Concurrent Engineering for **Composites**

PROFESSOR IR DR. MOHD SAPUAN SALIT

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Contents

ABSTRACT

Customers want products that can satisfy their needs and product developers produce products to satisfy those needs while maintaining technical standards at reasonable cost. The balance between these two factors will ensure the success of the product developer and the satisfaction of the users. Concurrent engineering (CE) entails simultaneous consideration of life cycle issues from design brief to disposal, involving all functions within or outside the organization, including engineering designers, sales and marketing personnel, materials engineers, manufacturing engineers and suppliers. In this lecture, concurrent engineering philosophy is applied to composite material. The work involves total design, conceptual design, integration of IT tools, team-work and material selection, using conventional fibre and natural fibre composites. This lecture will begin with a definition of the various terms related to the topic, such as, concurrent engineering, composite materials and product design and development. Selected works on concurrent engineering for composites are reviewed and studies on materials selection systems used in the selection of polymer composites for engineering products are discussed. Further, reviews of conceptual design techniques in the development of composite products are presented. An important issue in composite development, i.e. manufacturing is also studied by looking at two important topics - mould flow analysis and the manufacturing process. Finally a new topic called “design for sustainability” is studied in detail, focussing on the development of ‘green’ products using natural fibre composites.

INTRODUCTION

Composite materials research is carried out widely by researchers worldwide. Composites have become very important materials due to the advantages they offer which individual constituent materials (matrix and fibre) do not possess. These advantages include high specific strength and stiffness, being aesthetically pleasing, corrosion resistance qualities, part integration and being lightweight. Composite materials research is normally carried out in isolation; i.e. the concurrent engineering aspect of composites is normally not taken into consideration. This lecture deals with the development of composite materials from the concurrent engineering point of view. Concurrent engineering (CE) for composites is a unique research field where design and manufacture are considered early in the design process during the composite component development stage. In fact, composite manufacturing itself is CE, because the manufacturing process and design of composites are carried out simultaneously. When a designer creates designs of a component made from composites, the design is governed mostly by the materials, and materials design cannot be carried out without considering the manufacturing process.

CONCURRENT ENGINEERING

In the past, product development was regarded as a process where the design engineer designed a product to satisfy the customers' needs and design was carried out in the design office without coordination with other functions from within or outside the organization. There was lack of emphasis on integration of functions, team work, integration of tools and communication. Once the design was complete, the design was handed over to manufacturing related functions. This created a syndrome called 'throw over the wall' and the full benefits from improvements in quality, time and cost (QTC) (Sapuan et al., 2006a) were not fully capitalized (Figure 1 (a)). By employing concurrent engineering, the departmental barrier, whether physical or virtual, is removed and the product development team can function as an effective team to produce high quality products (Figure 1 (b)).

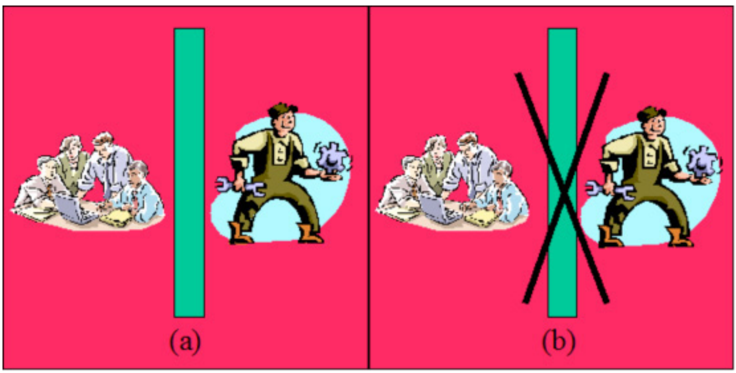


Figure 1 (a) Sequential engineering (b) Concurrent engineering

Concurrent Engineering Aliases

Concurrent engineering is also known as design for manufacture (DFM), design for manufacturability (DFM), design for manufacturing (DFM), design for assembly (DFA), design for quality, concurrent product development (CPD), parallel engineering, concurrent product and process design, integrated product and process development, multi-disciplinary team approach, design to cost (DTC), design for recyclability (DFR), design for the environment (DFE), design for test, design for sustainability, design fusion, concurrent/integrated engineering (CIE), synchronised engineering, integrated product development (IPD), simultaneous engineering (SE), design for 'X' (DFX) and design for 'X'ability.

In design for 'X', 'X' is referred to as different attributes such as assembly, environment and safety. The main essence of CE is to consider the manufacturing issue early in the design process.

Concurrent Engineering Definition

CE can be implemented well if it utilizes various tools and techniques such as quality function deployment (QFD), failure mode and effect analysis (FMEA), design for manufacture (DFM) and design for assembly (DFA). Further, CE requires the strong support of computer systems and involvement of all departments within a company and the spirit of team-work. The term concurrent engineering was coined by the Institute for Defence Analyses (IDA) (!986) Report R-338 and is defined as:

> *A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirement.*

Definitions of Product Design and Development

It is appropriate to examine some definitions of several other key terms used in this lecture.

A *product* is defined, in the *American-Heritage* dictionary, as 'something that is produced naturally or by human effort'. *Design* is defined by Sapuan et al. (2000) as the creation of a component, artefact, mechanical system, device, electronic circuit, software program or engineering process that meets a set of desired specifications. *Development* is defined by Nuese (1995) as the systematic application of advanced knowledge or technology toward the production of useful materials, devices, systems or methods.

Product design can be defined as a systematic process that involves idea or concept generation, concept development and evaluation, manufacturing and testing or implementation of an artefact or service. The scope of product design goes beyond industrial design. Industrial design is more concerned with the ‘art’ of a product such as aesthetics, form, colour, texture and feel. Product design is regarded as a blend of marketing, product management, industrial design and engineering. Mazumdar (2002) defined *product development* as:

> *A process for translating customer needs into product design and manufacturing which involves managing mutual dependencies between all stages of the product life cycle, including design, manufacturing, distribution, technical support, and disposal or recycle stages.*

Product Design and Concurrent Engineering

Product design is concerned with the definition of products that will be commercially successful. Products are any combination of components that together provide the functionality required by the customer. A commercially successful product can simply be defined as one that makes an acceptable level of profit for the company. Product design should consider both the mechanical as well as industrial design aspects in order that the product be well accepted by the consumers. The development in materials goes hand in hand with improvements in manufacturing technology. Developments in materials as well as in product design have been assisted by respected management techniques, notably CE, as has been expounded in detail earlier.

CE is regarded as an umbrella for a good product development process. In fact, product development is a key process in concurrent engineering. Producing a product within the time frame agreed between all the stakeholders involved, such as manufacturers and suppliers, is the important selling point of CE. It can rightly be claimed that CE is focussed on milestones rather than the conventional focus on process.

Product development is a practical task that requires the full-hearted involvement of a product development team to develop a product right from a very vague design brief or customer need through to specifications up to the fabrication of a working prototype. It is in fact, a process of translating the needs of the users into product through product design and manufacture. In CE, product development means integration of the various functions within and outside the organization, such as, engineering designers, manufacturing engineers, suppliers, technical support personnel, and administrative and sale personnel. It ensures good communication among them through advanced technology and IT tools and through regular meetings. Product development is not only about looking after the product until it is ready to be marketed but also includes other after sale issues such as warranty, disposal, maintenance and recycling.

Many models on product development and design have been proposed and reported in published literature. The main core activities in a typical design process model include conceptual design, embodiment design and detail design. Ashby and Johnson (2002) suggest that inputs or major contributing factors to this design process (concept, embodiment and detail design) include the market, science and technology, sustainability and environment, economics and investment climate, and aesthetics and industrial design. The task of carrying out product design is the work of a professional called a designer. The designer is also referred to as a design engineer, engineering designer or design and development engineer (Haik, 2003). In CE, the engineering designer cannot work in isolation, but has to work in collaboration with other personnel from within and outside the organization, as strongly preached by CE experts. Through the implementation of CE during the product development process, many design problems can be solved at an early stage in the design process (Sapuan et al., 2000).

During the conceptual design stage the amount of resources required is less as compared to that required at the manufacturing stage. This implies that it is still very economical to make changes in design during this stage. Hence CE promotes cost reduction by engaging other personnel early in the design process, whereby any changes made at this stage is very desirable. In achieving this, a well-accepted design model comprising conceptual, embodiment and detail design is normally used (Pahl et al., 2007). The design inputs to this model include solid modelling and finite element modelling. The materials selection should go hand in hand with accomplishing the design input activities in order that the materials are considered from the very early stage of design process as depicted in Figure 2.

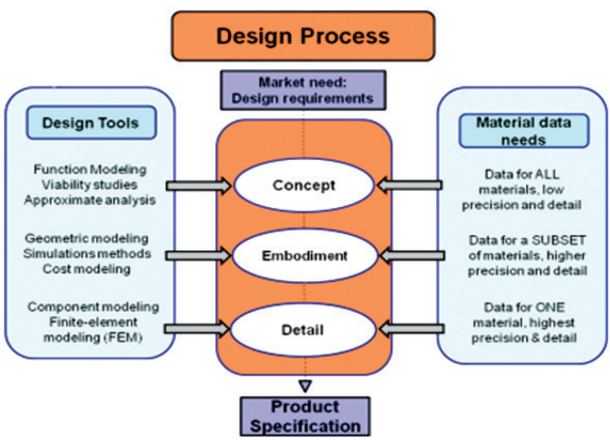


Figure 2 The design process showing how the breath and the materials data required at each stage differed greatly (Ashby, 2005)

COMPOSITES

A composite material has a chemically distinct phase distributed within a continuous phase (Sapuan et al., 2006b). The matrix is the continuous phase, normally thermoplastic or thermosetting polymers, but could be ceramic or metal, while the distributed phase is called the reinforcement. This can be in the form of particles, short fibres, continuous fibres or laminate. Reinforcement materials are normally glass, carbon and Kevlar fibres but natural fibres now play a major role as potential replacements. In selecting composite constituents, their synthesis and chemical composition and the mechanical properties of the composite are important in determining the performance of the composite. An infinite number of combinations of matrices, fibres, fibre arrangement and manufacturing processes are possible and therefore, selection of composite materials can be very complicated. For example, consider the case of natural fibre composites. Here the fibres may be taken from various plants such as oil palm, jute, sisal, sugar palm, hemp, kenaf, pineapple leaf, banana pseudo-stem, coir, rice husk, wood, bamboo, abaca, henequen, sugarcane bagasse and coir (coconut husk), or even from animal products such as shells, skins and feathers. The fibres could be arranged in a variety of ways: unidirectional, bi-directional, multi-directional, randomly distributed short or continuous fibres or used in the form of fillers. The choice of matrix is extensive, covering a range of thermoplastics and thermosetting polymers.

Composite materials are formed by combining two or more materials, which, taken individually, have quite different properties from the composites. Composite materials have been applied in various industrial applications such as automotive, aerospace, civil, marine, etc. Recently, the use of composites has rapidly increased due to improved awareness regarding product performance and increased competition in the global market for lightweight components. Figure 3 shows the development of materials over time whereby composite materials have become the main contenders in recent years.

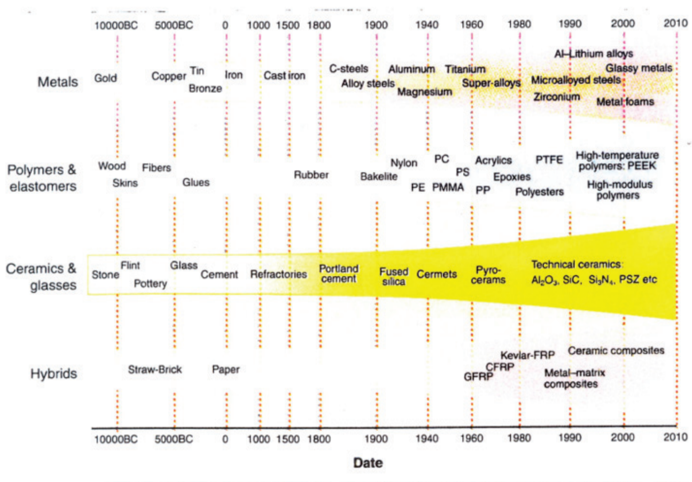


Figure 3 The development of materials over time (the emergence of advanced composite materials) (Adapted from Ashby et al., 2007)

CONCURRENT ENGINEERING FOR COMPOSITES

In realizing a new product, design is considered in total, i.e. from customer needs, product design specification (PDS), concept generation, detail design to manufacture. During detail design stage, activities can broadly be divided into two categories, namely, component design and process design. The link between these two categories is an important element of concurrent engineering (Strong, 2006). Examples of component design given by Strong (2006) include layout/drawing, constraints, analysis and material selection, while examples of process design include manufacturing method selection, sequencing, machine/tool selection, system layout, integration of system and manufacturing procedures. However, Pugh (1991), did not fully share this view. According to Pugh (1991), concurrent engineering is not only relevant during the detail design stage but it is also applicable during other stages of the total design process such as market investigation, product design specification and conceptual design.

Whether component design is in conceptual design, PDS, market investigation and detail design stages as stated by Pugh (1991) or only at detail design stage as stated by Strong (2006), both require simultaneous consideration of the manufacturing process at the product design stage. According to Strong (2006), concurrent engineering requires that while designing a component the designer must consider the manufacturing process in order that the component is designed to be compatible with the manufacturing method. For example, if the component is to be manufactured using the hand lay-up process, the designer would want to include design features that facilitate ease of fabrication to reduce fabrication complexity because labour cost is a key cost element in the hand lay up process. Figure 4 shows selected activities within the CE environment as reported in Sapuan (2001). It is sometimes called ‘CE wheel’ and it is hoped that its successful implementation will lead to a ‘wheel of fortune’.

Review

Imihezhi (2005) has successfully performed component design and process of the automotive composite clutch pedal. She carried out simulation and analysis work to study the effects of increasing the number of gates for a clutch pedal made from short glass fibre reinforced polyamide composites. The study compared the effects of a single gated and double gated mould. Two software packages were used in the study i.e. the Moldflow Plastic Insight (MPI), a mould flow analysis software, and LUSAS, a finite element analysis software. The former was used to investigate the effects of mould design on fill time, pressure, temperature, weld line, air traps and fibre orientation and distribution in the injection moulding process. The latter was used to analyse stress distribution for pedal profiles and rib patterns. A prototype of the composite clutch pedal model was then fabricated and compared with the simulation works.

Hambali (2009) carried out the research work, which considers and determines the most optimum decisions on design concept, material and manufacturing processes for an automotive composite bumper beam. He proposed selection frameworks using the analytical hierarchy process (AHP) under the concurrent engineering environment. Eight new design concepts of the automotive composite bumper beam were generated. Various parameters or criteria that were normally used to manufacture automotive composite bumper beams were considered in generating design alternatives. To determine the most optimum decisions on design concepts, materials and manufacturing processes for the automotive composite bumper beam, an analytical hierarchy process, utilizing the Expert Choice software, was used. The study revealed that it is important to address various design tools and consider the most optimum decisions on design concept, material and manufacturing process at the conceptual design stage under the concurrent engineering environment.

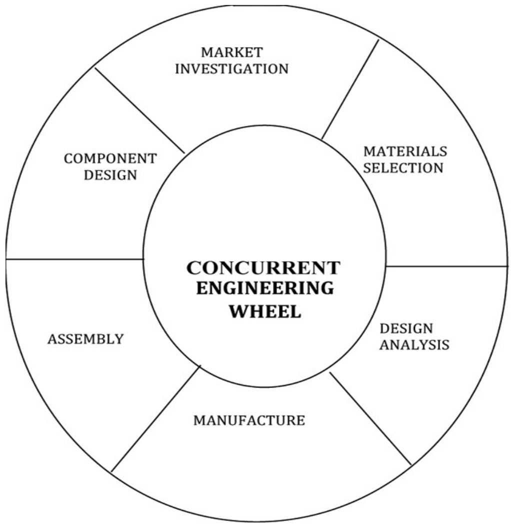


Figure 4 Concurrent engineering 'wheel': if properly implemented can turn into a 'wheel of fortune' (Sapuan, 2001)

Sapuan (1998) carried out research work on the development of a system for concurrent engineering of polymeric composites for the automotive pedal box. The system was designed in such a way that it enabled designers to identify the materials that satisfied a set of predefined design constraints in terms of weight and cost reductions. The system comprised an integrated knowledge based system, solid modelling system, materials database and design analysis tools. The development of such a system ensured the success of the use of polymer composites for a pedal box system in terms of reducing the number of parts, weight, processing and assembly time and cost while at the same time improving quality and design flexibility. The work was extended to more manufacturing related processes such as mould flow analysis, rapid prototyping and component fabrication (Sapuan, 2003).

According to Murphy (1994) CE is possible with the use of various IT tools in the design process of polymer composites performed by the design team, mould maker, and processor. They are all linked electronically, so that they can all make contributions throughout the progress of the project. Quinn (1995) presented an approach in the design of composite components, i.e. by using the principle of design process similar to the non-concurrent engineering approach except that in his approach the geometry or shape is designed concurrently with materials selection. Materials selection is highly dependent on the manufacturing process adopted.

Jones (1995) used concurrent engineering techniques in the development of a complex high performance polymer composite component using resin transfer moulding (RTM). Design of components, preform and tooling were performed concurrently by means of modelling, using as much common geometry and material data sets as possible. Extensive use of IT tools such as expert systems, computer aided design (CAD) and finite element analysis was reported.

Kim et al. (2000) reported that their work called Concurrent Engineering Systems for Composite Design (CESCD) and concurrent engineering is purely through integration of various software tools such as the expert system and finite element analysis. The system was divided into several modules such as design and analysis using FEA and buckling and post-buckling analysis, thermo-elastic analysis and optimum design using an expert system. A graphic based design environment with multi-tasking and graphical user interface features was utilised for the purpose of managing and integrating the FEA and expert system software.

Mayer (1993) reported that CE is important in the design of polymer composites and emphasized that the properties of composites can only be fully realized during manufacture. The composite product is tailor made, and product design, materials selection and manufacturing process are considered during the early stage of the design process.

The following sections discuss selected works on CE for composites based on the activities proposed by Sapuan (2001).

MATERIALS SELECTION

As stated by Strong (2006), material selection is one of the activities during the component design stage. As many detailed studies have been conducted on material selection, a special section is devoted to this subject.

Design is the process of translating a new idea or a market need into detailed information from which a product can be manufactured. One of the design activities is the selection of materials. Selecting the best materials for a component is not an easy task because various criteria that influence the selection need to be considered. Ashby (2005) reported that the main issue in materials selection is the connection between the various important aspects of a product such as process, material, function and shape, and this is particularly true for mechanical design. Materials selection is an activity normally carried out by the materials or design engineer.

Gutteridge and Waterman (1986) described the objective of material selection as the identification of materials which, after appropriate manufacturing operations, will give the dimensions, shape and properties necessary for the end-product so that it will perform its required function at the lowest total cost. Typically, for most designers the material selection process begins by generally reviewing the material data sheets provided by the material supplier. A misinterpretation of the data sheets is one of the most common reasons for selecting and specifying the wrong material for a given application. Incorrectly chosen material can lead not only to failure of the component but also to unnecessary life-cycle cost. Poorly chosen material can add to manufacturing cost and unnecessarily increase the cost of the component. Hence, a proper materials selection system is needed to identify the most optimum materials for a particular product. The caricature in Figure 5 depicts the problems that may arise in an organization as a result of improper materials selection.

Concurrent engineering for composite materials considers material selection as the main activity because in composite design, the design of product, process and material selection have to be carried out at a very early stage of the design process. An integral part of design for manufacture or concurrent engineering is the systematic early selection of material and process combination for the manufacture of parts, which can then be ranked according to various criteria.

The Kingdom of materials can be divided into families, classes, sub-classes and members as described by Ashby (2005). For the family of composite materials, classes, sub-classes and members can be obtained. Selection of the right material can make or otherwise break the design. As the product becomes very complex, the selection of materials becomes more difficult to perform and design engineers have to study many functional and economic requirements before arriving at the decision to choose a particular material. Materials selection is an interrelated activity that requires knowledge of various fields such as layout and form design, safety, ergonomics, production, quality control, assembly, transport, operation, maintenance, costs, scheduling and recycling (Pahl et al., 2007).

Figure 5 Caricature describing the importance of material selection in product design

In the selection of materials, inputs from engineering analysis and synthesis are very important and must go hand in hand with industrial design aspects (Ashby and Johnson, 2002). Many computer-based materials selection systems are available to assist the designer in the selection of the most optimum materials. Materials selection of composite materials, compared to homogenous materials like metals and plastics, is quite difficult to perform due to the anisotropic nature of the materials that are required to be tailor made with due consideration of products and materials.

Ermolaeva et al. (2004) developed an optimisation system for material selection of some engineering materials, including natural fibre composites. Kim et al. (2000) have developed concurrent engineering for composite structures by starting from material selection. In their material selection module, some adequate materials are selected by appointing fibre and matrix types along the design objectives. In their material selection module, Kim et al. (2000) studied composite structure based on a laminated composite approach where ply angles, stacking sequence, properties of lamina and laminate and rule of mixture are considered. It is not certain whether the approach can be adapted to short fibre composites in complex components like automotive components where majority of manufacturing processes involve injection moulding, compression moulding and RTM.

It is stated in Mayer (1993) that there are three ways of incorporating fibre into a matrix based on different manufacturing technology:

1. fibre and matrix are acquired separately and the user has the choice to make composite materials through the fabrication process.
2. semi cured moulding compound with exact mixture fibre, matrix, filler and additives are ready for fabrication. These intermediate materials, such as, sheet moulding compounds (SMC), glass mat thermoplastic (GMT) and prepreg, are obtainable from material suppliers. The user has little choice in the preparation of the composites.
3. Finished products ready to be made into components like pultruded section and filament wound pipe.

In the author's opinion, many material selection systems, including that of Kim et al. (2000), have been developed for the case (1) above, but there is still a lot of scope for research for cases (2) and (3).

Materials Selection Strategy

Ashby (2005) has enumerated four steps in the selection of materials from the broad spectrum of materials to a final material where the essential steps are: (1) translating design requirements by expressing them in terms of objectives, constraints, free variables and function; (2) screening the materials using constraints or in other words removing the materials that do not satisfy the constraints; (3) ranking the materials using objectives by finding the screen materials that can perform the task best; and finally (4) obtaining supporting information by studying in detail the family history of the optimum materials. Figure 6 shows the function of materials and processes in product design (Ashby et al., 2007).

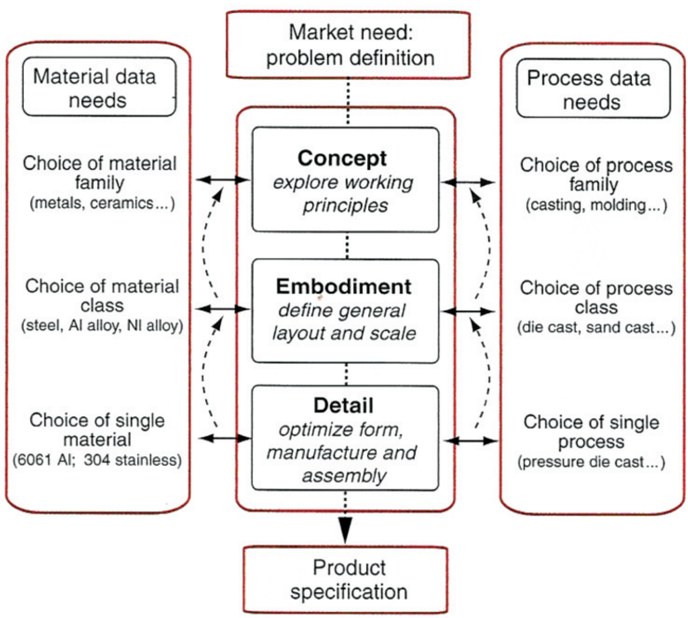


Figure 6 Function of materials and processes in product design (Ashby et al., 2007)

In CE of composites, material selection is considered a very important activity. In the CE design environment, IT tools are integrated and various activities of composite development are stored in a computer in different modules. For instance, in the work of Kim et al. (2000), various modules of activities are stored together in a computer i.e. activity like materials selection is located in one module, design analysis with FEA is stored in another module and so on.

Selecting the right composite material for a product is a difficult task due to the many factors that have to be considered in ensuring that the selected composite material can produce a component with the desired performance, quality and cost. Since the composite material can be a combination of various kinds of fibers and matrices, the selection of suitable composite materials for a product becomes a difficult task for inexperienced designers. Thus, various material selection tools or methods have been developed to assist materials and design engineers (Sapuan et al., 2009a) to select the right composite materials for a product.

Without a systematic materials selection system, it is difficult to carry out a proper product design process. Composite materials selection is difficult to perform because this class of material is very dynamic in nature. Its technology keeps on expanding every day. Its family is also huge due to, in principle, the infinite possible combinations of fibre and matrix types, fibre arrangement and manufacturing processes.

There is no standard tool or techniques used by the materials and design engineers to select a right material for an application. Sometimes, materials and design engineers depend on the materials that they are familiar with. However, when design requirements exceed the constraints of such materials or exceed the constraints on material properties, designers must consider alternative materials.

The task of materials and design engineers is to determine the optimum material for a product by utilizing a materials selection tool, which can reduce the cost of manufacturing and improve product performance. Thus, various tools have been developed to assist designers in selecting the most suitable material for a product such as the knowledge-based system, neural network and analytical hierarchy process.

Knowledge-based System

The expert system or knowledge-based system is an intelligent computer system that uses knowledge and inference procedures to solve problems, which are so difficult as to require significant human expertise for their solution (Hunt, 1986). Application of a knowledge-based system in materials selection is quite obvious. The knowledge-based system is most often used in the context of a system which gives advice; where some representative examples include the work of Sapuan (1998) and Sapuan and Abdalla (1998) where they developed an expert system for material selection for polymeric-based composite automotive components. Knowledge-based systems can capture the knowledge of experts that may otherwise be lost through death or retirement. They can contain the cumulative knowledge of several experts, and are available any time day or night, and can be distributed widely throughout and organisation (Dieter, 2000). However, the knowledge-based system suffers from some disadvantages such as unclear relations between rules, ineffective search strategy, complexity and being difficult to learn (Sapuan, 2005).

In a knowledge-based system (KBS) a series of rules are used to select materials. A KBS has the ability to select the most suitable material and can rank the materials according to its properties (Sapuan et al., 2002). Sapuan (2001) has reviewed various KBSs for materials selection in mechanical engineering design. The work carried out by Sapuan (1998) and Sapuan and Abdalla (1998) involved the use of KBS for composite material selection. The selection of suitable materials for an automotive pedal box system was the main emphasis in this research work. Figure 7 shows the general architecture of the research work.

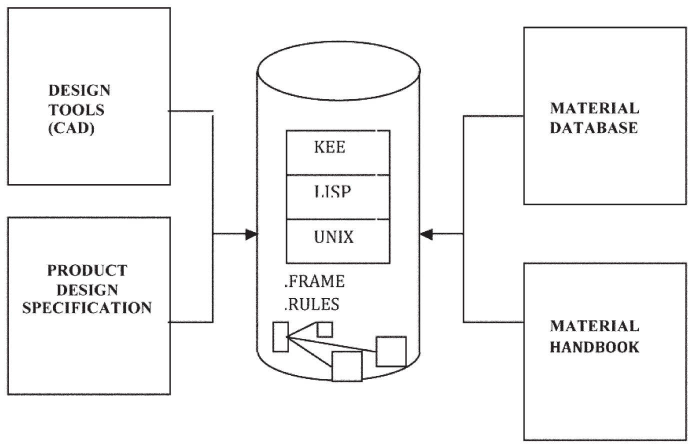


Figure 7 General structure of KBS of material selection (Sapuan and Abdalla, 1998)

The KBS enables users to select suitable materials that satisfy all pre-defined criteria and constraints. A material must satisfy all the constraints in order to become a suitable candidate for a particular component. In the work of Sapuan (1998) and Sapuan and Abdalla (1998), reasoning was carried out via decision rules whereby the rule-based system is the major tool in the material selection process. The system was used to select suitable materials for the polymeric composite automotive pedal box system (See Figure 8).

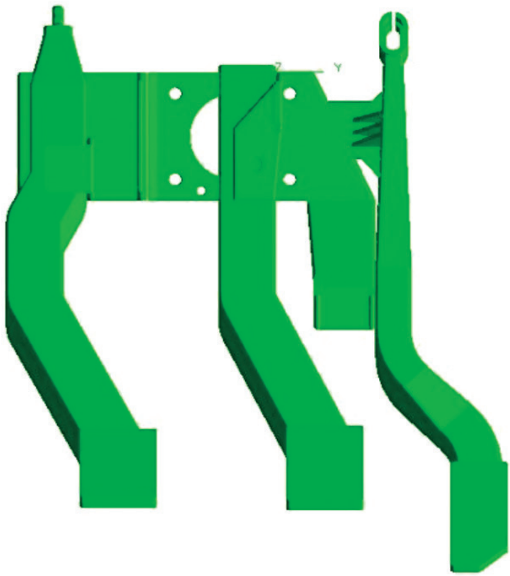


Figure 8 3D solid model for polymeric composite pedal box system

The rules are chained using forward chaining and the candidates for the component, are proposed. When the conditions of a rule are satisfied then the conditions are valid. The rule is in the form of: *If* (condition) *Then* (conclusion). If the conclusion of a rule is satisfied, then the conclusion of the rule is set as the result. This prototype was developed using the KEE tool-kit and the selection was carried out using rule base: If, Then, Else. For example, the selection of material for the accelerator pedal can be defined through the following rules:

If

(the corrosion resistance of this material is high) and
(the water absorption of this material is low) and
(the cost of this material is low) and

(the dimensional stability of this material is good) and
(the modulus of elasticity of this material is high) and
(the yield stress of this material is high) and
(the density of this material is low) and
Then
(this material is a candidate for the accelerator pedal)

The knowledge-based system also contained a frame-based system which acts as a database for material properties and manufacturing process capability. A number of constraints in the material selection are represented inside the expert system using the rules in KEE. In this context material property criteria have been utilized as rules to approve constraints. Using the material properties' rules, the designer can examine whether or not the proposed materials are suitable candidates using a particular component. For instance, if the designer specifies the material with specific modulus of elasticity (E_m), in a frame-based system hierarchical graph, the system will compare this modulus of elasticity with the predefined modulus of elasticity limit:

$$E_m < E_{max}$$

Warning is given in the case of inconsistency or an invalid parameter using the constraint violation facility in KEE. Consequently, the material with this modulus of elasticity is singled out.

The work was extended to the selection of ceramic matrix composites for automotive engine components using the KBS tool kit, Kappa-PC (Sapuan et al., 2002). The selectioncriteria were based on pre-defined constraint values such as mechanical and physical properties.

Neural Networks

Today, neural networks (NN) or artificial neural networks (ANN) are used to solve a wide variety of complex scientific and engineering problems including materials selection. In fact, a neural network is a powerful mathematical tool for modeling material properties. A neural network is defined as a massive parallel-distributed processor made up of simple processing units, which has a natural propensity for storing experiential knowledge and making it available for use. It resembles the brain in two respects: i) knowledge is acquired by the network, from its environment, through a learning process, and ii) inter-neuron connection strengths, known as synaptic weights, are used to store the acquired knowledge (Aleksander and Morton, 1990).

Many studies have been carried out by researchers in solving composite material problems in the literature. Zhang and Friedrich (2003) reviewed the use of neural networks in the field of polymeric composite property prediction and design. Various principles of the neural network approach for predicting certain properties of polymer composite materials such as fatigue life, wear performance, response under combined loading situation, and dynamic mechanical properties were discussed. Bezerra et al. (2007) used neural networks to predict the shear stress–strain behavior from carbon fiber/epoxy and glass fiber/epoxy composites. Jiang et al. (2007) employed an artificial neural network technique to predict the wear properties of polymer-matrix composites; and Yang et al. (2003) proposed a genetically optimized neural network system to assist the decision maker in dealing with the composite material selection and operating conditions problem.

Case study

(This section is reproduced from Chapter 12 of a book edited by Sapuan and Mujtaba (2010) with permission from CRC Press, Boca Raton).

The book dealt with the topic of neural network application in polymer composites which gathered expertise from USA, Australia, UK, Italy, Brazil and some other Asian countries (Sapuan and Mujtaba, 2010). In the final chapter of the book, Sapuan and Mujtaba (2010), presented work on the development of a prototype computational framework for selection of natural fibre reinforced polymer composite materials using the neural network. Figure 9 shows the structure of the material selection system using ANN.

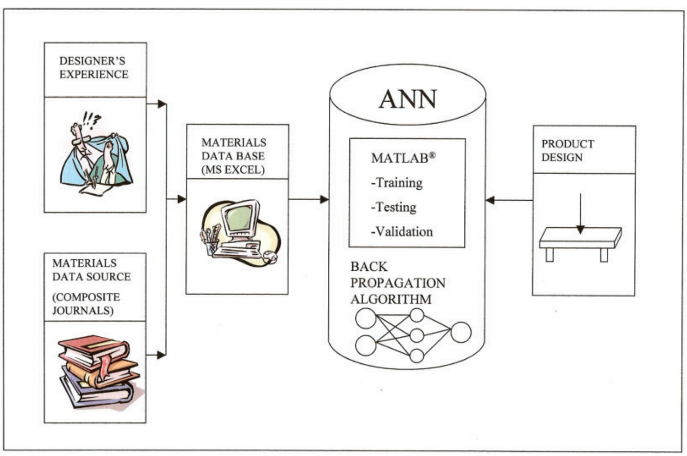


Figure 9 Structure of natural fibre reinforced composite material selection system

For the purpose of this research, the data were gathered from previous published work of the author and his co-workers carried out at Universiti Putra Malaysia. In addition, data from various journal papers were also collated in order to enrich the database. A total of 121 datasets were gathered, which represent 121 different types of natural fibre composites (different combination of fibre weight, treatment method, fibre types and other parameters) for optimum neural network construction. For each material, the properties included in datasets selected were tensile strength, tensile modulus and flexural strength and the total datasets (S) are represented as:

$$S = [\,(I^{(i)}, O^{(i)}) \mid i = 1, \ldots P\,] \qquad (1)$$

P is the maximum number of datasets. The datasets were divided into training datasets (R), testing datasets (T) and validation datasets (V).

The training datasets are:

$$R = [\,(I^{(i)}, O^{(i)}) \mid i = 1, \ldots M] \qquad (2)$$

M is the maximum number of training datasets.

The testing datasets are:

$$T = [(I^{(i)}, O^{(i)}) \mid i = M{+}1, \ldots N] \qquad (3)$$

N is the maximum number of testing datasets.

The validation datasets are:

$$V = [(I^{(i)}, O^{(i)}) \mid i = N{+}1, \ldots P] \qquad (4)$$

where $I^{(i)}$ is the ith input parameter and $O^{(i)}$ is the ith output parameter.

In this study, approximately 50% of the total datasets are training datasets (M = 61 datasets), 30% for testing (N - M = 30 datasets) and 30% for validation (P - N = 30 datasets).

There are various challenges in obtaining comparable data of natural fibre composites such as:

1. Problems in obtaining complete sets of data on tensile strength, tensile modulus and flexural strength (many papers were excluded due to incomplete sets of data).
2. Fibre fractions were given both in weight and volume and it is not very clear whether the researchers were consistent in their definitions.
3. Insufficient information given in the papers such as no mention of fibre fraction, the length of fibre (for short fibre) etc.

As a result, big variations in data was observed, for instance the minimum value of tensile modulus in coir/polypropylene composite was 337 MPa and in jute/polypropylene composite it was 11590 MPa and this caused the distribution to be biased towards the lower end value of the data. To minimize these variations as much possible, data were taken from previous works of the author.

The datasets (inputs and output) were stored in MS Excel software format and were normalized in the range of –1 and +1 using the following formula to facilitate data training, testing and validation:

$$X_n = [2^* (X-X_{min}) / (X_{max} - X_{min})] - 1 \quad (5)$$

Where X_n is the normalized value of the parameters, and X_{max} – X_{min} are the minimum and maximum of variable X.

Material selection requirements

It was obvious from the earlier data collection section that strength and modulus are the two main properties considered in the materials selection process for structural components. In fact it is an established fact in materials selection that strength and stiffness are often referred to as the materials selection drivers (Sapuan and Abdalla, 1998). Tensile strength is normally regarded as a very important property attribute, but in the case of the component under study, i.e. horizontal shelf, where the load is mainly that of bending in nature, the flexural strength of the materials is more significant and hence will become the output in the study. In addition, only one output parameter is fixed in this study because, as reported in Zhang and Friedrich (2003), majority of the work on neural networks in composite materials have only one output and to be consistent with them, this norm is followed. In a situation where load is applied to the shelf, the shelf has to sustain the constant load applied for a prolonged period and in such situation creep failure is significant. The study should consider such potential failure.

The parameters consist of numerical data (tensile strength and modulus, and flexural strength) and qualitative data (aesthetics, manufacturability, availability and cost). In this study, there was difficulty in obtaining comparable creep data for all the materials and therefore it is not included in the materials selection system. All the input and output parameters are broadly divided into three main categories to satisfy the materials selection requirements, namely functional, manufacturing and economic considerations.

As far as manufacturing requirements are concerned, the aspect of manufacturability and aesthetics are selected. Manufacturability here is referred to as the ease of accomplishing a certain manufacturing process to produce a particular material. If the manufacturing process is the manual hand lay up process, the process is very easy to accomplish and the cost to produce the mould and sample is very low and hence, it is given high rating. As for the injection moulding process, the machinery is very costly and the process to produce the specimens is more complicated, and so the process is assigned lower rating based on a 5-point scale. Today, product design should consider both the engineering design aspect as well as industrial design aspect of a product. Issues like form, shape, colour, texture, ergonomics and aesthetics must also be given due attention. In line with this, the aesthetics of the product is selected as one of aspects considered in this study. It is categorised under manufacturing requirements because the aesthetics of a product is ensured during the manufacturing stage.

Under economic requirements, cost and availability are regarded as important. Direct material cost is very important in materials selection but up till today, there is no published work on cost comparison of natural fibre composites. Further, some of the materials can be obtained at no cost at all and they are regarded as agricultural waste. As a result, only related qualitative data can be provided. Availability can be regarded as indirect cost because, if the material is cheap but it is not available locally, the cost to import the material can be very high. Its being unavailable inhouse will result in high cost incurred. Once again actual data of such items is not available and only qualitative data can be provided.

First stage of material selection

The MATLAB® neural network toolbox was employed in the development of a material selection system for natural fibre reinforced polymer composites. Neural network modelling is a non-linear statistical analysis method that is in the form of a 'black box'. In this 'black box', input data and output data are connected by means of a set of non-linear functions. In this study, a fully connected four-layer (one input, two hidden and one output layers) feed-forward network with sigmoid transfer functions is employed as shown in Figure 10.

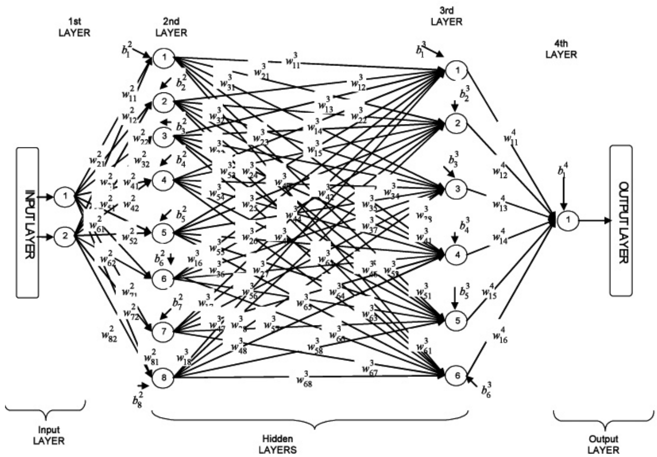


Figure 10 A typical structure of fully connected four-layer network

Data training

Before the neural network composite material selection system can be applied, the procedure for obtaining the neural network model, i.e. the forward model used in these strategies, are initially performed together as a method to train the system.

Forward Modelling

The procedure of training a neural network to represent the dynamics of the system is referred to as forward modelling. Forward modelling in this case refers to training the neural network model to predict the output of property at the next instant of time $(t+1)$. Data used for development of the model is shown in Table 1.

Table 1 Data used for development of the model (italic data denotes validation and bold data denotes test dataset)

Input1	Input2	output	prediction	Input1	Input2	output	prediction	Input1	Input2	output	prediction
19	370	1.67	23	350	2	20	291	34	38	600	69.5
21	365	1.73	27.5	325	2.05	25	3500	34	41.4	3751	72.6
26	*323*	*1.75*	*27*	*330*	*2.1*	*16*	*370*	*36*	*148*	*11450*	*73*
23	**332**	**1.77**	**24**	**337**	**2.13**	**30**	**4141**	**38**	**32**	**1081**	**73.3**
21.5	380	1.77	27	350	2.13	31	600	43	46	1890	74
20	375	1.78	27	328	2.15	126	7860	43	152	11590	74
22	*352*	*1.8*	*24*	*330*	*2.15*	*20*	*375*	*45*	*46*	*620*	*76*
20	**355**	**1.8**	**27**	**340**	**2.17**	**128**	**7920**	**47**	**30.8**	**1032**	**77.5**
21	365	1.8	30	322	2.25	39	1347	48	38	620	79
22	375	1.8	2	550	3	23	398	50	17	560	80
21.5	*363*	*1.82*	*7*	*175*	*10*	*26*	*556*	*50*	*35*	*2750*	*81*
22	**357**	**1.83**	**13.2**	**559**	**11.3**	**25**	**1400**	**51**	**172**	**12150**	**82**
24	340	1.85	12.9	1026	13.9	51	1443	53	52	1000	83
21	370	1.85	15.4	1379	17.6	52	6800	54	32.5	1153	83.3
22	*350*	*1.87*	*3*	*600*	*19*	*58*	*1597*	*56*	*44.3*	*1161*	*84*
24	**352**	**1.87**	**94**	**5250**	**19**	**27**	**2300**	**56**	**30.64**	**3657**	**85.3**
24	348	1.88	19.9	2356	21.8	142	8390	56	41.85	3772	90.7

26	332	1.9	101	5280	22	23	720	57	49.6	1196	92.6
24	*337*	*1.9*	*24.4*	*1483*	*23*	*37.6*	*3849*	*57.1*	*52.3*	*1220*	*93*
23	**338**	**1.9**	**22.8**	**1282**	**24.4**	**29**	**640**	**60**	**63**	**680**	**94**
25	345	1.9	21.2	2049	24.7	57	1601	62	49.9	3782	96.7
26	340	1.95	12	268	25	37.9	3869	64.4	72	2600	97
24	*368*	*1.96*	*14*	*976*	*26*	*30.5*	*1056*	*64.7*	*51.7*	*1255*	*108*
25	**360**	**1.97**	**33**	**5300**	**26**	**48.4**	**5250**	**64.9**	**56**	**1270**	**113**
22.5	350	1.98	22.7	2410	26.6	32	620	65.6	81	2750	131
22	358	1.98	10	1300	27	35	540	66.2			
27	322	1.99	23.1	2135	27.4	42.7	3247	66.5			
26	330	1.99	20.6	2400	27.7	30	2780	67			
25	342	1.99	114	5740	28	43	1664	67.7			
27	328	2	27	6800	28	39	660	68			
24.5	330	2	27.1	2711	32	40.7	3517	69.4			
22.5	348	2	6	197	34	36	550	69.5			

The correlation can be found by expanding the equation (equation 6) shown in Tanvir and Mujtaba (2006). Similar architecture of this work is shown in Figure 11. Figure 12 shows the MATLAB output graph for the dataset used.

$$a_1^4 = f_1^4\left(\sum_{k=1}^{4} w_{1k}^4 \times a_k^3 + b_1^4\right) \tag{6}$$

all the symbols shown here are similar to that of Tanvir and Mujtaba (2006).

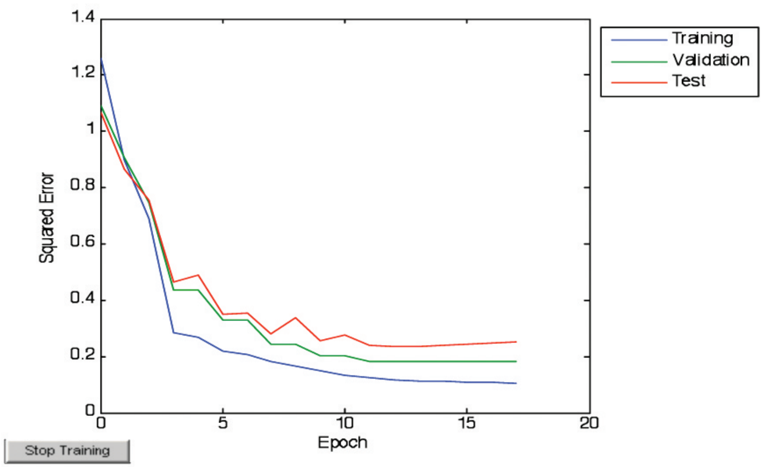


Figure 11 MATLAB training graph for the data used above

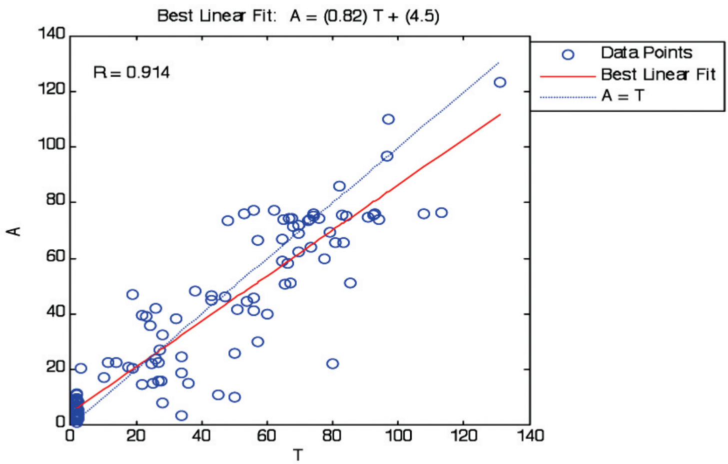


Figure 12 MATLAB output graph for the data set used

Table 2 shows the results of the predicted output data after ten sets of random data (designer's choice) are input into the correlation equation. The designer proposed a set of inputs and using the ANN and the output is predicted. In this first stage of selection, five materials with values of flexural strength very close to output predicted are selected as the candidate materials. In this study, the designer proposed 10 sets of input data. The results of materials selection based on all 10 predicted data outputs (5 materials for each output) are shown in Table 3.

For random inputs of 90 MPa and 7500 MPa tensile strength and tensile modulus respectively (random input dataset 1), the output (flexural strength) predicted from the correlation is 50.055 MPa, and five candidate materials ranging from 48 MPa to 53 MPa are selected. Next, the data for original tensile strength and tensile modulus are obtained for each material.

Table 4 shows the results of correlation between random data input and predicted output as well as the flexural strength of candidate materials and their corresponding tensile strength and tensile modulus.

Table 2 NN prediction for the input provided

Input1 (tensile strength, MPa)	**Input2 (tensile modulus, MPa)**	**Prediction (flexural modulus, MPa)**
90	7500	50.055
15	12,000	78.347
35	5700	30.349
50	1500	75.937
4	350	21.24
100	800	92.475
150	6000	16.513
18	390	13.896
20	3500	6.6588
77	3850	132.84

Table 3 Results of materials selection based on all 10 predicted data outputs (five materials for each output)

Output predicted (MPa)	**50.055**	**78.347**	**30.349**	**75.937**	**21.24**	**92.475**	**16.513**	**13.896**	**6.6588**	**132.84**
Material 1 (MPa)	51	77.5	28	73.3	19	92.6	19	10	2.25	108
Material 2 (MPa)	50	81	28	74	22	96.7	13.9	19	2.17	96.7
Material3 (MPa)	50	79	27.4	76	23	90.7	17.6	11.3	2.15	113
Material4 (MPa)	48	76	32	73	21.8	93	21.8	13.9	10	94
Material5 (MPa)	53	80	27.7	74	19	94	19	17.6	3	131

Table 4 Correlation between random data input and predicted output, flexural strength of candidate materials, and corresponding tensile strength and tensile modulus

Random Input Tensile Strength (MPa)	Random Input Tensile Modulus (MPa)	Predicted Flexural Strength (MPa)	Selected Flexural Strength (MPa)	Corresponding Tensile Strength (MPa)	Corresponding Tensile Modulus (MPa)
90	7500	50.055	51	25	1400
			50	26	556
			50	23	398
			48	39	1347
			53	51	1443
15	12,000	78.347	77.5	30.8	1032
			81	36	2057
			79	38	620
			76	46	620
			80	17	560
35	5700	30.349	28	27	6800
			28	114	5740
			27.4	23.1	2135
			32	27.1	2711
			27.7	20.6	2400
50	1500	75.937	73.3	32	1081
			74	46	1890
			76	46	620
			73	148	11,450
			74	152	11,590
4	350	21.24	19	94	5250

			22	101	5280
			23	24.4	1483
			21.8	19.9	2356
			19	3	600
100	800	92.475	92.6	49.6	1196
			96.7	49.9	3782
			90.7	41.85	3772
			93	52.3	1220
			94	63	680
150	6000	16.513	19	94	5250
			13.9	12.9	1026
			17.6	15.4	1379
			21.8	19.9	2356
			19	3	600
18	390	13.896	10	7	175
			19	94	5250
			11.3	13.2	559
			13.9	12.9	1026
			17.6	15.4	1379
20	3500	6.6588	2.25	30	322
			2.17	27	340
			2.15	24	330
			10	7	175
			3	2	550
77	3850	132.84	108	51.7	1255
			96.7	49.9	2782
			113	56	1270
			94	63	680
			131	81	2750

Second stage of selection

The second stage of selection is quite straightforward compared to the first. In the second stage of selection, parameters and properties like aesthetics, manufacturability, availability and cost are used in conjunction with flexural strength, tensile strength and tensile modulus to come up with the most suitable material. Since it is not easy to quantify data on aesthetics, manufacturability, availability and cost, as explained in the earlier section, only qualitative data are used in the selection process. The data for flexural strength, tensile strength and tensile modulus are quantitative .

According to Sergent (1991) the material selection problem is considered trivial if there is only one property to be considered and the materials are ranked according to the value of that property. In the case of multi-attribute problems, like in the current study, various solution methods are available such as Simpson's paradox, Condorcet's paradox, non-inferior set, Arrow's impossibility theorem and von Neumonn and Morgenstern axioms (Sergent, 1991). Arrow's impossibility theorem is used in this study. It uses the principle based on ranked orders of seven different attributes and properties. The selection process is carried out by listing the seven properties and attributes in the top row of a table. Candidate materials for each designer input data are listed in the left column of the table. For each material, a total score is given by adding the scores of all the individual properties. The Candidate material with the highest score is selected. Table 5 shows the multi-attribute ranking for the materials selected after the first stage of materials selection resulting from the first sets of random input data proposed by the designer. Similar approach is carried out for the other nine random input datasets. In this study, since mixed data are available (qualitative and numerical), all the data are normalized for the sake of consistency and to obtain comparable data and are given scores in the scale of 1 to 5. The desirable attributes are assigned high scores and vice versa.

Table 5 Multiattribute ranking of the materials for random input dataset 1

Candidate Material	Tensile Strength	Tensile Modulus	Flexural Strength	Aesthetics	Manufac-turability	Avail-ability	Cost	Total Score
1	2	4	4	2	4	4	1	18
2	3	2	3	1	5	4	4	22
3	1	1	2	4	1	2	2	13
4	4	3	1	5	3	3	3	22
5	5	5	5	3	2	5	5	30

Analytical Hierarchy Process

The analytical hierarchy process (AHP) (Saaty, 1980) is a multiple criteria decision-making tool that has been used in almost all applications related to decision-making problems. Materials selection is considered a multi-criteria decision making problem due to the large number of factors affecting selection of materials. Thus, AHP can be implemented in selecting the most appropriate material for a particular product. DSS Resource defined AHP as an approach to decision making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives (Anon., 2007). Basically, factors that are considered by the designers are determined and arranged in a hierarchy as shown in Figure 13. The designer is then asked to indicate the relative importance of the factors in the hierarchy to construct a pairwise comparison matrix. Eigen-value theory is used to calculate, from the matrix, a figure that represents the relative merit of a particular alternative (Kusiak, 1993).

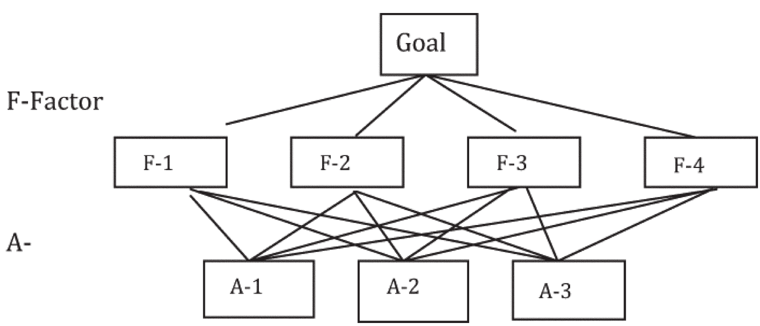


Figure 13 A three level hierarchy model

Application

(This section is reproduced from Hambali et al. (2010) with permission from Springer, Heidelberg, Germany).

As a case study, AHP was used to select the most suitable material for a polymeric composite automotive bumper beam. The selection of the best material for the polymeric composite automotive bumper beam depends on the following factors:

a. **Energy absorption (EA)**

The most important consideration in selecting the most appropriate material for the polymeric composite automotive bumper beam is the ability of the material to absorb enough kinetic energy. The bumper beam is the main structure which absorbs the energy of collisions. The property of a material that show ability of the material to absorb energy is impact toughness (Strong, 2007).

i. Impact Toughness (ITH)

Impact toughness is defined as a measure of the ability of a material to absorb energy during impact.

b. **Performance (PR)**

Performance is defined as the ability of a bumper beam to stay intact or rigid at high-speed impact and prevent damage to the bodywork in minor impacts. There are two material properties that should be considered, namely, flexural strength and flexural modulus.

i. Flexural Strength (FS)

Flexural strength is defined as a measure of a material's ability to withstand failure due to bending.

ii. Flexural modulus (FM)
Flexural modulus is also known as stiffness. It is defined as the capability of materials to resist bending or deflection.

c. Cost (CS)

Cost plays a very significant role in determining the best material at a early stage of the product development process. In this case study, raw material cost (RMC) is considered as the main factor in determining the most appropriate material.

i. Raw material cost (RMC)
Raw material cost is defined as the cost of raw materials that will be used in fabricating the product.

d. Weight (W)

One of the primary reasons material engineers begin to investigate composite materials for a specific vehicle application is weight reduction. Thus, selecting a material which contributes to reducing the weight of vehicle is very important.

i. Density of materials (DS)
The density of a material is defined as its mass per unit volume. Low density of materials can contribute to weight reduction.

e. Service conditions (SC)

As the bumper beam is exposed to weather, etc., the candidate materials under consideration are expected to satisfy the resistance to weather conditions. Thus, service conditions during product use are also important and should also be taken into account in materials selection. Two material properties that need to be considered in this instance are corrosion resistance (CR) and water absorption (WA).

i. Corrosion resistance (CR)
Corrosion resistance is defined as the ability of a material to resist corrosion.

ii. Water Absorption (WA)
Water absorption is defined as the amount of water absorbed by a material.

f. Manufacturing process (MP)
It is also necessary to consider the manufacturing process when determining the best material at a early stage of the product development process.

i. Shape (SH)
Shape is defined as the ability of a material to be shaped into the finished product. As the bumper beam has a very complex shape, how easily the materials can be formed or shaped according to design requirements needs to be considered.

g. Environmental considerations (EC)
Due to increasing environmental concerns, especially in dealing with products' end of life phase, it is important to select the material which can easily be recycled and disposed off for a better environment.

i. Recycling (RY)
Recycling is defined as the ability of a material to be recycled at the end of its life phase.

ii. Disposal (DP)
Disposal is defined as the ability of a material to be disposed of in an environmentally friendly way such as in landfills and through incineration.

h. Availability of material (AVM)

Availability of material can be categorized into two factors, namely availability of raw material (AM) and availability of materials' information (AI).

i. Availability of raw material (AM)
The availability of raw material means the existence of the raw material in the place of manufacturing

ii. Availability of materials' information (AI).
The availability of materials' information is where the materials' information is readily available to designers during the design process.

AHP steps at the concept selection stage

AHP is a powerful and flexible weighted scoring decision making process to help people set priorities and make the best decisions when both qualitative and quantitative aspects of a decision need to be considered. Generally, AHP is based on the following three principles: decomposition, comparative judgment and synthesis of priorities. These principles can be elaborated by structuring them in a more encompassing nine step process as shown in Figure 14:

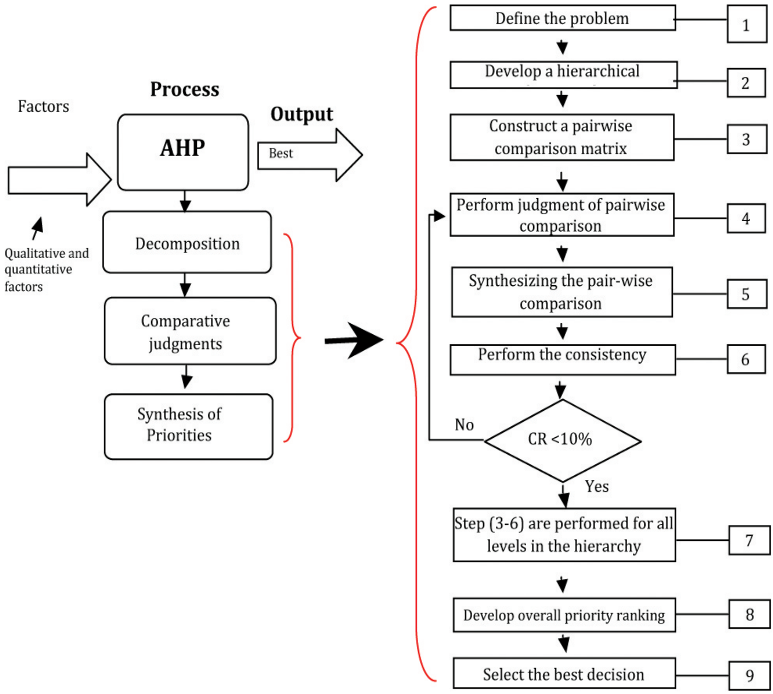


Figure 14 AHP principles and its steps

Step 1: Define the problem

The first step in using AHP 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. According to Zavbi and Duhavnik (1996), the most creative and crucial part of the method is the determination of factors influencing the selection process.

Step 2: Develop a hierarchical structure

The most influential part of decision making is the structuring of the decision as a hierarchy. Thus, after determining the problem, goal, criteria, sub-criteria and decision options, decision makers are required to construct a complicated problem in a hierarchical structure or model presenting the relationships of the overall goal, criteria, sub-criteria and alternatives, as shown in Figure 15. Generally, the structure of the hierarchy comprises four basic levels as follows:

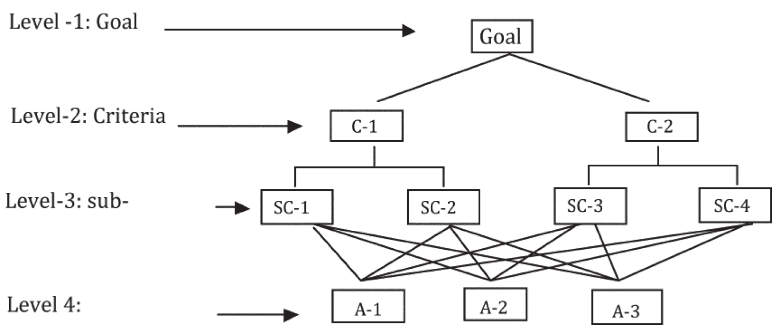


Figure 15 A four level hierarchy model

Level 1: Goal

The objective or the overall goal of the decision is presented at the top level of the hierarchy (Level 1). The goal represents the problem to be solved. For instance, 'to select the best materials for the composite automotive bumper beam'.

Level 2: Criteria

The second level (level 2) represents the main criteria or major factors that affect the selection process. The criteria identified by decision makers are based on the type of problems that contribute to the objective.

Levels 3:Sub-criteria

The sub-criteria are placed at the third level (level 3) of the hierarchy. This allows more detail in the AHP model. By adding sub-criteria or more specific criteria of the problem, the process of selection can be performed more accurately to determine the best option.

Level 4: Decision options

Finally, the decision alternatives or options are presented at the lowest level (level 4) of the hierarchy.

Step 3: Construct a pairwise comparison matrix

One of the major strengths of the AHP is the use of pairwise comparison to derive accurate ratio scale priorities. Pairwise comparisons are fundamental to the AHP methodology (Forman and Selly, 2001). Then, a pairwise comparison matrix (size n x n) is constructed for the lower levels with one matrix in the level immediately above. The pairwise comparisons generate a matrix of relative rankings for each level of the hierarchy. The number of matrices depends on the number of elements at each level. The order of the matrix at each level depends on the number of elements at the lower level that it links to.

Step 4: Perform judgement of pairwise comparison

Pairwise comparison begins with comparing the relative importance of two selected items. There are n x (n-1) judgments required to develop the set of matrices in step 3. The decision makers have to compare or judge each element by using the relative scale pairwise comparison as shown in Table 6. The judgements are reached based on the decision makers' or users' experience and knowledge. The scale used for comparisons in the AHP enables the decision maker to incorporate experience and knowledge intuitively.

Table 6 Scale for pairwise comparisons (Saaty, 2001)

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	

To do pairwise comparison, for instance (Table 7) if C-1 is strongly more important than C-3, then a=5. Reciprocals are automatically assigned to each pairwise comparison.

Table 7 Perform judgement of pairwise comparison of criteria with respect to goal

Goal	C-1	C-2	C-3	C-4
C-1	1		a=5	
C-2		1		
C-3	1/5		1	
C-4				1

Step 5: Synthesizing the pairwise comparison
Hierarchical synthesis is now used to weigh the eigenvector entries by the weights of the criteria and the sum is taken as overall weighted eigenvector entries corresponding to those in the next lower level of the hierarchy. There are a number of methods that can be used to calculate eigenvector or vectors of priorities, and one of them is the average of normalized column (ANC) method (Hsiao, 2002). ANC is to divide the elements or scale points of each column by the sum of the columns, to add the element in each resulting row and divide this sum by the number of elements in the row (*n*). This is a process of averaging over the normalized columns. In mathematical form, the eigenvector or vector of priorities can be calculated as

$$Wi = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i}^{n} a_{ij}}, i, j = 1,2,.......n \qquad (7)$$

Where W is eigenvector (priority vector)

a_{ij} is relative scale i.e. 1, 3, 5, etc

n is a number of criteria

Step 6: Perform consistency analysis

As the comparisons are carried out through personal or subjective judgments, some degree of inconsistency may occur. To guarantee that the judgments are consistent, the process called consistency verification, which is regarded as one of the most important advantages of the AHP, is incorporated in order to measure the degree of consistency among the pairwise comparisons by computing the consistency ratio. The consistency is determined by the consistency ratio (CR). Consistency ratio (CR) is the ratio of consistency index (CI) to random index (RI) for same order matrices. To calculate the consistency ratio (CR), there are three steps that have to be implemented as follows:

i. Firstly, calculate the eigenvalue λ_{max}

$$\lambda_{\max} = \sum_{i=1}^{n} \left\{ \frac{\sum_{j-1}^{n} a_{ij} \times w_j}{w_i} \right\} \quad (8)$$

ii. Secondly. calculate the consistency index (CI)

$$CI=(\lambda max-n)/ (n-1) \quad (9)$$

Where n is the matrix size or criteria.

iii. Finally, calculate the consistency ratio (CR).

The CR can be calculated using the formula

$$CR=CI/RI \quad (10)$$

Where RI is a random index of the same order matrix (Table 8)

Table 8 Random index (RI) of analytic hierarchy process (AHP) (Saaty, 2001)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

The CR is acceptable if it does not exceed 0.10. If it is more, the judgment matrix is inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved by repeating steps 4 to 6.

Step 7: Repeat steps 3 to 6
Step 3 to 6 are performed for all levels in the hierarchy.

Step 8: Develop overall priority ranking
Develop overall priority to determine the best alternatives arrangement. After the consistency calculation for all levels is completed, further calculation of the overall priority vector to select the best design concept must be performed.

Step 9: Select the best decision
Select the best decision option according to the results derived in step 8.

Determination of the best material during concept selection

In order to determine the most suitable material, AHP steps have to be employed by utilizing the Expert Choice software. This software which was developed by Forman et al. (2000) is a multi-attribute decision support software tool based on the AHP methodology, and it is easy to use and understand, as well as provides visual representations of overall ranking on a computer screen. The following are the steps of using AHP utilizing the Expert Choice 11 software:

Step 1: Define the problem

The case study used in this research is concerned with the problem of determining the best material for the automotive bumper beam. After implementing several design steps in the product development process, six materials were considered (Table 9).

Table 9 Materials used in automotive bumper beam design

No	Composite materials
1	Glass-fibre epoxy (M-1)
2	Carbon-fibre epoxy (M-2)
3	Carbon fibre reinforced polypropylene (10%) (M-3)
4	Glass fiber reinforced polypropylene (40%) (M-4)
5	Glass fibre-reinforced Polyester (30%) (M-5)
6	Glass fibre vinylester SMC (60%) (M-6)

Step 2: Develop a hierarchy model for material selection

In this step, a hierarchy model for structuring material decisions is developed. The factors that influence the selection process are translated to the hierarchy structure as shown in Figure 14. A four level hierarchy decision process, as shown in Figure 16, is described as follows:

Level 1:

Initially, the objective or the overall goal of the decision is presented at the top level of the hierarchy. Specifically, the overall goal of this case study is to 'select the best material for the polymeric composite automotive bumper beam'.

Level 2:

The second level represents the main criteria that affect choice which can be classified into eight aspects: energy absorption (EA), performance (PR), cost (CS), weight (WE), service conditions (SC), manufacturing process (MP), environmental considerations (EC) and availability (AV).

Level 3:

The sub-criteria are represented at the third level of hierarchy. Impact toughness (ITH) is a sub-criterion that affects energy absorption. There are two sub-criteria that affect the performance crieterion: flexural strength (FS) and flexural modulus (FMF). Raw material cost (RMC); low density (LD); resistance to corrosion (RC) and resistance to water absorption (RW); Shape (SH); recycle (RY) and disposal (DP); and availability of raw material (AM) and availability of materials information (AI), are sub-criteria that affect the cost, weight, service condition, manufacturing process, environment considerations and availability respectively.

Level 4:

Finally, at the lowest level of the hierarchy, the alternative materials for the automotive bumper beam are identified, which are the decision options.

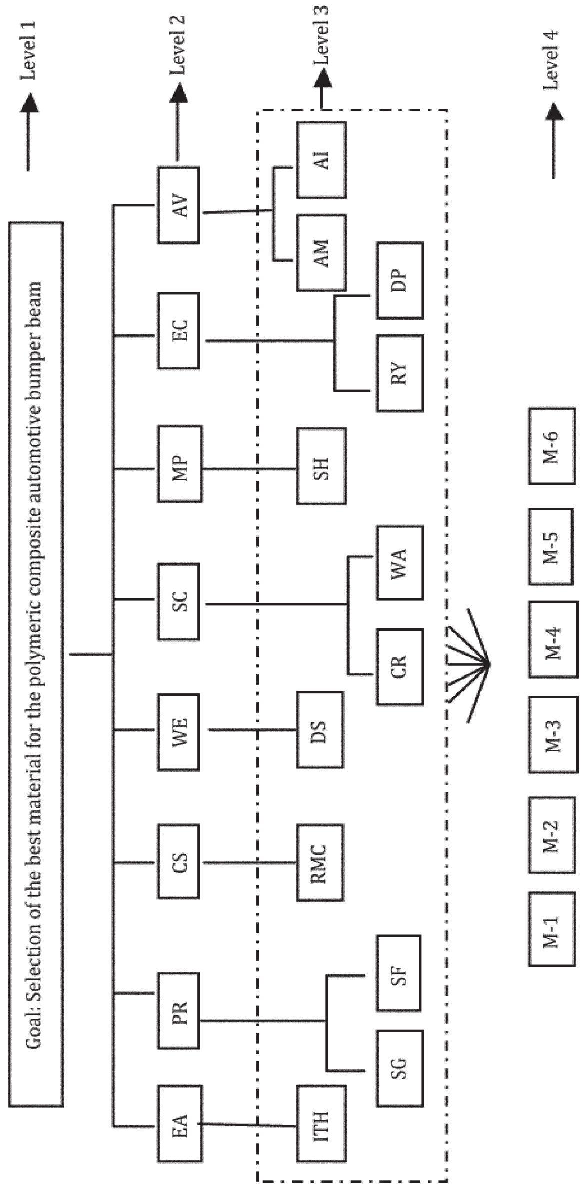


Figure 16 The hierarchical structure of the decision problem to select the best material for the polymeric composite automotive bumper beam

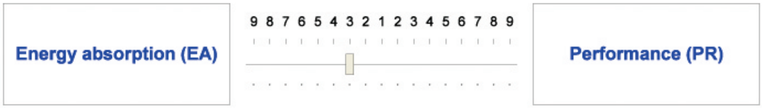
Step 3: perform judgements of pairwise comparison matrix
Pairwise comparison begins with comparing the relative importance of two selected items by using the pairwise numerical comparisons provided by the Expert Choice 11 software or relative scale pairwise comparison, as shown in Table 6. Table 10 shows the data used to do pairwise comparisons taken from the various sources (Rosato and Rosato, 2004; Mallick, 2008; Callister, 2003; Miracle and Donaldson, 2001). The judgements or assigned values as shown in Figure 17 are based on the experience and knowledge of the author and his co-workers.

Table 10 Data used to determine the most appropriate material for the polymeric based automotive bumper beam

Criteria	**M-1**	**M-2**	**M-3**	**M-4**	**M-5**	**M-6**
ITH (J/cm)	21.1	10.6	3.2	7.52	8.54	12.8
FS (MPa)	483	656	75.8	294	179	472
FM (GPa)	20.7	34.5	13.8	11.4	11.9	17.9
RMC ($/kg)	4	6	5	1	2	3
DS (kg/m^3)	1400	1600	1110	1560	1850	1900
RC	excellent	excellent	excellent	excellent	excellent	excellent
WA (%)	0.1	0.1	0.01	0.07	0.25	0.05
SH	high	high	high	high	High	high
RY	no	no	possible	possible	Possible	no
DP	high	high	high	high	High	high
AM	available	available	available	available	Available	available
AI	available	available	available	available	Available	available

Note: The cost of raw materials is estimated by range, between high cost (6) and low cost (1)

Numerical Assessment



Compare the relative importance with respect to: Goal: Select the best material for composite

	Energy	Perfor	Cost	Weigh	Servic	Manu	Enviro	Availa
Energy absorption (EA)		3.0	4.0	4.0	7.0	5.0	7.0	9.0
Performance (PR)			3.0	3.0	5.0	4.0	5.0	7.0
Cost				1.0	4.0	3.0	4.0	5.0
Weight (WE)					4.0	3.0	4.0	5.0
Service conditions (SC)						(3.0)	1.0	3.0
Manufacturing process (MP)							3.0	4.0
Environment considerations (EC)								3.0
Availability (AV)	Incon:							

Figure 17 Pairwise comparisons of the main criteria with respect to the goal

Step 4: Synthesis and consistency of the pairwise comparison

After the pairwise comparison process has been completed, the priority vectors and the consistency ratio must be analyzed. The results of priority vectors and consistency test for the main criteria with respect to the goal are shown in Figure 18. Energy absorption (EA) contributes the highest points to the goal, with a priority vector of 36.4% (0.363), while Availability (AV) contributes the lowest points, with a priority vector of only 2.2% (0.022). As the value of the consistency ratio (CR=0.05) is less than 0.1, the judgements are acceptable. If CR >0.1, the judgment matrix is inconsistent and to obtain a consistent matrix, judgements should be reviewed and improved.

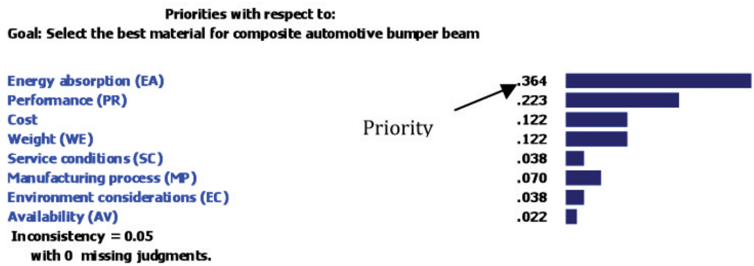


Figure 18 The priority vectors and consistency test for the main criteria with respect to the goal

Step 5: For all pairwise comparisons

Steps 3 to 4 are performed for all levels in the hierarchy. The results shown in Figure 19 represent the priority vectors for all the criteria and sub-criteria. The judgements for all levels are acceptable due to the fact that CR is less than 0.1.

Step 6: Selection of the best material

AHP reveals that the glass fibre epoxy (M-1) is the most appropriate material for the polymeric composite automotive bumper beam if all criteria and sub-criteria were considered. Figure 20 shows that the glass fibre-reinforced polyester (M-3) with a weight of 0.257 (25.7%) as a first choice, the second choice is the carbon fibre epoxy (M-2) with a weight of 0.184 (18.4%), and the last choice is the glass fibre reinforced polyester (M-5) with a weight of only 0.112 (11.2%).

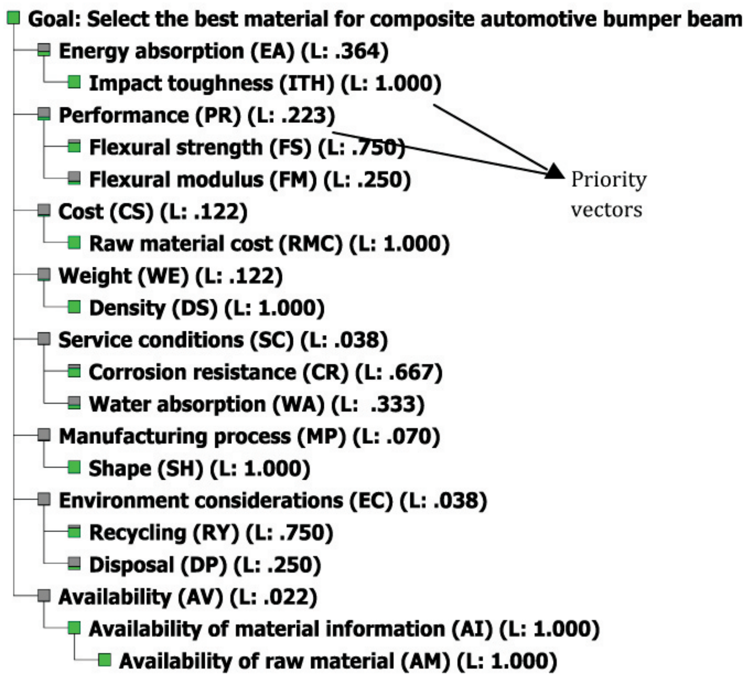


Figure 19 All priority vectors for all the criteria and sub-criteria

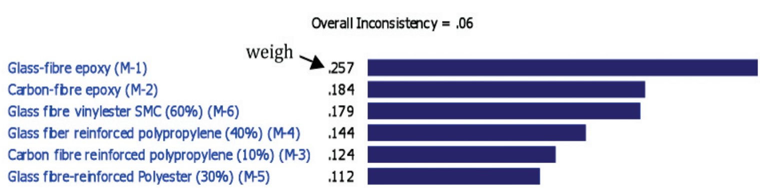


Figure 20 Results of selection

CONCEPTUAL DESIGN

Component development for composite material requires the use of a thorough design process. The total design method developed by Pugh (1991) has been widely accepted for development of products, including composite products. Many methods normally used for any product design are applicable to composite design, particularly at the conceptual design stage, such as mindmapping (Buzan, 2002), morphological chart (Cross, 1994), brainstorming, (Wright, 1998), gallery method (Pahl et al., 2007), problem decomposition (Wright, 1998), analysis of existing technical system (Pahl et al., 2007), function analysis method (Cross, 1994), quality function deployment, (Cohen, 1995), failure mode and effect analysis (Wright, 1998), fault trees analysis (Wright, 1998), weighted evaluation (Ulrich and Eppinger, 1995), Pugh selection method (Pugh, 1991), and value analysis/value engineering (Cross, 1994). In addition, in composite design, aspects of industrial design such as aesthetics (Norman, 2002), texture and colour must be considered hand-in-hand with the engineering aspects of the products (Ashby and Johnson, 2002).

In general, designing composite products at conceptual design stage is similar to other products. The major issue in composite conceptual design is idea generation. However, in some instances, there are some features which are unique to composite conceptual design. In composite conceptual design, the designer must consider manufacturing issues. Although in other products, under concurrent engineering, manufacturing should be considered early, for composite products, it is a must because without choosing the manufacturing method early in the design process, no concept can be developed.

Conceptual design is also known as design concept or conceptualisation and it is an important step in the design process.

Based on the argument by Pugh (1991), it is an important element of CE. It is the initial step in design after the development of product design specifications (PDS). It is related to creativity and creativity is a means to generate alternative solutions to a design problem (Ertas and Jones, 1996). Creativity is defined by Smith (1964) as 'sinking down taps into our past experiences and putting these selected experiences into new patterns, new ideas and new products'.

Many textbooks describe design in terms of failure prediction and laminate design (Mallick, 2008), but in this lecture, the scope of composite design is restricted to the product design approach proposed by design experts such as Dieter (2000), Pugh (1991), Cross (1994) and French (1971).

It is important to develop design concepts to come up with the best concept to be developed further. Concept development is carried out after product design specification and it is developed based on the information obtained from market investigation. At concept generation phase, functional models are developed and these models can describe the inputs and outputs (and transformation) of the product. The following sub-sections describe selected methods of design concept that are suitable for composite materials.

Mindmapping

Buzan (2002) defined the mind map as a means of putting and taking information out of one's mind and it is a creative and effective means of note-taking. Figure 21 shows a mind map of design implications for a conceptual design of an automotive composite front bumper system (Sapuan et al., 2005a). The central 'topic' is expressed as a diagram that identifies those parts of the structure being considered. In addition to the central topic, sub-areas and their critical offshoots are circled to highlight them. In addition to identifying the issues to be dealt with, the map also records questions that the designer needs to address before progress can be made (Wright, 1998).

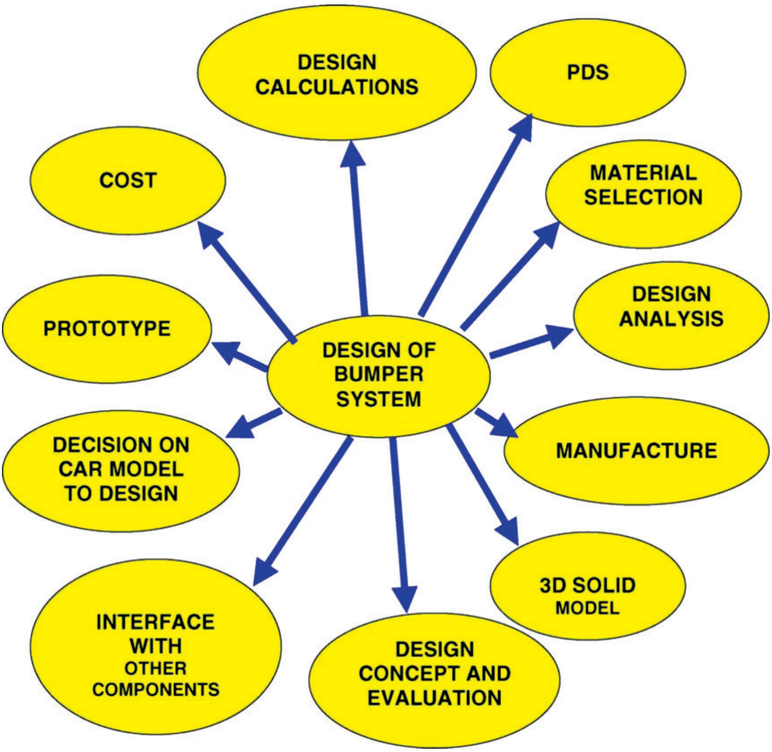


Figure 21 Mind map of design implications for conceptual design of a front bumper system (Sapuan et al., 2005a)

Brainstorming

Brainstorming is regarded as the most accepted and widely used technique of idea generation (Pugh, 1991). It was initially developed by Osborn (1957) and it is defined as 'to practice, a technique by which a group attempts to find a solution for a specific problem by amassing all the ideas spontaneously contributed by its members'.

There are two different brainstorming techniques; they are the 'controlled input' and '6-3-5' methods. Two common elements of these techniques include suspended judgement and multiple concept generation. Details about the methods can be found in Wright (1998). Brainstorming is used to generate as many solutions and ideas as possible and they can be combined and suited for logical interconnection. From those combinations, several concepts can be created (Sapuan et al., 2005a). In the generation of design concepts of a composite skateboard, a group of designers used brainstorming to come up with the design concepts. Figure 22 shows a sample design sketch generated from the brainstorming session.

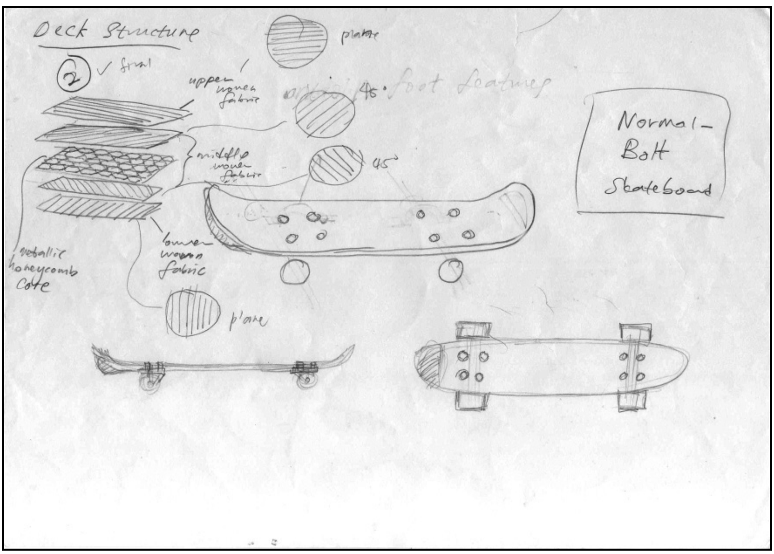


Figure 22 A sketch of deck structure of a composite skateboard

Analysis of Existing Technical System

This method is described in detail in Pahl et al. (2007) and it is related to the analysis of existing technical systems that can be used to generate new or improved solution variants in a step-by-step manner. The analysis of existing systems is one way of initiating new or improved solutions. This analysis involves mental or physical analysis of finished products. Existing products used for analysis could be (Pahl et al., 2007):

- Competitor's products,
- Older products of one's own company
- Similar products or assemblies in which, several sub-functions or parts of the function structure correspond with those for which a solution is being sought.

A case study of a similar product with similar assembly is presented here (Davoodi et al., 2008). The information is taken mainly from Davoodi et al. (2008) and it is reproduced with permission. In the development of a composite absorber, systematic exploitation of proven ideas or experiences was used. Initially, the work of BASF (2006) and AISI (2004) were used as a guide to produce composite absorbers in a bumper system. The BASF product called Neopolen® P was initially studied. In Neopolen® P, a series of absorbers were installed in between fascia and beam where the material used was expanded polypropylene (EPP). EPP is a type of polypropylene foam normally used as energy absorbing material in bumper systems. Each EPP beam acted as an absorber in the bumper and a flange was installed at the end of the EPP as a guide for better placement of whole absorbers. The cross section of the Neopolen® P bumper is shown in Figure 23.

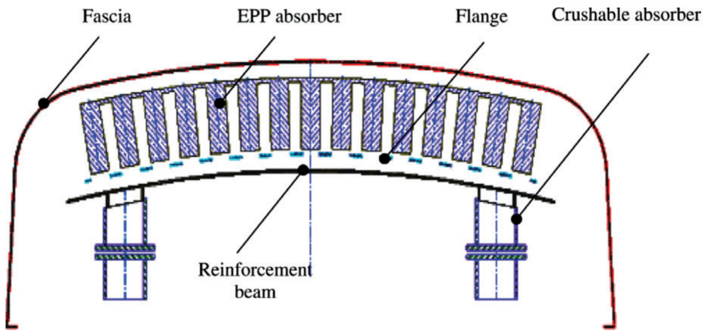
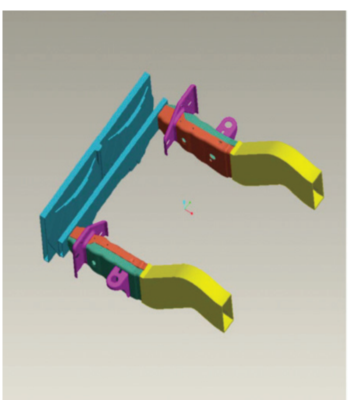
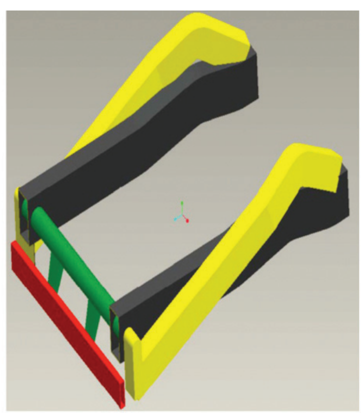


Figure 23 Cross section of Neopolen® P (BASF, 2006)

In a report published by the American Iron and Steel Institute (AISI, 2004), pertaining to the design of absorbers in leaf spring (similar product to the composite bumper absorber to be developed), out of 21 design concepts and 11 design specifications, three concepts were selected as the best concepts for energy absorption systems in engineering applications. The idea in the design of energy absorption in the leaf spring is adapted from the current design of bumper energy absorption systems (See Figure 24).



(a) Reinforced rail / leaf spring



(b) Torsion bar / firewall

Figure 24 Mechanical energy absorber in leaf spring (AISI, 2004)

In their work on the general application of crushable absorbers, Wu and Carney (1997) installed a brace to strengthen the elliptical shape absorber. Their work was on the elliptical shape reversible energy absorber. A concept similar to the work of Wu and Carney (1997) was adopted in this study but with the brace removed. The method of mounting the absorber to the bumper system was also designed. The final design was based on existing products and after some analysis a fibre reinforced epoxy composite bumper energy absorber was developed as shown in Figures 25 and 26.

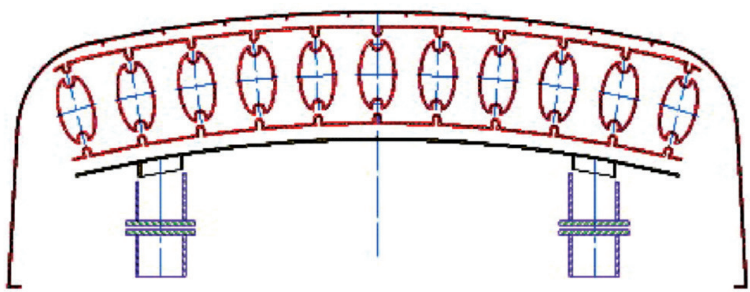


Figure 25 Schematic view of new concept of bumper absorber (Davoodi et al., 2008)

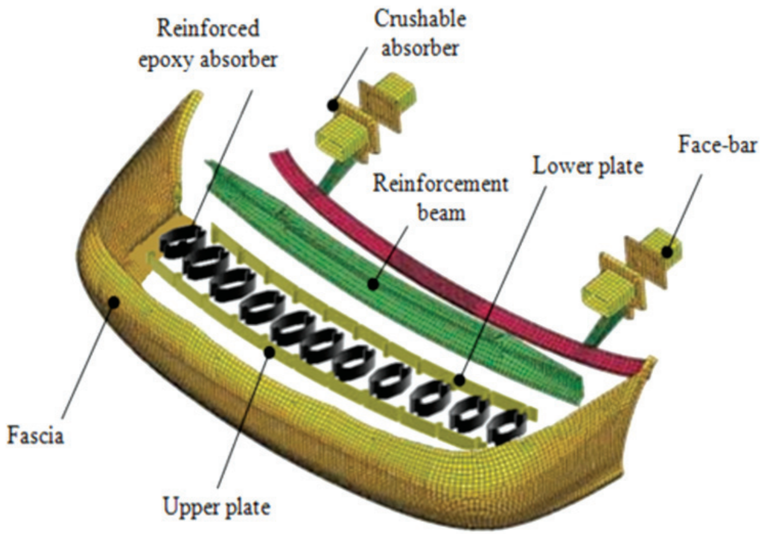


Figure 26 Pictorial view of composite energy absorber (Davoodi et al., 2008)

Morphology Chart

The purpose of the morphological chart technique is to generate different arrangements and enable designers to select new combinations of elements (Cross, 1994; Ullman, 1997). The chart provides the range of elements, components or sub-solutions that can be combined together to form a solution. Morphology is concerned with the study of the structure, shape or form of things, so a 'morphological analysis' is a systematic attempt to analyse the form that a product might take and a 'morphological chart' is a summary of this analysis. Designers use a morphological approach when they consider all the different ways that they can meet the various functional requirements of a design problem. Sapuan (2006) presented a work on a morphological chart in idea generation for a polymeric based composite automotive pedal box system. The use of the charts enables designers to identify the sub-solutions for each sub-function of a design.

Generating concepts using a morphology chart for an accelerator pedal concept

The Morphological chart method is used to generate alternatives for each function of the accelerator pedal. This chart is a grid of empty squares. On the left-hand side is a list of the essential functions of the accelerator pedal. Then across each row of the chart is the appropriate means of achieving the functions. There is no relationship within the columns of the chart; the separate squares are simply convenient locations for the separate items. There might be, for instance, three means of achieving the first function, five means of achieving the second, two means of achieving the third, and so on.

When it is finished, the morphological chart will contain the complete range of all the possible different solutions for the accelerator pedal. These solutions consist of the combinations made by selecting one sub-solution at a time from each row.

The morphological chart of the accelerator pedal is shown in Figure 27. The sub-functions identified are means of controlling pedal movement, pedal profile, ribbing pattern, pad attachment to pedal lever, pivot shaft location, means of connecting pedal to carburettor and pedal attachment to cable. For each sub-function, between two and five solutions are generated. The combinations of final solutions are circled. The final concept is a pedal controlled by an extension return spring hooked to the carburettor, with a "V" ribbing pattern. The pad is an integral part of the pedal lever. The pedal is mounted on the bulkhead by means of a small shaft enclosed by a pair of anchorage. The throttle cable is used to link the pedal and the carburettor. This is a logical choice and based on conventional designs.

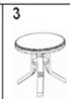
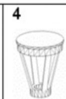
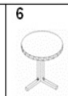
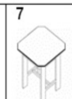
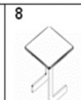
	SUBFUNCTION \ SOLUTION	1	2	3	4	5
1	MEANS OF CONTROL-LING PEDAL MOVEMENT	Extension spring	compression spring	Torsion spring	Hydraulic system	Spring in carburet tor
2	PEDAL CON-NECTION TO CARBURET-TOR	Hydraulic cylinder	Cable			
3	PEDAL ATTACHMENT TO CABLE OR CYLINDER	Shaft	Single slot	Double slot	Clevis pin	
4	PEDAL PAD DESIGN	Integral with pedal	Design separately then attached			
5	PEDAL PROFILE	I	U	O	C	H
6	RIBBING PATTERN	V	X	No ribbing	2 rows of V	2 rows of X
7	PIVOT SHAFT LOCATION	End of pedal	Along pedal lever			

Figure 27 Morphological chart of accelerator pedal (Sapuan, 2006)

Concept Evaluation

Concept scoring matrix

The most popular method of design concept evaluation is the concept scoring matrix (Ulrich and Eppinger, 1995). It is also called the evaluation matrix (Wright, 1998) and weighted objective method (Cross, 1994). In Figure 28, eight concepts of multi-purpose composite tables were evaluated, using weightage factors and evaluation of each concept on a scale of 0 - 5. W means the weight for the characteristics, R means the score for the concept and S is the product of weight and score of the concept. From this evaluation, concept 8 was used as the concept for more detail design work (Sapuan et al., 2007a).

Concepts		1		2		3		4		5		6		7		8	
																	
Characteristic	W	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
Stability of product	5	4	20	5	25	5	25	3	15	5	25	2	10	5	25	4	20
Cost of manufacture	5	3	15	2	10	2	10	2	10	2	10	3	15	2	10	5	25
Ease of manufacture	4	3	12	3	12	2	8	2	8	3	12	5	20	3	12	5	20
Reliability of service	5	4	20	4	20	4	20	4	20	4	20	3	15	4	20	3	15
Ergonomic to user	3	2	6	3	9	4	12	4	12	2	6	3	9	4	12	4	12
Low setup time	3	3	9	2	6	1	3	1	3	3	9	4	12	2	6	4	12
Ease to carry and light	3	3	9	3	9	3	9	4	12	3	9	4	12	2	6	4	12
Total Score		91		91		87		80		91		93		91		116	

Note. **W** means the weight for the characteristic. **R** means the score of the concept. **S** is the product of weight and score of the concept.

Figure 28 Concept scoring matrix of a multipurpose composite table (Sapuan et al., 2007a)

Pugh selection method

A variation of the concept scoring matrix is the Pugh selection method (Sapuan et al., 2009b). In this method, a concept is chosen as a datum against which all other concepts are to be compared. In considering each concept and criteria against the chosen datum, legends + (plus), - (minus) and S (same) are used. Plus (+) means better than datum, minus (-) means worse than datum and S means same as datum. The concept, which has the biggest positive difference between plus and minus, is chosen as the best concept. Details of this method can be found in Pugh (1991). To understand this method, a design of a composite garbage bin was performed and the best concept was selected using the Pugh selection method. From the product design specification (PDS), the important features and requirements to design a garbage bin are identified. A few design concepts are generated as alternative solutions. The concepts generated are described as follows.

Concept 1

It has the following features (Figure 29): i) basic shape of a normal dust bin; ii) use handle for easy pickup; iii) body quite high for extra capacity; iv) cap has small door for small garbage; and v) has drainage for water waste. In this design, it is used as a datum.

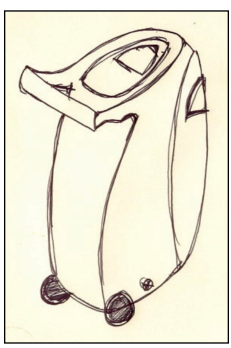


Figure 29 Concept 1 (Datum)

Concept 2

It has the following features (Figure 30): i) An ergonomic shape with no sharp edges; ii) a wing pad and belt for easy carrying on a motorbike; iii) a magnet for easy sticking on a car boot; iv) small capacity; v) has water waste drainage; vi) has a puller and roller; and vii) has a hook for easy throwing up.

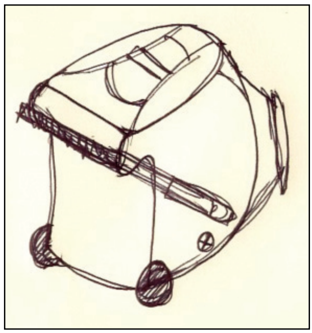


Figure 30 Concept 2

Concept 3

It has the following features (Figure 31): i) A box shaped bin; ii) medium capacity; iii) medium high; and iv) has a small door at cap for small garbage.

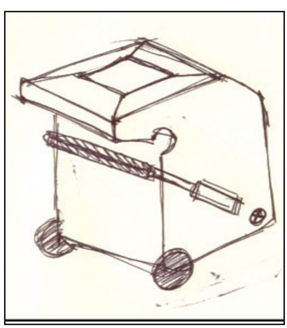


Figure 31 Concept 3

Concept 4

It has the following features (Figure 32): i) Long horizontal shaped bin; ii) large capacity; iii) has 4 pairs of rollers; iv) has two drainage systems; and v) has two garbage spaces, dry and wet.

Figure 32 Concept 4

Concept 5

It has the following features (Figure 33): i) Bag type bin; ii) with back cushion; iii) can be placed vertically; and iv) can be picked up using handle bar or carried like a back pack.

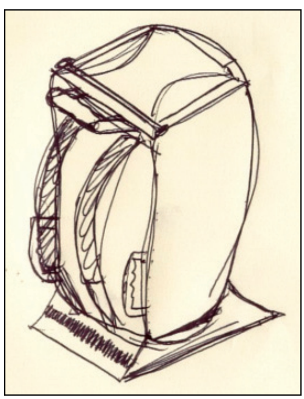


Figure 33 Concept 5

Concept 6

It has the following features (Figure 34): i) Ergonomic look; ii) with roller and flexible puller; iii) medium capacity; and iv) has a hook and a handle at the bottom for easy dumping.

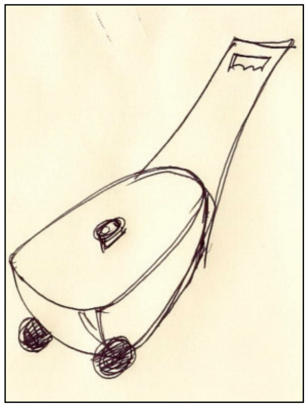


Figure 34 Concept 6

After evaluation of the concepts against datum (See Figure 35), the final concept (concept 6) was chosen. This is because the shape and size makes it suitable for multipurpose uses. The design looks simple but still meets the requirements. The cap is closed using strong magnetic plate inserted in the composite or attached to the composite and it can be used with or without the cap.

Concept	1	2	3	4	5	6
Criteria	DATUM					
Size		-	-	+	S	-
Weight		-	S	+	S	-
Safety		S	-	S	-	S
Material		S	S	S	S	S
Testing		S	S	S	S	S
Target cost		-	-	+	S	+
Manufacture and process		S	S	S	S	S
Competition		+	-	-	-	+
Life in service		S	S	S	S	S
Target market		-	-	+	S	+
Aesthetics, appearance and finish		S	-	-	S	S
Ergonomic		S	S	-	S	+
Customer		S	-	-	-	+
Results		4- 1+	7- 0+	4- 4+	3- 0+	3- 5+

Figure 35 Pugh selection method in composite garbage bin design

Beyond Conceptual Design

The next step in the total design process is detail design (Pugh, 1991). However, authors like Ashby (2005) and Pahl et al. (2007) introduced another step called embodiment design after conceptual design. Wright (1998) described embodiment design as 'putting flesh to the bone' and it is an activity that gives a concrete or discernible form to an idea or concept. Embodiment design and detail design are not discussed in this lecture.

Computer Software Tools in the Design of Composites

Apart from the idea generation techniques described above, when designing components from composite, during the design process, one cannot keep away from discussing the use of various software tools in an integrated way. Although this topic is normally dealt with in detail during the detail design stage, it is presented here as many designers would prefer to use various software tools extensively during the conceptual stage in composite product development. While the products may vary from automotive components to children's toys, some composite materials designers prefer to use 3D solid modelling systems like Pro/Engineer, CATIA and Unigraphics and integrate the drawings with finite element analysis like ANSYS, ABACUS and LUSAS. In FEA the structural composites can be analysed using for example shell elements so that ply orientation or lay up can be accurately considered in stress and stiffness calculations. Although this topic is currently discussed under the conceptual design stage, most of the time, composite designers would use these types of CAD and FEA work during the detail design stage. Some researchers have come up with artificial intelligence (AI) systems to support the design of composite materials. In fact, the Department of Mechanical and Manufacturing, Universiti Putra Malaysia has strong integrated CAD, CAM and CAE (C^3) (Figure 36) that can cater to composite design, along with other designs, as pointed out by Chatwin (2009). An Integrated IT system is one of the major tools in CE (Prasad, 1996).

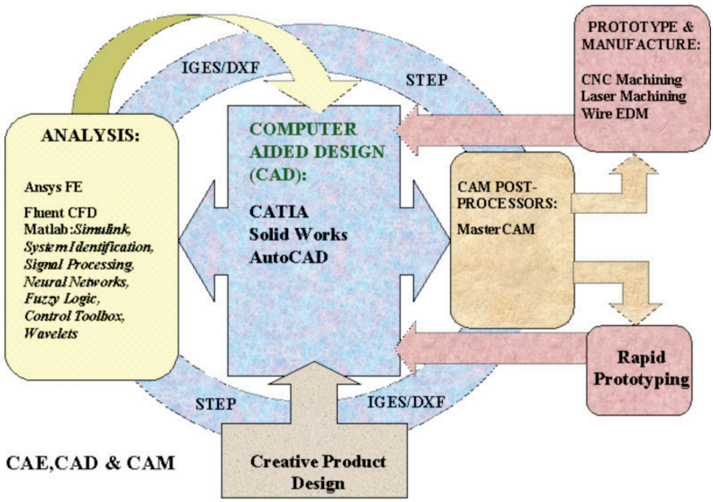


Figure 36 UPM C³ facility (Chatwin, 2009)

Rapid Prototyping

An engineering graphic is not good enough to be used as a communication tool targeted at customers to enable them to conveniently visualize what the model looks like. It is difficult for some customers to imagine what a design engineer is creating just by seeing his product on paper. For that reason, an advanced technology called rapid prototyping (RP) has been developed in order to facilitate easier communication between customers and design engineers. Rapid prototyping can be defined as a technology that uses various techniques to manufacture three-dimensional models by translating the data from computer-aided design (CAD). Rapid prototyping is a technology capable of directly generating physical objects from graphical data (Boon et al, 2003).

The first rapid prototyping technique is Stereolithography (SLA), which was developed by 3D Systems. Year after year, many other techniques of RP have emerged, such as selective laser sintering, fused deposition modelling (FDM), laminated object manufacturing and 3D printing with diverse finishing techniques, and different speeds and materials. RP begins with a design generated from computer-aided design software, which is then converted into the standard triangle language (.STL) format and transferred to the RP machine for fabrication. The model is created by the addition of a layer by layer process in which, after the first layer is finished, the second layer is added on top of the first layer. This is repeated continuously until the object appears. Rapid prototyping is a user-friendly technology and a convenient way to communicate with customers by displaying the product with some functionality. The purpose of RP is to facilitate easy communication of products to the customers. It can point out design flaws and analyse the part for aesthetics, ergonomics and manufacturability. Sapuan et al. (2005b) reported a comparative study of the performance of two RP methods for modelling composite clutch pedals. These methods are SLA (Figure 37) and 3D printer (Figure 38). It was found that the cost of producing a SLA model was RM 4,000 while for a 3D printer it was RM 3125. The surface roughness of the SLA was 4.85 microns and for a 3D printer it was 8.3 microns. The speed to produce a SLA model was 88.7 hours while for a 3D printer it was 12 hours.

Figure 37 RP model using SLA for composite clutch pedal

Figure 38 RP model using 3D printer for composite clutch pedal

RP has the capability to mimic the actual assembly of products. Figure 39 shows an assembly of a pedal box system using a 3D printer (Boon et al., 2003).

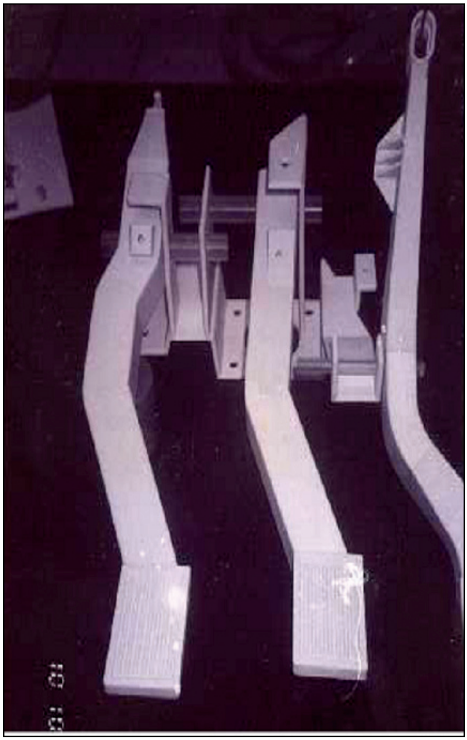


Figure 39 A completed assembly of composite pedal system using a 3D printer

In a more recent study, Sapuan and Shuhaimi (2006) reported the RP development of composite clutch pedal (Figure 40) using fused deposition modelling (FDM). The cost to produce this model was RM 1,800, the surface roughness was 13.25 microns and the speed to produce the model was 21.5 hours.

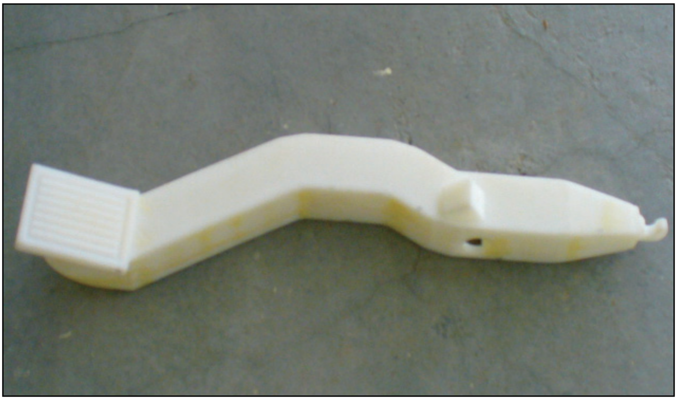


Figure 40 RP model using FDM for composite clutch pedal

MANUFACTURING ISSUES

Two major manufacturing related issues are discussed in this lecture and they are mould flow analysis and the manufacturing process itself.

Mould Flow Analysis

Mould flow analysis is an activity related to manufacturing carried out at the design stage. In the design office, the designer considers all related activities in moulding of composite products. It is normally applicable to short fibre composites with processing methods of injection moulding and extrusion. It can also be used in the resin transfer moulding process and in this case, the fibre or preform is not necessarily short fibre as long or continuous fibre is also applicable. The mould flow analysis of injection moulding of an automotive clutch pedal from fibre reinforced polymer composites is an example.

Mould flow analysis simulation results

Information presented in this sub-section is mainly taken from Imihezri et al., (2006) and it is reproduced with permission. This sub-section highlights the results of MoldflowPlastic Insight software. This software is used to predict and simulate the fill pattern, fill time, air trap, weld line, temperature and pressure distribution for these two rib designs. The results are then compared, and finally the chosen rib design is incorporated as part of the composite clutch pedal design. The computer simulation presents only elements of the "V" and "X" rib with standardized thickness of 2.5mm and runs at optimum settings.

Fill time results

The fill time result represents the behaviour of the melt polymer at regular intervals. Thermoplastic polymer flow inside the mould is simulated using a program that calculates a flow front that grows from interconnecting nodes at each element, starting at the injection node. The cycle repeats until the flow front has fully expanded to fill the last node. One of the goals in selecting polymer injection locations is to ensure that all flow paths in the cavity fill at the same time (balanced flow paths). This prevents overpacking along the flow paths, which might otherwise fill first. The fill time analysis can be used to estimate possible areas of short-shot, hesitation, overpacking, weld line and air traps.

It can be seen in Figure 41(b) that the "V" design rib provides a more balanced flow pattern as indicated by the evenly spaced contour, which means that the melt polymer flowed at a balanced speed to all corners of the rib sections. The uneven and closely (narrow) spaced contour at the intersections in the "X" rib shows that at that location, the material is flowing slowly (Figure 41(d)) compared to other parts of the rib.

The results also show that an "X" rib design fills in at a slightly faster time compared to a "V" rib design. An "X" rib fills completely at 0.71 s while a "V" rib fills at 0.81 s and such difference is attributed to the fact that the injection point for an "X" rib is located closer to the rib intersections. This hastens flow to all corners of the design. The effect can be seen in Figure 42(a and b), where the melt polymer spreads wider at a faster rate for the "X" rib. The location of the gate also forces the melt polymer to move in a radial motion (Figure 43(a and b)). This influences the fibre orientation.

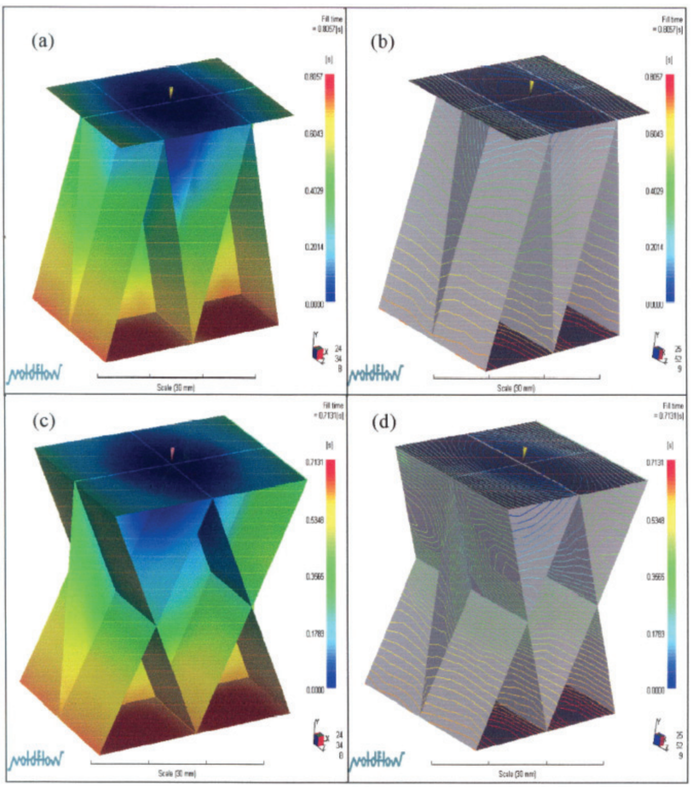


Figure 41 Smooth and contoured fill time results for (a and b)"V" rib and (c) and (d) "X" rib.

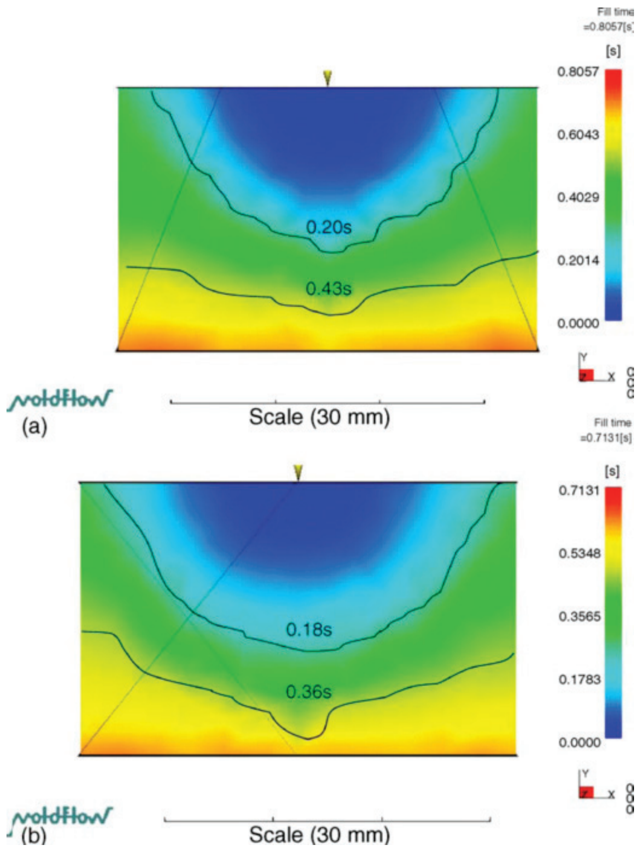


Figure 42 Flow distribution for (a)"V" rib (side view) and (b) "X" rib (side view).

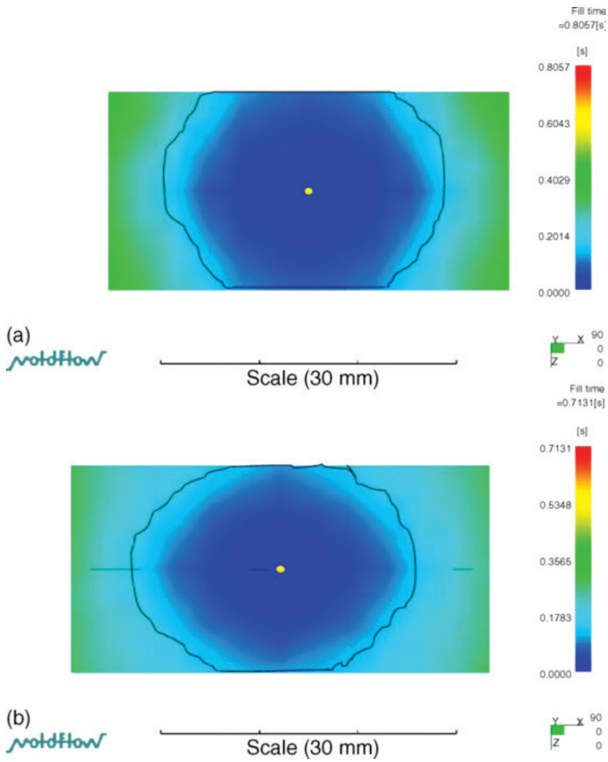


Figure 43 Radial flow pattern for (a) “V” rib (top view) and (b) “X” rib (top view).

Pressure results

Pressure (end of filling) presents pressure distribution at the end of the filling phase. The pressure results show that an “X” rib requires slightly higher injection pressure of 5.09MPa compared to a “V” rib that requires 4.83MPa (Figure 44). A higher injection pressure is indicative of occurrence of higher shear rate and shear stress levels (Anon., 2003).

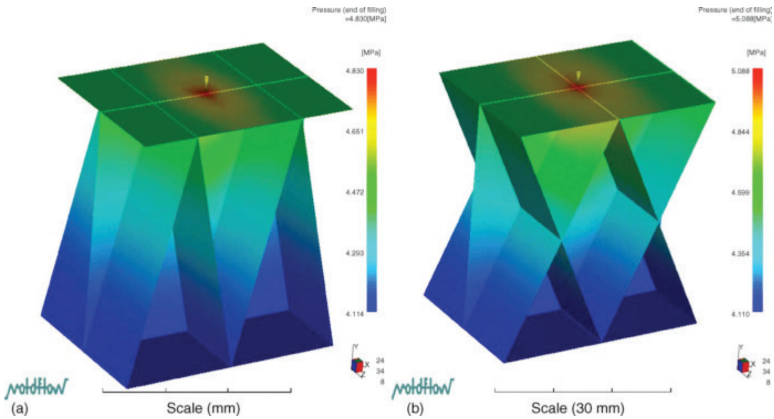


Figure 44 Pressure distribution for (a) “V” rib and (b) “X” rib.

Air trap results

Air traps can be used to indicate the presence of surface defects, such as burn marks, surface blemishes and short shot. Figure 45 revealed that both designs produce similar amount of trapped air. The only difference is its location.

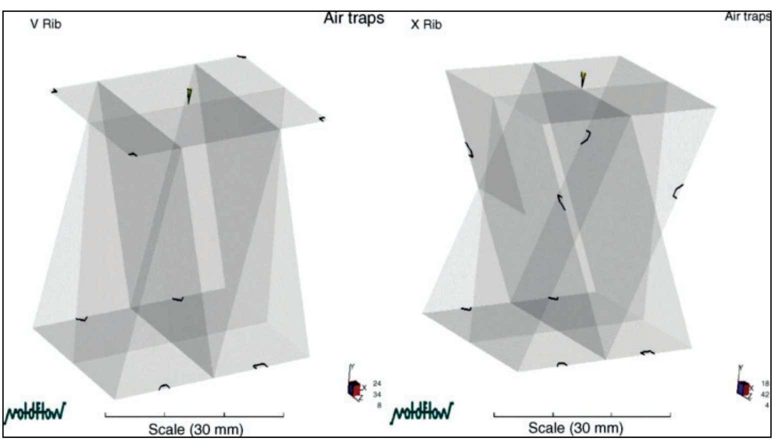


Figure 45 Location of air trap for “V” and “X” rib.

Weld line results

Weld lines occur in places where two flow fronts have converged and its presence may indicate a structural weakness, since the part may be more likely to fracture or deform at a weld line, especially if the weld line is located at areas of highly concentrated stress. In the "X" rib design the weld line is non-existent while a slight weld line occurs for a "V" rib (Figure 46(a)). However, the weld line did not occur at the critical stress area.

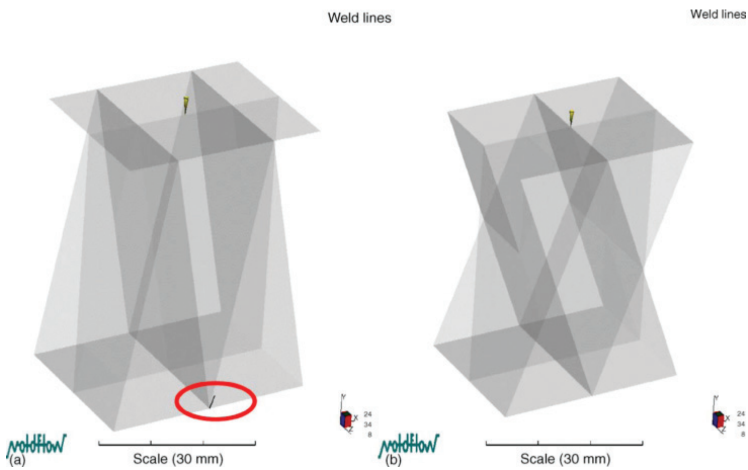


Figure 46 Weld line location for (a) "V" rib and (b) "X" rib.

Average fibre orientation

Average fibre orientation result indicates the movement of fibres during the injection moulding process, averaged over the part thickness and expressed in the global coordinate system.

A gate placed centrally provides a radial flow that moves outwards and dictates the average fibre orientation. At this state, when the polymer melt enters through a constricted gate, it experiences divergent flow, which causes transverse alignment to the flow direction. As the melt progresses to the skin of the mould, the shear flow has a more significant effect causing longitudinal fibre alignment. In both cases, the fibres become more oriented as the melt polymer moves further outward from the point of injection location (Figure 47). A front view of the rib design indicates that the degree of radial orientation for an "X" rib is less than that for a "V" rib due to plane intersections (Figure 48).

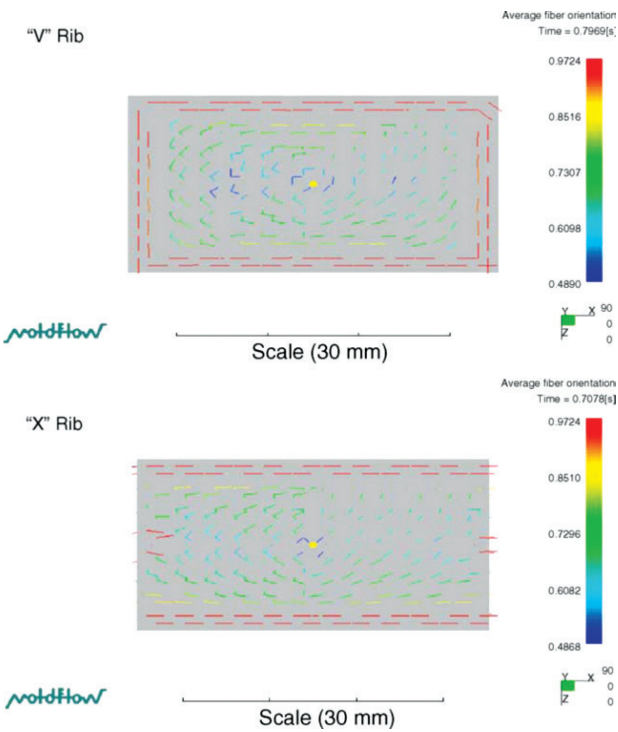


Figure 47 Top view of the average fibre orientation for "V" and "X" rib

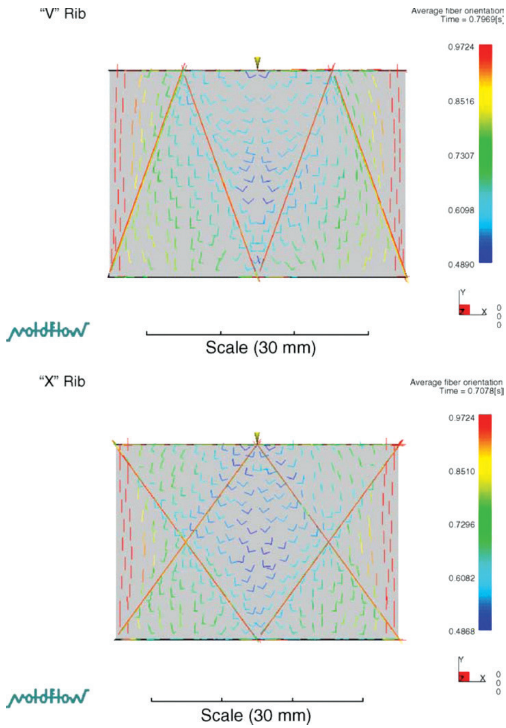


Figure 48 Front view of the average fibre orientation for "V" and "X" rib.

Manufacturing Process with Injection Moulding

This section is taken mainly from Sapuan et al., (2007b) and is reproduced with permission. Injection moulding is a process that involves heating the granular polymer material in a heated screw barrel after being fed through a hopper and pressurizing this molten polymer to inject into a closed mould. The composite is then allowed to form and cure. It requires the use of moulds tailored to the design of the components and is commonly used for high volume production of small articles, often with intricate shapes such as valves, pumps, helmets, fans, toys and automotive components (Sapuan et al., 2007b).

Generally, there are two types of moulds, i.e two-plate and three-plate moulds. In order to produce the sample clutch pedal, a two-plate mould is opted for two main reasons. Before any mould machining process can begin, it is important to decide the location of the parting line. The location of the parting line depends on the product design and type of mould used.

Other common components include a runner system, which is located at the centre of the parting line, cooling channel, air vent, ejector pins and support plate. The mould for the clutch pedal incorporates the use of inserts for two main reasons; to ease the machining of ribs using EDM and to ease any machining process. The dimension of the mould base for the model is 300 x 500 mm and made from steel S45C (S45C is the code of the steel supplied by the supplier). Figures 49 and 50 indicate the locations of ejector pins, runner system and gates respectively. The mould set is then mounted to the injection moulding machine (Figure 51).

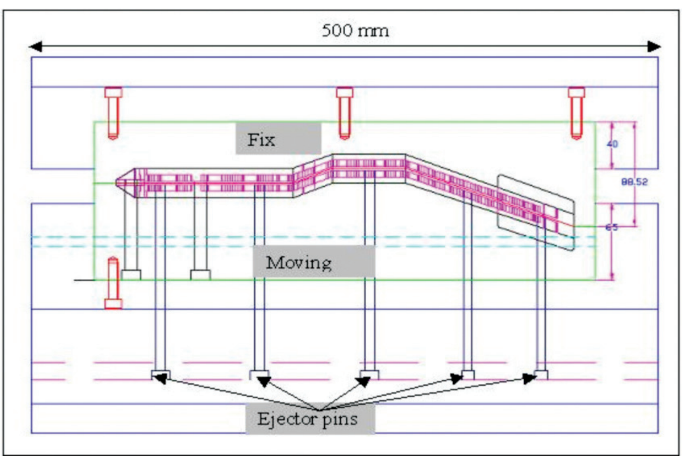


Figure 49 Location of ejector pins in the mould

The initial weight based on volume (96 401 mm^3) and density of the composite material (1.37 g/cm) is calculated to be at 132 grams. However due to transverse and longitudinal shrinkage factor, the produced samples of the fibre reinforced clutch pedal have an average weight of 125.8 grams. Hence there exists a percentage of shrinkage of 4.6%. A weight reduction from 647.7g (steel clutch pedal) to 125.8g (fibre reinforced polyamide clutch pedal) was achieved (a reduction of 80.6 %) due to the fact that the density of a composite is much lower than that of steel. This is the most important feature when employing a composite clutch pedal. In fact many leading car manufacturers in the Western world, such as General Motors, Porsche, Jaguar and Ford, have employed composite material in their car models (Sapuan, 1999). It is the right time for local car manufacturers to seriously consider this material in automotive components and not only limited to clutch pedals.

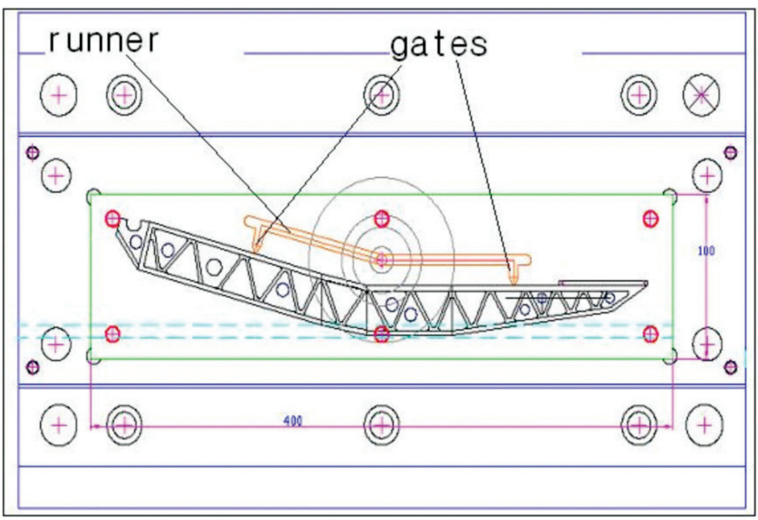


Figure 50 Location of runner system and gates in the mould

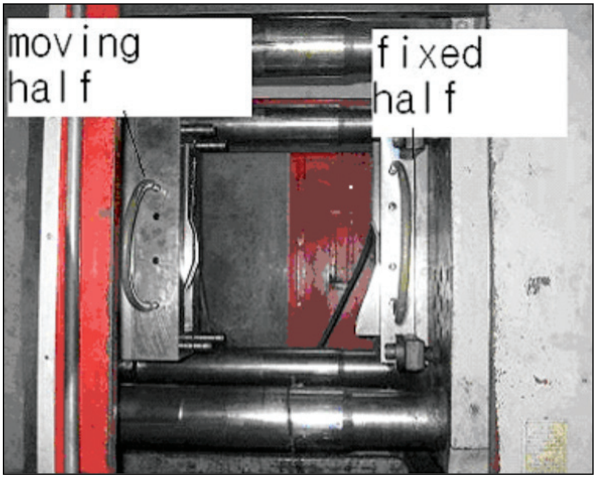


Figure 51 Mounted mould set used in fabrication of the clutch pedal

The injection machine used to produce the injection-moulded clutch pedal is a Kawaguchi K265 model with a tonnage capacity of 265 tonne (Figure 52).

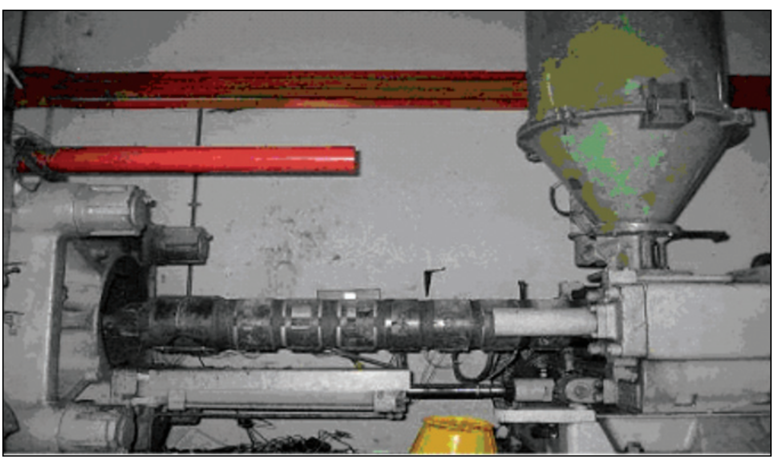


Figure 52 Injection moulding machine, Kawaguchi 265

The fibreglass reinforced polyamide 6,6 composite clutch pedal can be seen in Figure 53. An actual model of glass fibre reinforced PA 6,6 composite automotive clutch pedal was also fabricated and the results showed great consistency with the simulated model in terms of air fill time, air traps and weld line formations. A weight reduction from 647.7g (steel clutch pedal) to 125.8g (fibre reinforced polyamide clutch pedal) was achieved (a reduction of 80.6 %) due to the fact that the density of the composite is much lower than that of steel.

Figure 53 Actual model of glass fibre reinforced PA 6,6 composite automotive clutch pedal developed

DESIGN FOR SUSTAINABILITY FOR COMPOSITES

In recent years, sustainability has been a major issue in product development and product developers take this issue very seriously. Design for environment and design for sustainability are new terms being coined in relation to current product design and CE. The importance of sustainability-oriented design and manufacture within the community of material scientists and engineers is beginning to be realized. The traditional approach in CE was to focus on design, manufacture and maintenance of a product. Although it is clearly stated in CE definition that product life cycle, from inception to disposal, is taken into consideration, CE practitioners normally limit themselves within the design, manufacture and maintenance of a product.

A lot has been reported about sustainability and environmental conservation. Fortunately CE for composites can provide some solutions to these issues. Design for sustainability (DFS) is another design for 'X' and it is sometimes called design for the environment (DFE) although DFE is normally regarded as a subset of DFS.

It is important to design a product by considering the environment early in the design process. This is to safeguard the planet for future generations. Design for the environment in product development has become important in recent years because consumers are now more aware of environmentally conscious products as well as the implementation of global environmental legislation (Haik, 2003). In designing a composite product, the issue of design for sustainability is very easily visible in natural fibre composites (Sapuan, 2009). Design for sustainability can be realised by using sustainable materials in product development. Among the objectives of design for sustainability include concerns of renewability, reusability and recyclability of materials and these can be achieved by using natural fibre composites.

Design for the environment is defined as:

> *the effort to adjust present design methods to correct known, measurable, environmental degradation with the time-scale of an average product's expected life of approximately 10 years* (Ashby, 2005).

Design for sustainability is defined as:

> *the effort to adapt present design methods to meet present lifestyle needs without compromising the needs of future generations in decades or centuries to come without the knowledge that sustainability requires social and political changes* (Ashby, 2005).

DFS requires reduction of harmful side effects to consumers, workers and natural ecosystems by reducing the rate of materials and energy consumptions that leads to harmful side effects (Tipnis, 1998). DFS seeks to address climate change and manage natural resources effectively. At the end of the day, when we discuss DFS, we inevitably have to talk about natural resources and in Malaysia, one of the main important natural resources is natural fibre composites. The DFS initiative in composites is invariably referred to as 'green' composites either in the form of biopolymer matrix (bio- resin) or in natural fibre or both. Examples of bio-resins include polylactic acid (PLA) and starch polymer. Design and manufacture of products from natural fibre composites provide ways to support sustainable and environmentally responsible technologies. By resorting to natural fibre composites, among the issues of environment and sustainability addressed include indoor air quality, global warming, energy conservation and deforestation. Natural fibre composite, particularly wood composite, is mainly used in indoor panels and floors. One way to ensure the quality of air in houses is to reduce the levels of volatile organic compounds emitted by the panels. This can be achieved by selecting panels (See Figure 54) that are manufactured using high efficiency methylene diphenyl di-isocyanate (MDI) binders that contain zero added formaldehyde (Scharf, 2007).

Figure 54 Wood composite floor panel

Global warming currently poses a threat to mankind and the natural fibre composite industry can play a role by ensuring that the supply of fibres and wood and timber are obtained from managed and sustainable forest resources. This will ensure that more trees are planted than those cut. As they grow very fast, young trees generally absorb more carbon dioxide than mature trees and will help to trap the carbon contained in one of the principal green house gases (Scharf, 2007).

According to Bowyer (2007), illegal logging causes problems of corruption, financing of regional conflicts, loss of billions of revenue to the forest products industry, and most relevant to the current topic, forest loss and degradation. It is a shame that Malaysia is listed among the countries that practise illegal timber logging together with Indonesia, China, West and Central Africa, Brazil, Russia and Eastern Europe. Deforestation and illegal logging also destroy habitats, reduce biodiversity and damage the water cycle (Scharf, 2007, Sapuan, 2002).Designs in the wood composite industry should consider the use of timber frame as an alternative to brick and concrete construction. This will reduce the cost of energy and reduce green house emissions (Scharf, 2007).

DFE could also mean considering the environmental safety issue as a part of the design process. Environmental safety is defined by Pahl et al. (2007) as the limitation of damage to the environment in which technical systems are used. Environmental safety of a product is considered to be in the higher hierarchy when discussing the relationship between component and functional reliability of a product and safety concerns. Lower level safety concerns include operational and operator safety as shown in Figure 55.

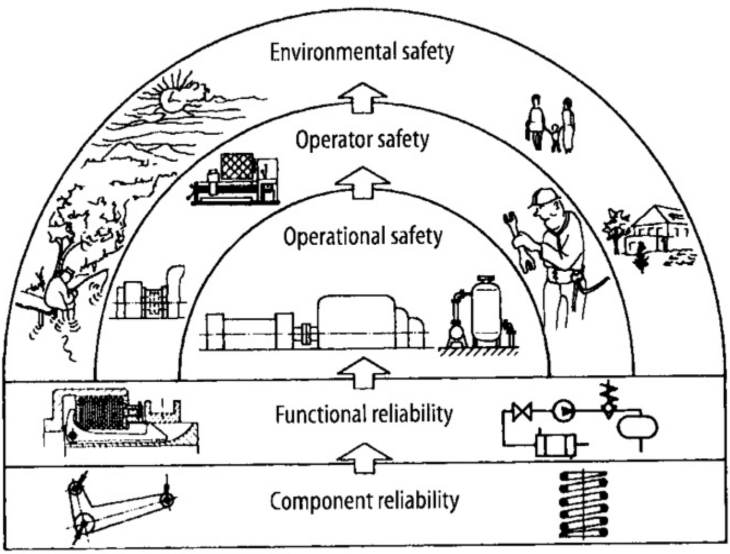


Figure 55 Relationship between component and functional reliability and safety concerns (Pahl et al., 2007)

Designing with composite materials is normally carried out for applications where static loading at or near ambient conditions is the governing design condition. However these ideal situations are not always the case and the effects of environmental factors such as exposure to chemical media, high temperature application and fatigue loading must be considered (Eckold, 1994).

According to the Design for Sustainability Programme of Deft University of Technology (Anon., 1990), the principles of design for sustainability include selection of low impact materials, reduction of material usage, optimisation of production techniques, optimisation of distribution systems, reduction of impact during use, optimisation of initial lifetime and optimisation of end-of-life systems.

One advantage of natural fibre composites is that the decomposition of the natural fibre composite does not add any new net CO_2 to the global environment, since the components come from plant material (overall balance). Figure 56 demonstrates the life cycle of natural fibre composites.

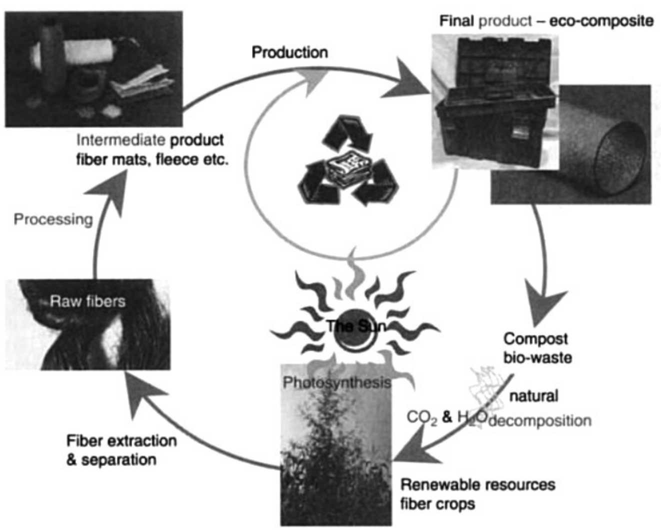


Figure 56 Nature's life cycle of natural fibre composite (Bismark et al., 2005)

Challenges in Material Development

Due to the vast variations in matrix type, fibre type, fibre arrangement, fibre dimensions and manufacturing methods, selection of natural fibre composites (see Figure 57) in particular and of composite materials in general is very difficult to perform.

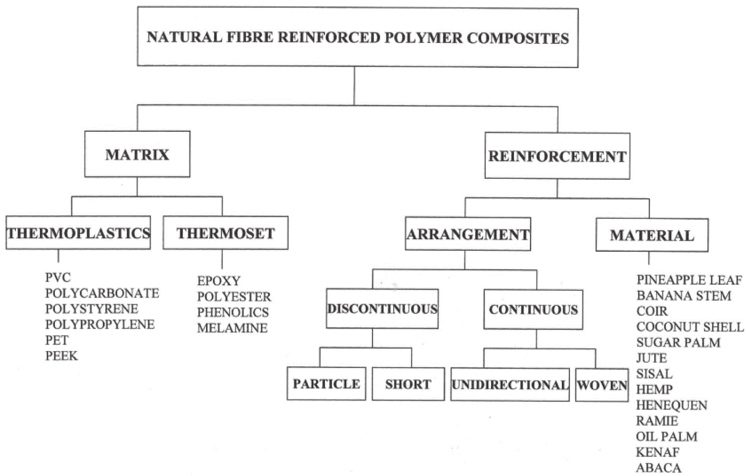


Figure 57 Materials hierarchy of natural fibre composites

Natural fibre composites are discussed because they are a group of materials with high potential for use in a wide range of applications. Materials can be developed at very low cost, materials are acquired at no cost or very low cost and are abundantly available. The author has carried out extensive studies in this area (Sapuan, 2009), the results of which suggest that natural fibre composites are good contenders to replace traditional materials in the near future.

Table 11 shows the advantages and disadvantages of natural fibre composites. Materials are available in abundance and can be acquired at little or no cost. Researchers are very keen to study the properties and characterization of these materials but there is very limited published work reporting on design and manufacturing efforts. This could be due the confidential nature of design and manufacturing efforts or could be due to lack of confidence that these materials can perform as well as conventional materials.

Table 11: Advantages and disadvantages of natural fibre composites

ADVANTAGE	DISADVANTAGE
Renewable	Variety of fibres to work on
Cheap	Lack of design and commercialisation efforts
Abundance	Lack of confidence in their capability
Published data on materials properties	Infinite number of possible arrangements of fibres
Availability	Issue of process capability (reliability and repeatability)

Development of 'green' products

Numerous studies have been conducted on the development of 'green' products from natural fibre composites. Selected works are discussed in this section.

Natural resin and flax fibre mats were used to manufacture a chair at the CCM laboratory using a vacuum assisted resin transfer moulding (VARTM) process. A mould designed at the University of the Arts in Philadelphia was made out of solid materials to assemble the chair shape and the fibre was laid-up and bagged for vacuum infusion. Figure 58 shows the finished chair after it was attached to a metal frame.

Figure 58 All natural composite chairs made of soya bean oil-based resin and flax fibre mats (Wool and Son, 2005)

The author has been involved in the development of 'green' products from natural fibre composites. Figure 59 shows the development of woven banana pseudo-stem fibres using hand lay up process.

Figure 59 Development of woven banana pseudo-stem fibres using the hand lay up process (Sapuan and Wirawan, 2008)

Figure 60 (a) shows a prototype of a multi-purpose table made from woven banana pseudo-stem fibre reinforced epoxy composite (Sapuan et al., 2007a). Figure 60 (b) shows a prototype of a small book shelf also prepared from banana pceudo-stem epoxy composite (Sapuan and Naqib, 2008). Figure 60 shows a prototype of a telephone stand made from woven banana pseudo-stem fibre reinforced epoxy composite (Sapuan and Maleque, 2005) and Figure 60 (d) shows the seat and back rest of a chair made from hybrid glass banana fibre reinforced polyester composite (Khamis et al., 2009). Figure 61 shows a computer casing made from oil palm fibre reinforced epoxy composite and Figure 62 shows a prototype of a trolley base made from kenaf fibre reinforced epoxy composite. All these products were developed by the author with his undergraduate students as their their final year projects and were purely driven by his interest in the area. It is his hope that in the future, there will be interested parties willing to invest in these 'low profile' efforts.

(a)

(b)

(c) (d)

Figure 60 Multi purpose table (a); book shelf (b) telephone stand (c) and chair (d) made from banana pseudo-stem composites

Figure 61 Computer casing from oil palm fibre reinforced epoxy composite (Ham et al., 2009)

Figure 62 Trolley base made from kenaf fibre reinforced epoxy composite

A government funded project was carried out to design and fabricate a small boat from sugar palm fibre reinforced unsaturated polyester composites (Ishak, 2009 and Misri et al., 2009). Photos showing the development of such a boat are shown in Figure 63. Sugar palm fibre shows good performance in the marine environment as studied by Leman et al. (2008).

Figure 63 Development of a small boat using sugar palm fibre composites

CONCLUSIONS

The ‘Throw over the wall’ syndrome has been replaced with concurrent engineering in product development of composites. Materials selection for polymeric composites can be carried out using various tools such as the knowledge based system, neural network and analytical hierarchy process, together will established tools like Ashby chart, materials handbooks and materials databases. Designers working with composite materials can use available engineering design methods to come up with design concepts in the development of composite products. Study of manufacturing issues related to composite development such as mould flow analysis is essential in order to obtain valuable information regarding the manufacturing process during the early stage of design. Rapid prototyping plays an important role in the development of composite products not only as a means of design communication but also as a means of highlighting design flaws and to analyse the aesthetics, ergonomics and manufacturability factors. Design for sustainability is an emerging technology related to CE and it is very much related to the study of natural fibre composites and ‘green’ products made from natural fibre composites.

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BIOGRAPHY

Professor Mohd Sapuan was born on 25 September, 1965, in Teluk Intan, Perak, Malaysia. He earned his B.Eng degree in Mechanical Engineering from University of Newcastle, Australia in 1990. Subsequently, he continued his studies and obtained his MSc in Engineering Design from Loughborough University, UK in 1994 and finally his Ph.D from De Montfort University, UK in 1998, in the area of Concurrent Engineering for Composites. Later he also pursued other qualifications including Life Fellow, International Biographical Association, UK; Fellow, Institute of Materials Malaysia; Life Member, Institute of Energy, Malaysia; Member, International Association of Engineers; Member, Society of Automotive Engineers Inc., USA; Fellow, Plastics and Rubber Institute, Malaysia; Honorary Member, Asian Polymer Association, India; and Member, International Network on Engineering Education and Research (iNEER), USA. He is now registered with the Board of Engineers, Malaysia as a Professional Engineer.

Professor Mohd Sapuan is the Head and Professor in the Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia (UPM) - the former since August 2008 and the latter in May 2007. Prof. Mohd Sapuan has also held other posts, including Research Assistant, Faculty of Engineering, Universiti Malaya (1990-1993), Executive, Proton Bhd., Malaysia (1993), Lecturer and Associate Professor, Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia (1998-2007), Lecturer and Head of Advanced Materials Research Centre, Institute of Advanced Technology, Universiti Putra Malaysia (1999-2001), Visiting Lecturer, Department of Engineering Design and Manufacture, Universiti Malaya (2001-2002), Research Associate, Advanced Materials and Nano-technology Laboratory, Institute of Advanced Technology, Universiti Putra Malaysia (2001-2006, 2008-now), Visiting Academic, School of Engineering, Design and Technology, University of Bradford, UK (2007-2008), Vice President, Asian Polymer Association (2008-now), Program Manager in Advanced Composite Materials, Advanced Materials and Nanotechnology Laboratory, Institute of Advanced Technology, UPM (June 2008- August 2008, September 2009-September 2010), Research Coordinator, Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia (UPM) (2008), Head, Engineering Composites Research Centre, Faculty of Engineering, UPM (February 2010 – now), and Research Associate, Biocomposite Laboratory, INTROP, UPM (June 2010 – now).

Prof. Mohd Sapuan's contribution to his research field is evidenced by his publications. To date he has authored and co-authored more than 600 publications on mechanical engineering, specializing mainly in composite materials and concurrent engineering, including in national and international journals (265 papers published/accepted), books authored/edited (8), chapters in book (15) and conference proceedings/ seminars (270). Among the prestigious journals he has written articles for are: Proceedings of IMechE Part A: Journal of Power and Energy, Proceedings of IMEch Part J: Journal of Materials: Design and Applications, Proceedings of IMechE Part E: Journal of Process Mechanical Engineers, International Journal of Fatigue, Industrial Crops and Products, Biomass and Bioenergy, Journal of the American Oil Chemists' Society, Polymer and Polymer Composites, Polymer Plastics Technology and Engineering, Materials World, Composites Part A: Applied Science and Manufacturing, Assembly Automation, Journal of Engineering Design, Industrial Lubrication and Tribology, Engineering Computations, International Journal of Food Properties, International Communications in Heat and Mass Transfer, Journal of Composite Materials and Materials and Design.

More than 90 of his papers were published in journals indexed in Thomson Reuters (formerly known as ISI) with cumulative impact factor more than 60. His papers were cited 233 times and his H index is 8.

The books that he has authored are titled Engineering Design, Polymer-Based Composites, Product Design and Concurrent Engineering, Industrial Management and Glossary of Composite Materials. He has also edited three books titled Research in Natural Fibre Reinforced Polymer Composites and Simulation for Engineering Undergraduates, both published by UPM Press, and Composite Materials Technology: Neural Network Applications, published by CRC Press, USA.

Professor Mohd Sapuan has also been on more than 20 international editorial boards, including as Editor-in-Chief, International Journal of Applied Engineering Research (2010-now), Regional Editor for Journal of Food, Agriculture and Environment, Finland (2006-2010), Regional Editor, American Journal of Engineering and Applied Sciences (2008-now), Editorial Board Member for International Journal of Mechanical and Materials Engineering (2007-present), Mechanical Engineering Research Journal (2005-now), BVIMR Management Edge Journal (2007-present), International Journal of Materials Engineering and Technology (2008-now), Pertanika Journal of Science and Technology (2009-now) and International Journal of Automotive and Mechanical Engineering (2009-2010). He was also invited by the American Journal of Applied Sciences as a 'Guest Editor' for the topic of 'Recent Advances in Composite Materials Technology' (2005), Pertanika Journal of Science and Technology (3 issues) in 2010 and 2011 and a journal of Institute of Physics Material Science Series in 2010. He was appointed Editor-in-Chief of the Bulletin of Faculty of Engineering (*Perintis*), UPM (2006-2007). He also serves as referee for more than 200 journal papers.

He has presented 11 keynote and invited lectures at conferences. He also served as a member of the advisory/organizing committee of 26 national and international conferences. He chaired the 9th National Symposium on Polymeric Materials (NSPM 2008) and is chairing the 8th International Conference on Composite Science and Technology (ICCST/8). Eight PhD and 12 MSc students have completed their research under his supervision. He has also served as an external Examiner for degree programs in UniKL and UTeM.

Professor Mohd Sapuan has one patent granted and 2 inventions to be registered as Malaysian patents. Further, over the years, Professor Mohd Sapuan has received numerous awards and honours, among others, Excellence Service Awards, UPM (2001-2006, 2008, 2009 (eight times); *Anugerah Karyawan Putra Cemerlang*, UPM (2002); Excellence Researcher Award (the highest number of papers published citation indexed journals) (2005); Excellence Award, science Publications, New York (2005); Excellence Researcher Award, UPM, (Publication Incentive Award; the highest in the category of Professor) (2007); Certificate of Excellence Award in Teaching, Faculty of Engineering, UPM (2007); Honorary Member and Vice President, Asian Polymer Association, (2008), Vice Chancellor Fellowship Prize, (Excellence in Research) UPM (2008), ISESCO Science Prize in Technology (Gold Medallist) (2008), Excellence Researcher Awards (Publication Incentive Award; the highest in the category of Professor (2008) and International Special Award (2008)). In 2010 he won the Plastics and Rubber Institute, Malaysia (PRIM) Fellowship Award and FRIM Publication Award (Semi/Non Technical Publication Category). Professor Mohd Sapuan is also listed among the ISESCO Science Laureates.

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The support from other students and staff at the Department of Mechanical and Manufacturing Engineering, UPM is also highly appreciated. The contribution of all UPM students and staff in general is highly appreciated.

GLOSSARY

Glossary for Concurrent Engineering

3D Printer: It is a rapid prototyping method developed by Z-Corp and it is the cheapest among the RP methods available.

Aesthetics: It is a branch of study dealing with art, taste and beauty, and product design partially looks at this attribute so that the product will be accepted in the market.

Analytical hierarchy process (AHP): Analytical hierarchy process is a multiple criteria decision-making tool that is used in almost all applications related to decision-making problems.

Artificial neural network (ANN): It is a computational model that simulates the structure and functional aspects of a biological system. ANN is now widely used in many engineering applications.

Ashby materials selection chart: It is a material selection chart developed by Professor Ashby from Cambridge University, which is normally used to select materials based on the performance index. It is now available as a software, jointly developed with Granta Design with the system called Cambridge Engineering Selector.

Computer Integrated Manufacturing (CIM): It is an integration of the computer and production process. The approach is through use of computers to control the whole production process by means of exchange of information and initiation of actions.

Computer-Aided Design (CAD): Technology that uses computer programs to design, generate and document objects.

Computer-Aided Manufacturing (CAM): Translation of computer-aided design data into the machine tools for manufacturing.

Conceptual design: It is the step in total design process performed after product design specification is prepared. It is an idea generation stage and tools and techniques can be used to generate the concept.

Detail design: A step in total design after the conceptual design where design analysis, design calculation and drawing can be involved.

Embodiment design: It is a stage in the design process after the conceptual design and before the detail design stage.

Ergonomics: It is the science of designing the job, equipment and workplace to fit the worker. It deals with good man-machine interface and human factors in design.

Expert System: A branch of artificial intelligence that is used to provide an answer for some problems, by consulting human experts in decision making.

Fused deposition modelling (FDM): It is a rapid prototyping process used for modelling, prototyping and production. FDM builds a model using thermoplastics acrylonitrile butadiene styrene (ABS), polycarbonate and polyphenylsulfone (PPSU).

Market investigation: It is the first stage in the total design process where designers should try to search for as much information as possible on the design by means of searching for the information through publications, interviews, studying competitors' products etc.

Materials database: Storage of materials' properties, where it is also used as interface with the computer system tool.

Materials handbook: Published materials that provide materials data.

Materials selection: A method of choosing suitable materials for an engineering product, normally carried out using software systems.

Mould flow analysis: It is software system that simulates the behaviour of molten materials inside the mould during manufacturing process using closed moulds such as injection moulding and resin transfer moulding

Patent search: It is an activity to search for existing patents during the design process to check if there is any patent infringement in the design.

Product design specification (PDS): In total design process, PDS is normally a dynamic document prepared during the design process and it becomes the design guide.

Pugh selection method: A evaluation matrix method developed by S. Pugh based on comparison of concepts with a datum. All the concepts will be given plus, minus or same against criteria and the concept with the highest positive difference between plus and minus is chosen as the best concept.

Quality Function Deployment (QFD): It is a method to transform user demand into design quality. It involves the use of House of Quality.

Rapid prototyping: An advanced technology that automatically constructs three-dimensional models from computer programs (computer aided design (CAD) data).

Simultaneous engineering: It is just another name for Concurrent Engineering. It is concerned with consideration of all manufacturing and related functions at an early stage of the design process.

Stereolithography (SLA): It is the first technique of rapid prototyping. It is a 3-D layering process, which builds a solid three-dimensional model using thin layers of ultraviolet (UV), one on top of the other.

Total Design: A model developed by Pugh used in the design of a product. It considers market need, specification, conceptual design, detail design, manufacture and sale.

Glossary for Composites

Advanced composite: A combination of one or more reinforcing materials with a compatible matrix system, applicable to many applications from household to aircraft construction.

Anisotropic material: A material that exhibits different properties in different directions.

Carbon fibre reinforced composites: Composites in which the reinforcing phase is carbon in the form of fibre.

Ceramic matrix composites (CMC): Composites in which the reinforcing phase is enveloped in ceramic material. Example: silicon carbide fibre reinforced aluminium oxide.

Compatibility: The ability of two or more substances to be mixed with each other to obtain high homogeneity of composition.

Compression moulding: The method of moulding a material already in a confined cavity by applying pressure and heat.

Drapability: The ability of a material to conform to a curved surface.

Fibre orientation: Direction of fibre alignment in a non-woven fibre composite.

Fibre: A bundle of individual cells with adequate strength, length and fineness required for various fibrous industrial applications.

Filament winding: An automated process which involves winding resin treated continuous filaments under tension over a mandrel in a pattern designed to achieve maximum strength in a certain direction. This process is normally suitable to make components with circular cross section.

Glass fibre reinforced plastic (GRP or fibreglass): A combination of plastic material and fibrous glass with better mechanical properties as compared to the base material.

Hand lay-up: A traditional, labour intensive, open mould composite manufacturing process to produce one-off or low volume products.

Hybrid composites: Composites with fibres made from two or more materials normally carried out to optimise the properties of the composites.

Injection moulding: Moulding of polymer or polymer composites under pressure in a closed mould.

Isotropic: Material that exhibits properties that do not change with the direction of measurement.

Matrix: The continuous phase which envelops the reinforcing phase in a composite material.

Metal matrix composites (MMC): Composites in which the reinforcing phase is enveloped in metallic material.

Natural fibre composites: Composites with the fibres derived from natural sources, particularly plant based, such as coconut fibre (coir), banana pseudo-stem fibre, sisal, ramie, hemp, jute, flax, pineapple leaf fibre, oil palm fibre, and sugar palm fibre. The major advantages of natural fibres include its being environmentally friendly, low density, low cost, available in abundance and renewable.

Polymer matrix composite: Composites in which the reinforcing phase is enveloped in polymeric material.

Pultrusion: A continuous manufacturing process of composites, consisting of pulling a resin impregnated fibre into a certain shape of die before the resin is cured.

Reinforced Plastics: A combination of plastic material with any kind of reinforcements with better mechanical properties as compared to those of the base plastic.

Reinforcement: The component, which provides a composite material with higher elastic modulus and/or strength as compared to the base material.

Resin transfer moulding (RTM): A form of liquid moulding whereby positive pressure is used to drive a liquid resin into a mould cavity containing dry fibres.

Resin: The term used to designate any polymer that is a basic material for plastics.

Strength: Resistance to stress. Yield strength is the stress to initiate plastic deformation. Ultimate tensile strength is the maximum stress that can be borne by the material, calculated on the basis of the actual area.

Tensile strength: A measure of the force, per unit area, required to break a test specimen when it is placed between two clamps and then drawn.

Thermoplastic polymer: A polymer, which is able to soften with increase in temperature, thus becoming mouldable, and re-hardens on cooling.

Thermosetting polymer: A polymer which is in liquid or semi-liquid state before curing, but may undergo a chemical reaction to form a well-bonded three-dimensional cross-linked structure and hence become more insoluble and infusible after curing.

Toughness: Resistance to fracture by impact loading and measured by the Izod or Charpy tests which give the amount of energy required to fracture a standard sample. It can also be represented by the total area under stress-strain diagram.

Wettability: The ability of one phase to spread over the surface of another.

Yield strength: Stress that causes the material to reach its elastic limit, i.e. resistance to the onset of plastic deformation.

Young’s modulus: Stress per unit of elastic strain, measured by the slope of the elastic part of the stress-strain curve, indicating the stiffness of the material.

LIST OF INAUGURAL LECTURES

1. Prof. Dr. Sulaiman M. Yassin
   The Challenge to Communication Research in Extension
   22 July 1989

2. Prof. Ir. Abang Abdullah Abang Ali
   Indigenous Materials and Technology for Low Cost Housing
   30 August 1990

3. Prof. Dr. Abdul Rahman Abdul Razak
   Plant Parasitic Nematodes, Lesser Known Pests of Agricultural Crops
   30 January 1993

4. Prof. Dr. Mohamed Suleiman
   Numerical Solution of Ordinary Differential Equations: A Historical Perspective
   11 December 1993

5. Prof. Dr. Mohd. Ariff Hussein
   Changing Roles of Agricultural Economics
   5 March 1994

6. Prof. Dr. Mohd. Ismail Ahmad
   Marketing Management: Prospects and Challenges for Agriculture
   6 April 1994

7. Prof. Dr. Mohamed Mahyuddin Mohd. Dahan
   The Changing Demand for Livestock Products
   20 April 1994

8. Prof. Dr. Ruth Kiew
   Plant Taxonomy, Biodiversity and Conservation
   11 May 1994

9. Prof. Ir. Dr. Mohd. Zohadie Bardaie
   Engineering Technological Developments Propelling Agriculture into the 21st Century
   28 May 1994

10. Prof. Dr. Shamsuddin Jusop
    Rock, Mineral and Soil
    18 June 1994

11. Prof. Dr. Abdul Salam Abdullah
    Natural Toxicants Affecting Animal Health and Production
    29 June 1994

12. Prof. Dr. Mohd. Yusof Hussein
    Pest Control: A Challenge in Applied Ecology
    9 July 1994

13. Prof. Dr. Kapt. Mohd. Ibrahim Haji Mohamed
    Managing Challenges in Fisheries Development through Science and Technology
    23 July 1994

14. Prof. Dr. Hj. Amat Juhari Moain
    Sejarah Keagungan Bahasa Melayu
    6 Ogos 1994

15. Prof. Dr. Law Ah Theem
    Oil Pollution in the Malaysian Seas
    24 September 1994

16. Prof. Dr. Md. Nordin Hj. Lajis
    Fine Chemicals from Biological Resources: The Wealth from Nature
    21 January 1995

17. Prof. Dr. Sheikh Omar Abdul Rahman
    Health, Disease and Death in Creatures Great and Small
    25 February 1995

18. Prof. Dr. Mohamed Shariff Mohamed Din
    Fish Health: An Odyssey through the Asia - Pacific Region
    25 March 1995

19. Prof. Dr. Tengku Azmi Tengku Ibrahim
    Chromosome Distribution and Production Performance of Water Buffaloes
    6 May 1995

20. Prof. Dr. Abdul Hamid Mahmood
    Bahasa Melayu sebagai Bahasa Ilmu- Cabaran dan Harapan
    10 Jun 1995

21. Prof. Dr. Rahim Md. Sail
Extension Education for Industrialising Malaysia: Trends, Priorities and Emerging Issues
22 July 1995

22. Prof. Dr. Nik Muhammad Nik Abd. Majid
The Diminishing Tropical Rain Forest: Causes, Symptoms and Cure
19 August 1995

23. Prof. Dr. Ang Kok Jee
The Evolution of an Environmentally Friendly Hatchery Technology for Udang Galah, the King of Freshwater Prawns and a Glimpse into the Future of Aquaculture in the 21st Century
14 October 1995

24. Prof. Dr. Sharifuddin Haji Abdul Hamid
Management of Highly Weathered Acid Soils for Sustainable Crop Production
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Fish Processing and Preservation: Recent Advances and Future Directions
9 December 1995

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Pesticide Usage: Concern and Options
10 February 1996

27. Prof. Dr. Mohamed Ismail Abdul Karim
Microbial Fermentation and Utilization of Agricultural Bioresources and Wastes in Malaysia
2 March 1996

28. Prof. Dr. Wan Sulaiman Wan Harun
Soil Physics: From Glass Beads to Precision Agriculture
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The Fascinating Numbers
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