an automobile front bumper using design of experiments, Proc. IMechE Part D. Automobile Engineering. 220: 1199-1207.
Lin YJ, Huang CW, Tseng JC, Shiau JY (2004). Issue resolution for conceptual design using AHP. In Proceedings of SPIE-Volume 5605,Intelligent Systems in Design and Manufacturing. 25-26 October 2004. Philadelphia, USA.
Ozer M (2005). Factors which influence decision making in new product evaluation. European J. Operational Res. 63: 784–801.
Pahl G, Beitz W, Feldhusen J, Grote KH (2007). Engineering Design: A Systematic Approach, Berlin: Springer.
Pugh S (1991). Total Design: Integrated Methods for Successful Product Engineering. Wokingham, England: Addison Wesley Limited.
Rehman F, Yan XT (2003). Product Design Elements as Means to Realise Functions in Mechanical Conceptual Design. In Proceeding of International Conference on Engineering Design ICED 03. 19-21 August, 2003. Stockholm, Swedan.
Rush KC (1990). An overview of Automotive Plastic bumpers, In Automotive Bumper system and exterior Panels. SAE Technical Paper 900420.
Saaty LT, Vargas LG (2001). Models, methods, concepts and applications of the analytical hierarchy process. Boston: Kluwer Academic Publishers.
Saaty TL (1980). The Analytical Hierarchy Process. New York: McGraw Hill.
Salonen M, Perttula M (2005). Utilization of concept selection methods – a survey of Finnish industry. In Proceeding of Engineering Technical Conferences and Computers and Information in Engineering Conference. 24-28 September, 2005. Long Beach, California, USA.
Sapuan SM (2005). Concurrent design and manufacturing process of automotive composite components. Assembly Automation 25: 146-152.
Sapuan SM, Suddin N, Maleque MA (2002). A critical review of polymer-based composite automotive bumper system. Polymers and Polymer Composite. 10: 627-636.
Sharpe N, Vendrig R, Houtzager K (2001). Improved Design for Frontal Protection. www.madymo.co.kr/data/improved_design_for_frontal_protection.pdf.
Steward RL, Osterman AJ, Jalbert DW (1992). Vehicle and bumper beam combination. US Patent: US 5080412.
Steward RL, Osterman AJ, Jalbert DW, Nulty JD (1994). Vehicle and bumper beam combination. US Patent: US 5340178.
Suddin MN, Din AT, Abdullah MF, Shamsudin SA (2007). Conceptual design of automotive bumper beam. Proceedings of the Conference on design, simulation, product development and optimization, 10-11 December, Penang, Malaysia.
Sullivan AR (2006). Automotive Carbon Fiber: Opportunities and Challenges. (Overview), 2006 November. pp. 77-79.
Ullman DG (1992). The Mechanical Design Process. New York: McGraw-Hill.
Ullman DG (2002). The Mechanical Design Process. New York: McGraw-Hill Professional
Xiao A, Park SS, Freiheit T (2007). A comparison of concept selection in concept scoring and axiomatic design methods. http://cden2007.eng .umanitoba.ca/resources/papers/69.pdf. Accessed on 22 Mac 2008.
Xu L, Li Z, Shancang L, Fengming T (2007). A decision support system for product design in concurrent engineering. Decision Support Systems. 42: 2029- 2042.
Yang CQ, Lin TS (1997). Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. Advanced Manufacturing Technology. 13: 618-629.
Yim HJ, Kim MS, Park J, Heo SJ (2005). Shape Optimization of Bumper Beam Cross Section for Low Speed Crash, Society of Automotive Engineers, Inc. SAE Technical paper 2005-01-0880.
Zavbi R, Duhovnik J (1996). The analytic hierarchy process and functional appropriateness of components of technical systems. Engineering Design 7: 313-327.
Zhang C, Jiang Z, Lu D, Ren T (2006). 3D MEMS design method via Solidworks. In Procedding of the 1st IEEE international conference on Nano/Mirco engineered and molecular systems. Zhuhai, China. pp. 18-21.