CRANFIELD UNIVERSITY

WEITAO MA

COST MODELLING FOR MANUFACTURING OF AEROSPACE COMPOSITES

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis
Academic Year: 2010 - 2011

Supervisor: Dr. Essam Shehab
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The application of composites has been increasing dramatically in aerospace structures recently, for example, composites have contributed over 50 percent of the structure mass of large transport airplanes Boeing 787 and Airbus 350XWB. However, the further usage has been restricted because of the high material and manufacturing costs. Hence, it is essential to utilize cost estimation tools for accurate cost estimation in the early design stages, and then efficient decisions and design optimizations could be made to reduce the cost of composite products.

This research project aims to develop a cost model for aerospace carbon fibre reinforced plastic (CFRP) composites, which will help designers and cost engineers with the cost estimation for composites manufacturing in the early development stages. The main objectives of the research are to: (i) recognise the standard manufacturing stages and activities of CFRP components; (ii) identify the cost drivers of composites manufacturing; (iii) identify the cost estimation relationships; (iv) develop a cost model that can assist designers and engineers with manufacturing cost estimation for CFRP components; (v) validate the developed cost model through case studies and expert judgements.

The process of model development was carried out through four main steps: firstly, conducting an integrated understanding of cost modelling for composites manufacturing; secondly, collecting data for cost modelling from industry and existing literature and databases; thirdly, developing the cost model with several function modules and databases; and finally, taking a validation of the developed model.

The developed cost model consists of several modules: material selection, process planning, cost estimation, cost reporting and a user friendly interface. Moreover, the selection and planning modules are combined with databases including material and process.

The developed model enables the user to estimate the manufacturing cost and process time of CFRP composites, and it can also help designers realize the impact of design changes on the manufacturing cost. The process planning can efficiently help estimators with manufacturing process understanding and accurate time estimation. Quality control activities are time consuming and investment sensitive in composites manufacturing.

Keywords:

Cost Modelling, Composite Material, CFRP, Hand Lay-up, Non-Destructive Testing, Aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACCEM	Advanced Composites Cost Estimating Manual
ATCAS	Advanced Technology Composite Aircraft Structures
BIS	Department for Business Innovation and Skills
CAD	Computer Aided Design
CATIA	Computer Aided Three-dimensional Interactive Application
CBR	Case-Based Reasoning
C-C	Carbon-Carbon
CER	Cost Estimation Relationship
CFRP	Carbon Fibre Reinforced Plastic
CMCE	Composites Manufacturing Cost Estimator
CMS	Cambridge Materials Selector
CNY	Chinese Yuan
DoD	Department of Defence
FBC	Feature Based Costing
FRP	Fibre Reinforced Polymer or Plastic
GBP	Great British Pound
GFRP	Glass Fibre Reinforced Plastic
HM	High Modulus
HS	High Strength
IM	Intermediate Modulus
MIT	Massachusetts Institute of Technology
MMC	Metal Matrix Composite
NDT	Non-Destructive Testing

PA	Polyamide
PAN	Polyacrylonitrile
PCAD	Process Cost Analysis Database
PE	Parametric Estimating
PEEK	Polyetheretherketone
PMC	Polymer Matrix Composite
PP	Polypropylene
PPS	Polyphenylene Sulphide
RFI	Resin Film Infusion
RTM	Resin Transfer Moulding
USD	United States Dollar
VARTM	Vacuum-Assisted Resin Transfer Moulding

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1 INTRODUCTION

1.1 Background

Advanced composites have been considered as the ideal structural materials to replace the traditional metals for aerospace applications, especially the fibre reinforced polymer or plastic (FRP) composites, owing to their excellent low density and high strength and stiffness. Driven by the high fuel price and the need of high performance, composites have been extensively applied in the aerospace industry since 1960s (Soutis, 2005; Bunselll et al., 2002). Now, they have contributed over 50 percent of the structural mass of large transport aircrafts, such as Boeing 787 and Airbus 350XWB (Marsh, 2007). Aerospace has grown to be the most important market of advanced composites. About 20% of the total global production volume of carbon fibre was consumed by aerospace industry, and about 78% of the UK production of carbon composites was used by aerospace and defence in 2008 (BIS, 2009).

Along with the progress of composite technologies, affordability is the major challenge facing designers and manufacturers of composite components, during the development of current and future aerospace products. Cost engineering and estimation technologies have led to assist design and manufacturing engineers with accurate cost estimation aiming to produce composite structures with reasonable affordability, particularly in the conceptual and preliminary design phase.

However, compared to the mature metallic materials, there is quite less knowledge and information available for composite cost estimation, due to the more complex techniques, like forming, test and repair, and the shorter history of application. Thus, plenty of research efforts have been contributed to the cost engineering for composites, especially in the aerospace area.

1.2 Research Motivation

Although composites have distinct advantages of performances in comparison with conventional metals, the further application has been restricted by the high material and manufacturing cost (Tan et al., 2008; Lemke, 2010; Chung et al. 2004). Reducing the manufacturing cost has become a major factor of commercial success for composite products (Clayton and Howe, 2004).

Undoubtedly, it is much more efficient to reduce the cost in the early design stage rather than in the production phase, as more than 70% of the manufacturing cost has been set during the design phase (Roy, 2003; Shehab and Abdalla, 2002). Hence, cost modelling and estimation are indispensible to assist designers to develop composite parts with more price competitiveness.

1.3 Problem Statement

The cost estimation can target the whole lifecycle or a specific lifecycle stage of a product. To get the whole product lifecycle cost, the basic approach is to estimate the cost of individual lifecycle stages first, and this project focused on the manufacturing cost of composites. Attentions were paid to the carbon fibre reinforced plastic composites as well as the hand lay-up process for aerospace applications in this thesis.

It will be a challenge to perform cost estimation for a composite component in the early design phase, as only limited product information can be determined. However, the historical data of composites and the proper cost estimation techniques can help to achieve this. It is more accurate to predict the manufacturing cost if all activities of composites manufacturing and all cost drivers of each activity are identified. Therefore, it is essential to study the manufacturing activities of composite products, including the part fabrication and also the quality control, and then a cost model can be developed with the captured knowledge.

1.4 Aim and Objectives

The aim of this project is to develop a cost model for the manufacturing of aerospace composites, with focus on CFRP composites. This cost model will help designers and cost engineers with the cost estimation for composites manufacturing in the early development stages of composite structures. Decision makers can use this model to estimate the CFRP composite projects. It can also be used to help designers realise the impact of design changes on the manufacturing cost.

To achieve that, a number of research objectives were set for this research and they are listed as follows:

a) To recognise the standard manufacturing stages and activities of CFRP components.

b) To identify the cost drivers of composites manufacturing.

c) To identify the cost estimation relationships (CERs).

d) To develop a cost model that can assist designers and cost engineers with manufacturing cost estimation for CFRP components.

e) To validate the developed cost model through case studies and expert judgements.

1.5 Thesis Structure

The remainder of this thesis comprises five chapters, and the overall structure of thesis is shown in Figure 1-1.

Chapter 2 states a general review of related literature, mainly including the cost engineering, composite materials, composites manufacturing and cost modelling for composites, and also the gap analysis of previous work. The methodology and its procedure for this research are discussed in Chapter 3. Chapter 4 is mainly about the process of developing the cost model and an introduction to the modelling system. Chapter 5 is concerning the model validation, which was carried out through case studies and expert judgements. In the final part Chapter 6, the achievements and limitations of present model, the contribution and overall conclusions of this research, and also the suggested future work are discussed.

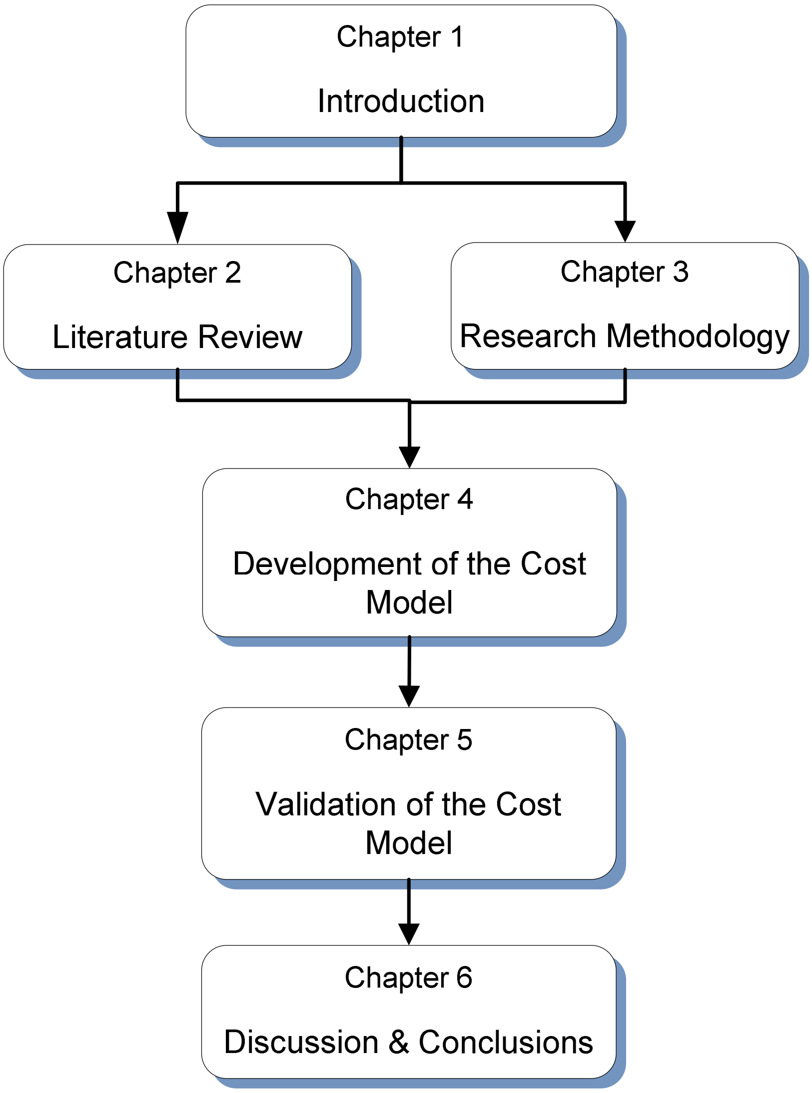


Figure 1–1: Overall Structure of Thesis

1.6 Summary

This chapter firstly gave a background of composite materials and cost engineering, and then the necessity of cost modelling for composites was stated. The problems and challenges for cost modelling were also discussed. Then, it was presented that the research aimed to develop a cost model for the manufacturing of aerospace composites, and the main objectives planned to achieve that were proposed. At the end, the overall thesis structure and the main contents of next five chapters were summarised.

2 LITERATURE REVIEW

2.1 Introduction

A comprehensive literature has been conducted on the major topics and areas associated with cost modelling for composites manufacturing. A brief review of related literature will be presented in this chapter, according to the structure as illustrated in Figure 2-1, and this review aims to gain the fundamental knowledge for conducting the research.

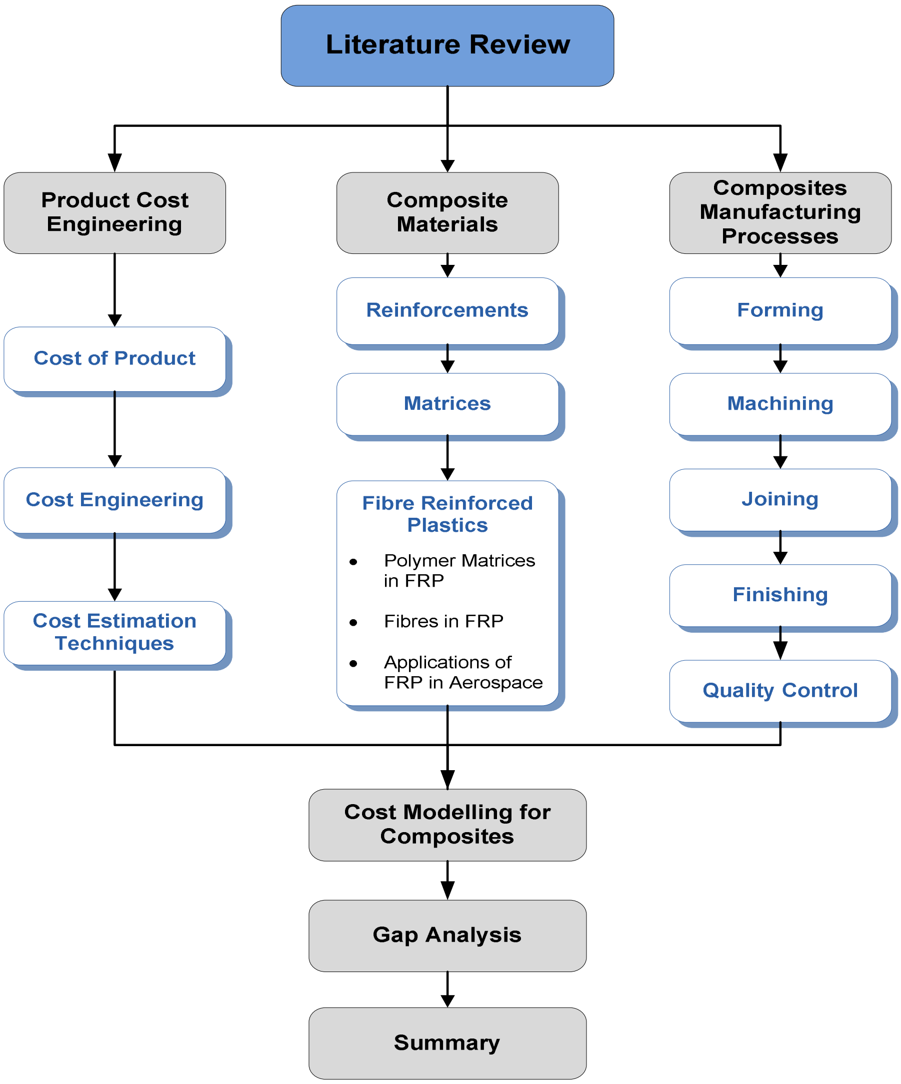


Figure 2–1: Literature Review Structure

2.2 Product Cost Engineering

2.2.1 Cost of Product

Generally, cost refers to the amount of money expended or liability incurred with delivery of products and/or services, and it should cover any expenditure of time, human, and physical resources, from the perspective of total cost management (Humphreys, 2005).

For a product or service, cost is a key factor in the profit and competitive or rather success. Companies are driven to develop new products with decreasing cost by the high competitive market (Bresnahan and Gordon, 1997; Ragatz et al., 1997; Renton 2001). Hoult et al. (1996) illustrated that companies, which had effective cost estimations in the development stages, could reduce the risks of project delay resulted from exceeding development costs. Hence, it is imperative to understand the cost of a new project well before it starts.

The previous research shows that over 70 percent of the product cost is determined in the conceptual design stage (Marapoulos et al, 1998; Shehab and Abdalla, 2001), as shown in Figure 2-2. However, the design phase itself attributes only 6 percent of the product cost, according to Roy (2003) and Hundal (1993). It is obvious that design optimization rather than production optimization towards cost reduction is encouraged.

The product costs are usually arranged with a cost breakdown structure, in which the total product cost is divided into various cost elements. There are some different classifications of the product cost. A brief of the various product costs will be given in the following sections.

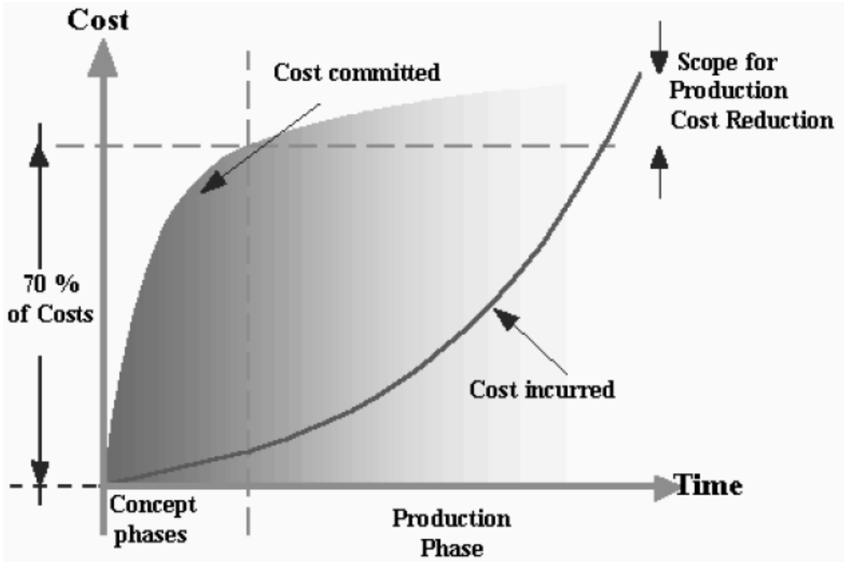


Figure 2–2: Cost Commitment Curve (Roy, 2003)

2.2.1.1 Recurring and Non-Recurring Costs

The recurring cost is the continuous cost that occurs throughout a product lifecycle. It could include any cost that is incurred repeatedly during the production and also the activities to ensure product line running normally, like: material procurement costs, commercial procurement costs, labour costs, production overhead costs, technical upgrade costs, consumable costs, utility costs, etc. (Curran et al., 2004). It must be highlighted that the recurring costs per product unit should decrease with the production quantity increasing (Curran et al., 2004; Mazumdar, 2002).

The non-recurring can be simply defined as the cost occurs only one time in a product lifecycle (Curran et al., 2004). Typically, it refers to the capital expenses that are invested before the first unit of production and it could be attributed by the following varieties: previous engineering costs during the design phase, the procurement and/or update costs of fixtures and tooling, the test and certification costs of system, the manufacturing engineering costs before production, etc. (Curran et al., 2004; Mazumdar, 2002).

2.2.1.2 Variable and Fixed Costs

The variable costs are the production costs that will vary with the rate of output or the performance of service, while the fixed costs will remain constant when those are changed (Curran et al., 2004). Fixed costs can be leasing expenditures, taxes, insurance, equipment maintenance costs, etc. Material costs, labour costs and machining costs are typical variable costs (Curran et al., 2004; Humphreys, 2005). To increase the profit, it is essential to identify the variable costs clearly first and then make effort to reduce them.

2.2.1.3 Direct and Indirect Costs

The direct costs are those associated or identified with a specific unit of output. Direct costs only benefit a specific project, product, service or function, so they can be easily traced with item-by-item basis. Oppositely, indirect costs are that cannot be directly associated or identified with a particular unit of output, and they do not only benefit one specific activity and are difficult to be traced. Examples of direct costs are raw material and/or indirect (or support) material costs, and production (or direct) labour costs. Overhead costs are commonly labelled as indirect costs, including electrical power costs, building work costs, supervisory costs and so on. Overhead costs are usually estimated with a proportion of the direct labour costs, since it will be difficult to identify or define them. (Curran et al., 2004; Humphreys, 2005)

2.2.2 Cost Engineering

As defined by Stewart et al. (1995), cost engineering is an engineering and scientific application and it mainly studies the principles and techniques that are utilized to estimate or predict the costs of activities or outputs. Cost engineering activities concern with problems of the estimation and control of cost, the analysis of profitability and the management, planning and schedule arrangement of project or business (Roy, 2003). According to the same author, it is mainly used to help companies or project groups to manage and budget the product and also to make decisions during the development of specific product.

Cost estimation is a predicting process to quantify the cost of an activity or output within a defined scope (Humphreys, 2005). During the early development stages of new products, cost has a crucial influence on the go or no-go decision, and a too low or too high estimate could lead to meagre profit or business loss, and cost engineering becomes essential to be surviving in the hyper-competitive market for companies (Roy, 2003).

2.3 Cost Estimation Techniques

The methods of cost estimation can be categorized into the following groups: traditional methods, case-based reasoning (CBR), feature based costing (FBC), parametric estimating (PE) and neural network based cost estimation, according to Roy (2003). Furthermore, Rush and Roy (2000) subdivided the traditional ones into first-sight estimates, which are done in the early stage of design process, and detailed estimates applied in the precision costing.

Shehab and Abdalla (2001) classified cost estimation techniques broadly as intuitive, parametric, generative, and variant-based approaches. As mentioned by the same authors, generative model is the most accurate estimating approach, and the based methods include knowledge, feature, operation, weight, material, physical relationship and similarity law.

Niazi et al. (2006) summarised these estimating methods with two major groups, qualitative techniques and quantitative techniques, and each group is hierarchically classified, as illustrated in Figure 2-3. For each technique, the advantages and limitations are also summarised by the same authors, and the details are shown in Table 2-1.

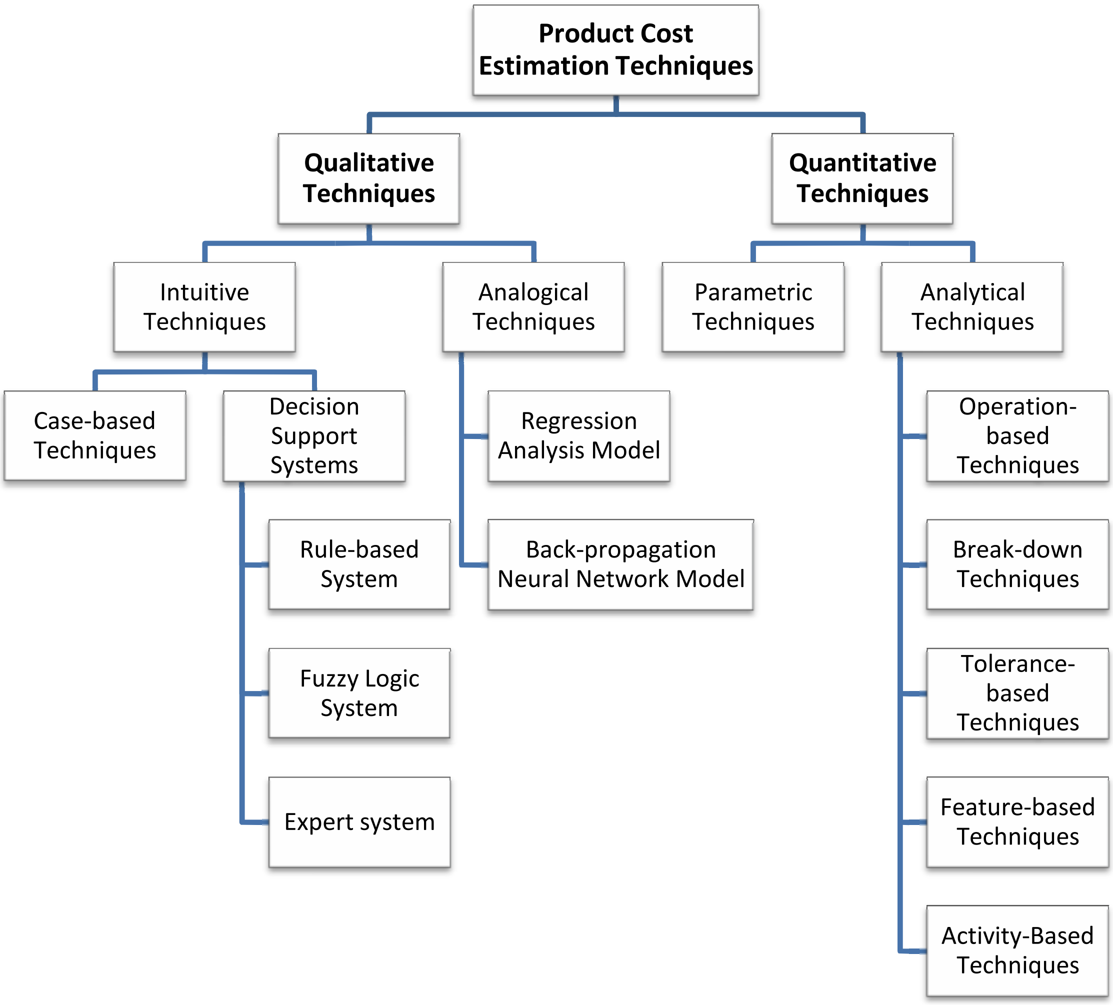


Figure 2–3: Classification of Product Cost Estimation Techniques (Niazi et al., 2006)

Table 2-1: Product Cost Estimation Techniques: key advantages and limitations (Niazi et al., 2006)

Product Cost Estimation Techniques				Key Advantages	Limitations
Qualitative Estimation Techniques	Intuitive Cost Estimation Techniques	Case Based System		Innovative design approach	Dependence on past cases
		Decision Support Systems	Rule Based System	Can provide optimized results	Time consuming
			Fuzzy Logic Systems	Handles uncertainty, reliable estimates	Estimating complex features costs is tedious
			Expert Systems	Quicker, more consistent and more accurate results	Complex programming required
	Analogical Cost Estimation Techniques	Regression Analysis Model		Simpler method	Limited to resolve linearity issues
		Back Propagation Neural Network Model		Deal with uncertain and non-linear problems	Completely data dependant, higher establishment cost
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified
	Analytical Cost Estimation Techniques	Operation-based Cost Models		Alternative process plans can be evaluated to get optimized results	Time consuming, require detailed design and process planning data
		Break-down Cost Models		Easier method	Detailed cost information required about the resources consumed
		Cost Tolerance Models		Cost effective design tolerances can be identified	Required detailed design information
		Feature-based Cost Models		Features with higher costs can be identified	Difficult to identify costs for small and complex features
		Activity-based Cost Models		Easy and effective method using unit activity costs	Required lead-times in the early design stages

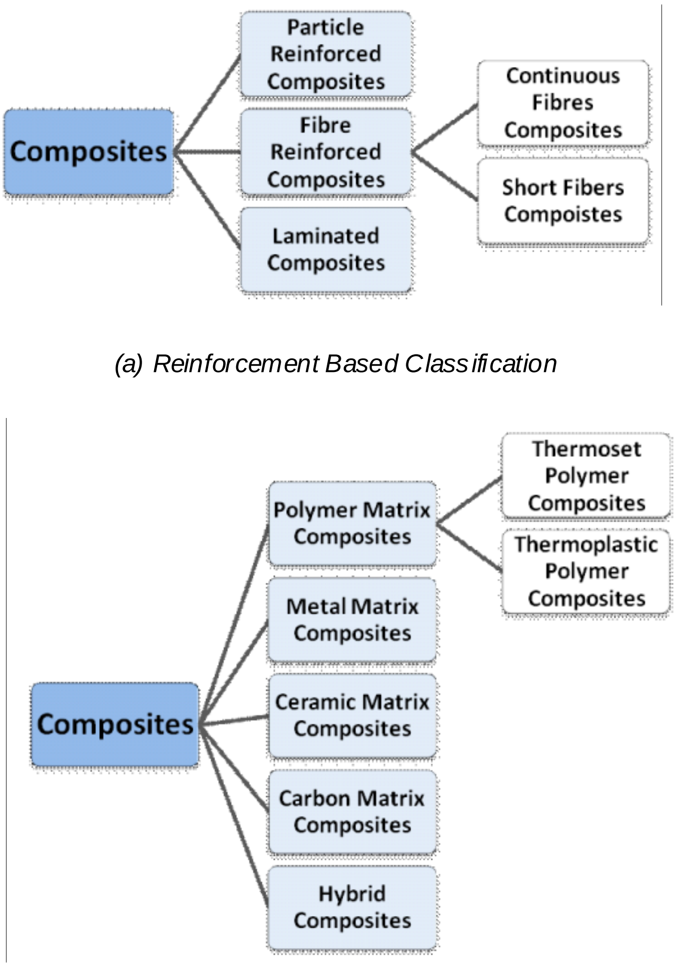
2.4 Composite Materials

Composite material is formed from at least two constitutive materials, which differ in chemical or physical properties and keep macroscopically distinct and separated within the combined structure (Akovali, 2001). The constituent materials are mainly divided into reinforcement and matrix. Fibres, particulates, and whiskers are the normal reinforcement materials, and polymers, metals, and ceramics are the main matrix materials (Mazumdar, 2002).

The composite concept is actually from the nature and has been well developed by human beings over centuries. One of the natural composite materials is wood, which contains cellulose fibres in the lignin matrix (Hull and Clyne, 1996), and other natural examples include bones, nacre etc. (Gao et al., 2003). Concrete is a common example of artificial composite materials (Ortiz and Popov, 1982). Nowadays, a variety of advanced composites have been developed as structure materials and been applied in various industries. The polymer matrix composite, which is reinforced with carbon, glass, aramid or other fibres, is widely used in aerospace (Bijwe et al., 2002; Mangalgiri, 1999).

As a result of proper combination, the composite materials can have better combined properties than constituent materials. As described by Akovali (2001), the optimized mechanical, chemical, physical, thermal, electrical, optical and acoustical properties are produced. In aerospace applications, the persistent demand of lightweight with high strength and stiffness for structural materials led to the increasing use of high performance fibre reinforced polymer composites (Quilter, 2010).

Composites mainly consist of reinforcement and matrix, as mentioned above. Hence composites are usually classified by reinforcement or matrix, as shown in Figure 2-4. A general introduction of reinforcements and matrices in composites will be given in the next subsections.



(a) Reinforcement Based Classification

(b) Matrix Based Classification

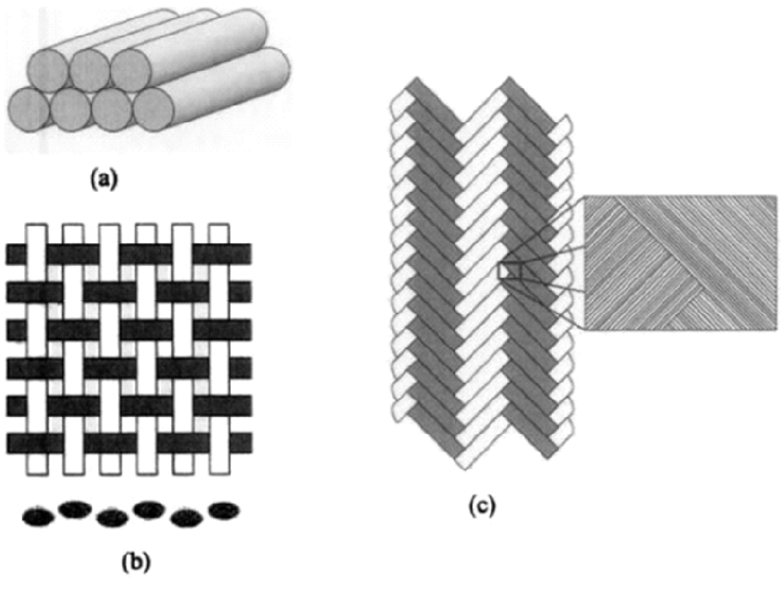
Figure 2–4: Classifications of Composites

2.4.1 Reinforcements

For composite systems, the reinforcements can be discontinuous (particles, flakes, whiskers, or short fibres) or continuous (long fibres or sheets), however, particles and fibres are the most frequently employed forms of reinforcing material. Akovali (2001) categorized composites into particle reinforced, fibre reinforced and structural (typically laminated and sandwiched) composites.

In particle reinforced composite systems, the particle phase is equiaxed and can be spherical, rod, flake or other shapes with roughly equal axes, and they can produce the most isotropic properties of composites, as Akovali (2001) stated. Particulate reinforcements are extraordinarily cheaper than fibre reinforcements, because of the much lower material and manufacturing cost (Ibrahim et al., 1991).

As presented by Akovali (2001), the reinforcing fibres can be in form of chopped strands, rovings (parallel and untwisted filaments), yarns, braids (twisted filaments), knits, woven rovings or woven yarns, and the fibre reinforcing materials employed are various, including polymer (e.g., nylons, polyethylene, and polypropylene), carbon, asbestos, glass, boron, ceramic and metals. Baker et al. (2004) introduced that fibre preforms, impregnated with polymer or other matrices to form the composite products, can be produced by several techniques, such as braiding and knitting, and even by three dimensional weaving for advanced applications. Figure 2-5 shows three different fibre forms, and Figure 2-6 and 2-7 are examples of different weave types.



(a) Unidirectional fibres; (b) Woven fibre fabric; (c) Knitted fibre fabric

Figure 2–5: Schematic of Different Fibre Forms (Chawla, 2006)

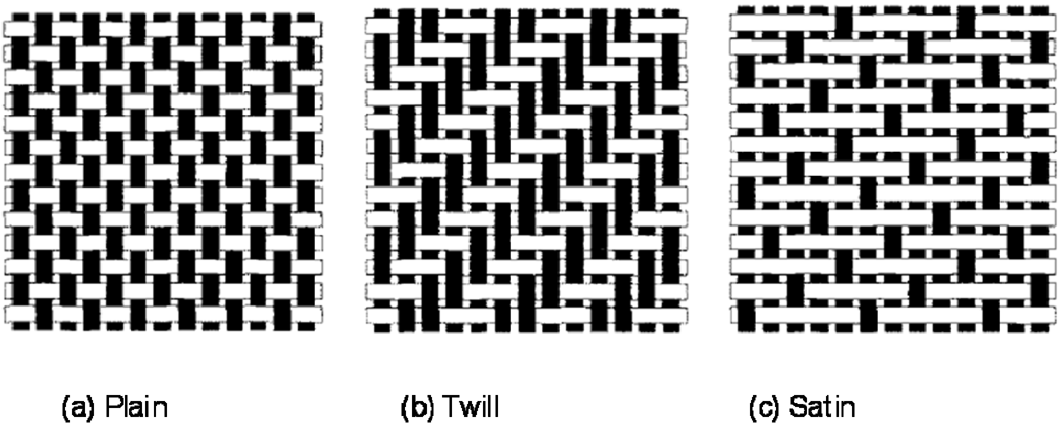
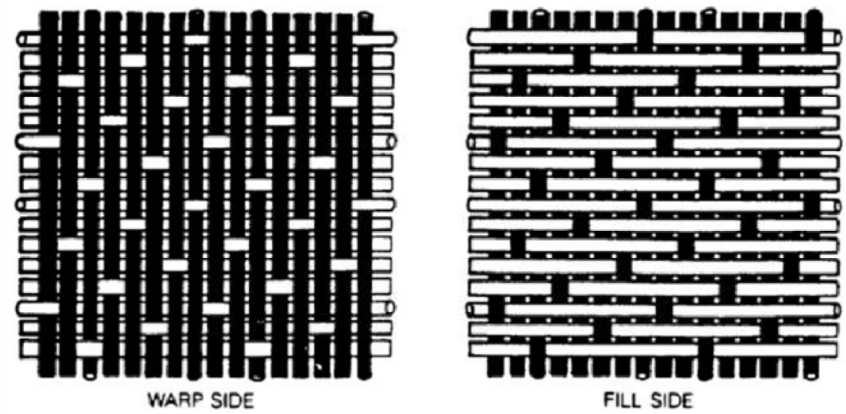


Figure 2–6: Schematic of Common Used Types of Weave
(Baker et al., 2004)



Each yarn goes over 7 and under 1 yarn in both directions.

Figure 2–7: Schematic of 8 Harness Satin Weave (DoD, 2002)

2.4.2 Matrices

The matrix is the continuous phase in a composite material. Its main functions are binding the constituents together and keeping the desired orientations and spacing, distributing uniform load to the composite system, and protecting the reinforcements and composite surface against abrasion, mechanical damage and external corrosion (Akovali, 2001; Baker et al., 2004).

Generally, the matrix can be polymer, metal, ceramic (Hull and Clyne, 1996). Figure 2-8 shows examples of three typical polymer, metal and matrix composites. In metal matrix composite (MMC) systems, pure metals or alloys including aluminium, cooper, steel, magnesium, nickel, and titanium have been applied as matrices (Chawla, 2006; DoD, 2002). Reinforcements in MMCs are discrete fibres or second phase additions, and common reinforcement examples are SiC, Al_2O_3, TiB_2, B_4C, and graphite (DoD, 2002).

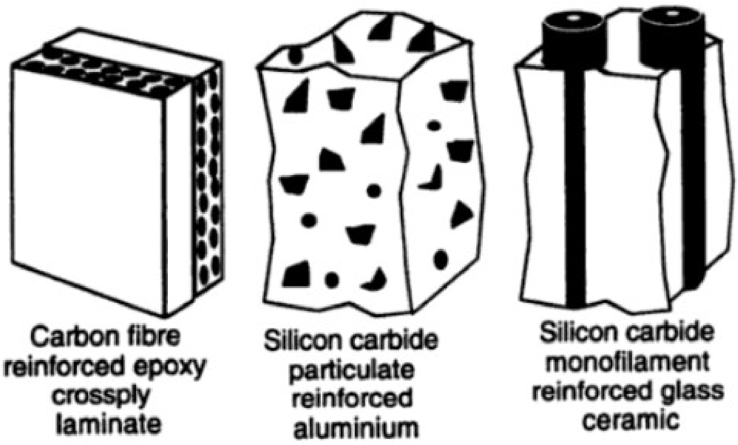


Figure 2–8: Typical Polymer, Metal and Ceramic Matrix Composites (Hull and Clyne, 1996)

Silicone nitride matrices are the commonly applications for ceramic matrix composites, since they have strong, tough, oxidation resistant and high temperature or thermo shock resistant, and one typical example is SiC (both matrix and reinforcing fibres) composites for gas turbine engines (Akovali, 2001).

Carbon matrix composites usually reinforced with carbon fibres are also known as carbon-carbon or C-C composites (Savage, G., 1993; Sheehan et al., 1994). C-C composites can resist high temperatures exceeding 2200 ℃, and hence its applications are in extremely high temperatures, such as the rocket engine nozzles and brake system of airplanes (Akovali, 2001).

Hybrid composites are generally laminates that consist of several thin sheets of alloys (typically aluminium or titanium alloys) boned with fibre reinforced polymers. Common examples of hybrid laminates are ARALL and GLARE, which respectively are aramid fibre or glass fibre reinforced epoxy adhesive bonding with aluminium alloys (Baker et al., 2004; Botelho et al., 2006). Glare has been used in upper fuselage panels of Airbus A380 (Botelho et al., 2006; Bunsell and Renard, 2005). Figure 2-9 shows one typical example of Glare plates.

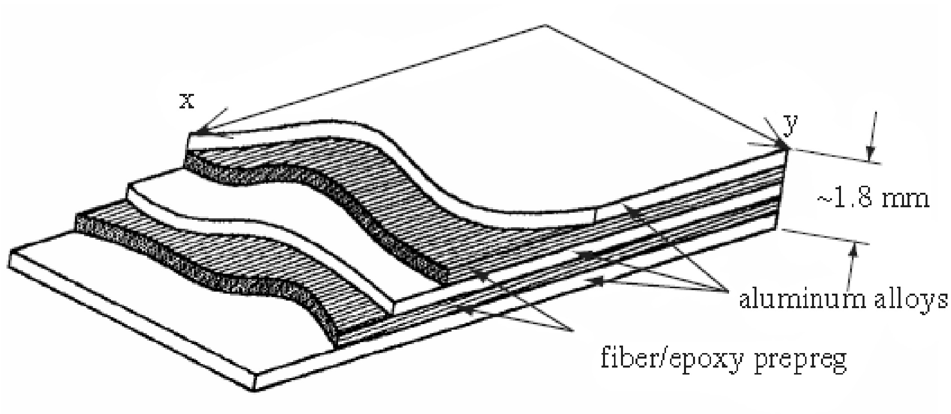


Figure 2–9: Schematic of Glare (Botelho et al., 2006)

2.4.3 Fibre Reinforced Plastics

Fibre Reinforced Plastic or Polymer (FRP) composites are one well developed fibre reinforced composites and they are extensively applied in aerospace industry, defence, sports as well as some other areas. For FRPs, thermoplastic or thermoset polymers are the matrix materials and fibres, usually continuous, are the reinforcements.

2.4.3.1 Polymer Matrices in FRP

According to Bunsell and Renard (2005), polymers are attractive as the composite matrix not only because of their low density, which results in the light weight of composite material, but also they can be applied, either in molten state or in solution state, to impregnate fibres at much lower pressures and temperatures than those for metals, which can significantly decrease the costs of composite manufacture and tool forming. The low elastic module of most polymers can transfer load to fibres by shear, which results in an effective use of the fibre properties. Certain polymer composites can be designed with particularly resistant to environment, impact and fatigue damage.

Polymer matrices are classified into two major types, thermoset and thermoplastic, by the molecular natures of polymers (Flower, 1995; Bunsell and Renard, 2005). Thermoset resins are the longest and most frequently used polymer matrix materials, because of their specialties of easy processing and better fibre impregnation (Bunsell and Renard, 2005; Akovali, 2001). The liquid resins are used in various applications like filament winding, resin transfer moulding and pultrusion (Mazumdar, 2002). According to Akovali (2001) and Mazumdar (2002), the solidification of thermoset occurs at either ambient or elevated temperatures, and the materials cannot be remelted and reshaped after curing. Most common thermoset materials for composites are epoxy, phenolics, polyesters (unsaturated), vinyl esters, cyanate esters, polyurethanes, polyimides and bismaleimides (Mazumdar, 2002).

Thermoplastics are able to be repeatedly reshaped and reformed, as they are heat meltable and cooling curable. Although the usage of thermosets is approximately as double as thermoplastics for composite matrix materials, the growing rate of theromoplastic matrix composites is higher than thermosetting composites, due to the capability of remelting and reforming mentioned previously and the increasing demand of faster composite production rates (Bunsell and Renard, 2005). The character of easy welding for thermoplastics makes the repair and joining of parts simpler than thermosets. However, according to Mazumdar (2002), thermoplastics need to be formed at higher temperature and pressure, and the higher viscosity of thermoplastics also raises the difficulty of manufacturing processes, in comparison with thermosets. Most common thermoplastic materials for composites are polyamide (PA) (nylon), polypropylene (PP), polyetheretherketone (PEEK), and polyphenylene sulphide (PPS) (Flower, 1995; Bunsell and Renard, 2005).

2.4.3.2 Fibres in FRP

As mentioned above, glass, aramid, and carbon fibres are the most important fibres for aerospace composites. However, carbon fibre reinforced composites take the vast majority of aerospace composites, because of the high performance requirements of aerospace structures. Carbon fibre and carbon fibre reinforced composites will be focused in this research.

Carbon fibres are usually produced from organic materials, and they can be made by carbonization process from pitch, rayon, and predominately from polyacrylonitrile (PAN), according to Baker et al. (2004), Bunsell and Renard (2005), and DoD (2002). Figure 2-10 shows one common fabrication process for carbon fibres, which is broken down into white fibre process and black fibre (carbon fibre) process.

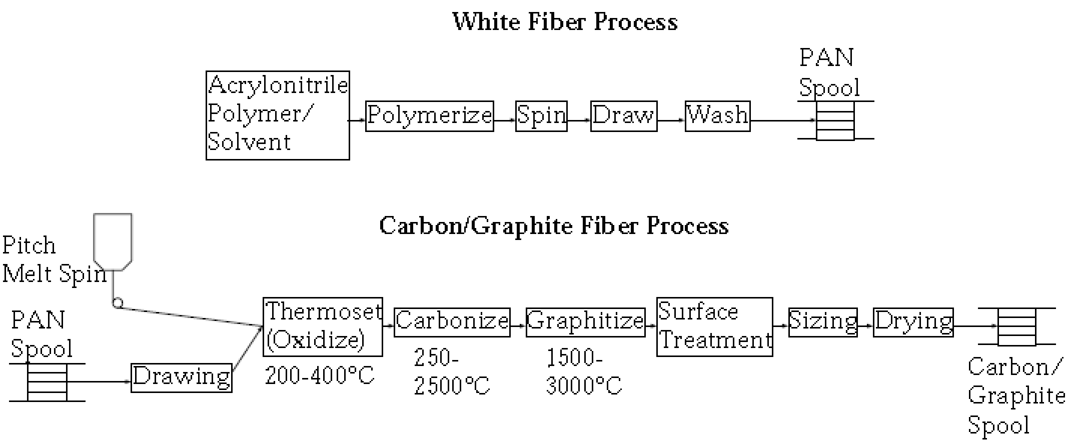


Figure 2–10: Typical Carbon Fibre Fabrication Process (DoD, 2002)

Carbon fibre can be continuous or discontinuous (short), however continuous fibres are the frequently used form in high performance required structures, like aircraft components. For aerospace applications, carbon fibres can be categorized into three types, which are intermediate modulus (IM), high strength (HS), and high modulus (HM) as shown in Table 2-2, according to Bunsell and Renard (2005).

Table 2-2: Typical Properties of Carbon Fibre: HM, HS and IM
(Bunsell and Renard, 2005)

Property	**HM**	**HS**	**IM**
Specific gravity	1.9	1.8	1.8
Tensile modulus (GPa)	276 - 380	228 - 241	296
Tensile strength (MPa)	2415 - 2555	3105 - 4555	4800
Ultimate strain (%)	0.6 - 0.7	1.3 - 1.8	2.0
Coefficient of thermal expansion ($\times 10^{-6}$ mm^{-1} K^{-1})	- 0.7	- 0.5	N/A
Thermal conductivity (Wm^{-1} K^{-1})	64 - 70	8.1 - 9.3	N/A
Electrical resistivity (μΩ m)	9 - 10	15 - 18	N/A

Continuous carbon fibres are normally supplied with yarns, continuous rovings (or tows), woven rovings, woven or knitted fabrics, which are illustrated in Figure 2-5, 2-6 and 2-7. Fibres are usually not in single filament, but in collection of multi-filaments, twisted or untwisted (DoD, 2002; Baker et al., 2004). For industrial designation, carbon rovings are usually identified with 1K, 3K, 6K, and 12K, e.g. 12K refers to 12,000, the amount of filaments in one roving.

Carbon fibres for manufacturing composite products can be supplied either by dry fibre forms, or by wet fibre forms. Prepreg is a common wet fibre form, which are pre-impregnated with uncured resin material (Akovali, 2001).

Prepregs can be purchased in rolls or sheets from material fabricators, and they are ready to manufacture composite products later. Figure 2-11 gives a sketch of the prepregs. Dry carbon fibres need a combination process with either thermosetting or thermoplastic resins by various composites manufacturing processes to form CFRP performs or final products, and this combination process can be generally called impregnation (Coulter and Guceri, 1989).

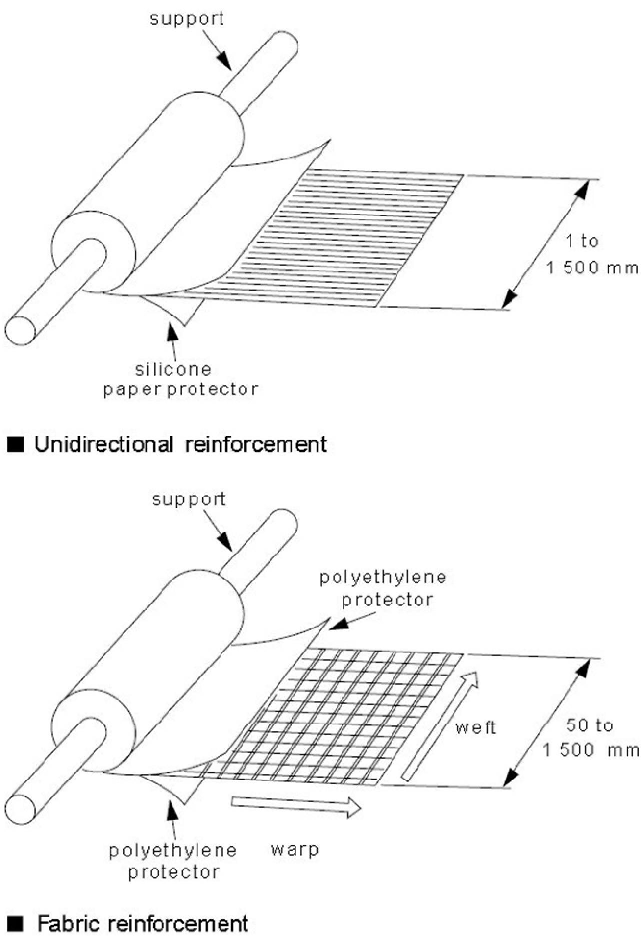


Figure 2–11: Schematic of Unidirectional and Fabric Prepreg (Hexcel, 2010)

2.4.3.3 Applications of FRP in Aerospace

Composite materials take a vital role in the aerospace industry, because weight reduction is one of the key drivers for development of new aerospace products (Botelho et al., 2006). Airbus A320 developed CFRPs on vertical and horizontal box, rudder, elevator, flaps, spoilers, and engine cowls etc., but not yet on primary structures, like fuselage and wing (Deo et al., 2001). However, Airbus has used CFRPs on the primary structures of A380, like centre wing box (Mash, 2004). In the new commercial jet B787, composites takes about 50% of the structural mass of airframe, and CFRPs (laminate or sandwich) take dominant part in B787 composites, as shown in Figure 2-12. According to Bunsell and Renard (2005), CFRP composites contribute 80% of the structure weight of a satellite.

Reducing weight is not the only attraction of fibre reinforced composites to aircraft manufactures, and also reducing part count to improve reducibility and simplify the assembly process, which can get benefit from the lower assembly cost, according to Deo et al. (2001), and Figure 2-13 shows an example of unitizing and integrating multiple components to cut down the manufacturing costs in the early design stages from the US air force programs.

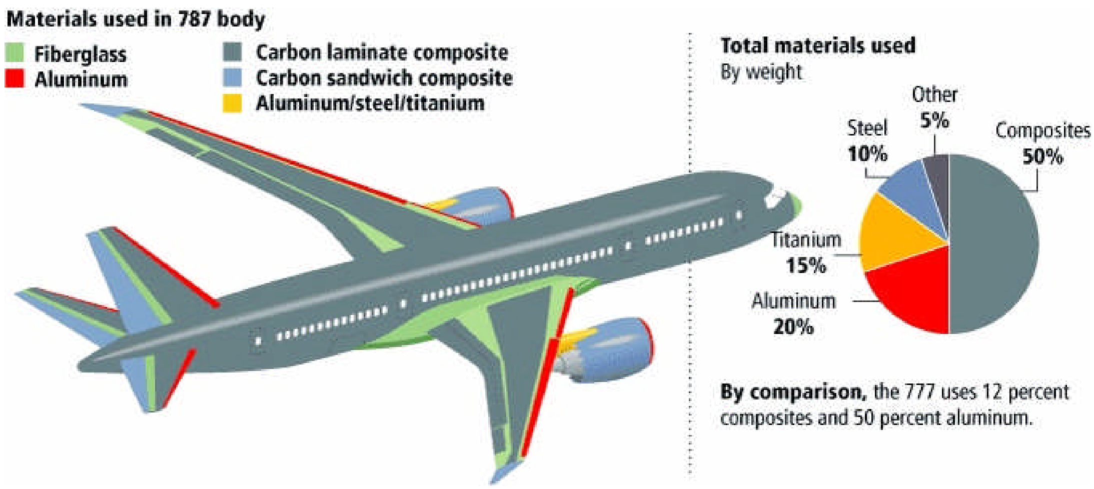


Figure 2–12: Materials in Boeing 787 Airframe (Grandine, 2010)

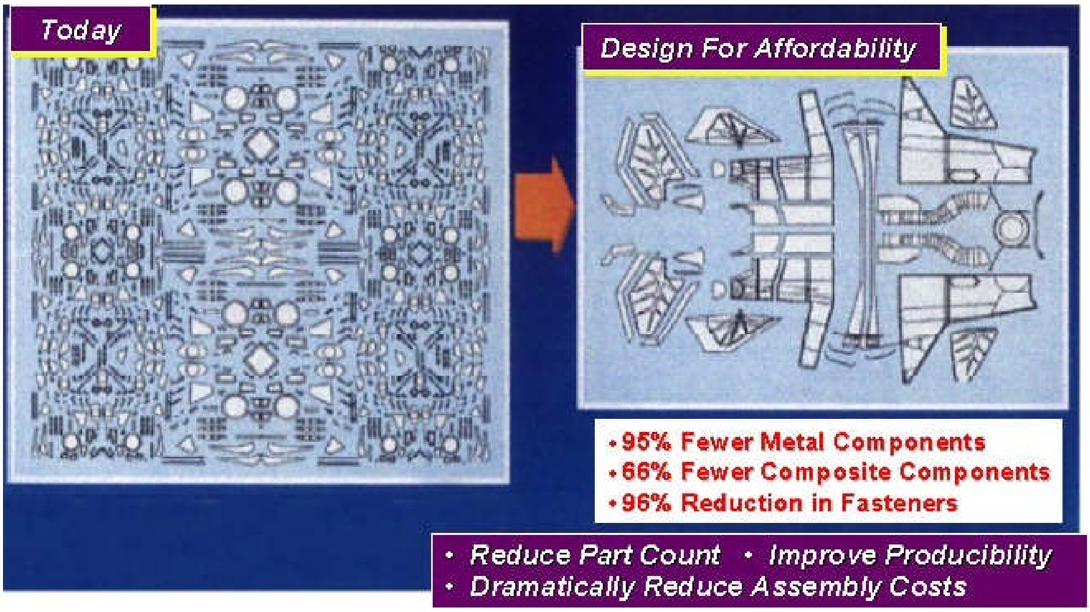


Figure 2–13: Design for Affordability (Deo et al., 2001)

2.5 Composites Manufacturing Processes

The manufacturing processes are quite different from traditional aerospace structural materials, such as metals, since composite materials consist of two or more different materials, and the processes are also various for different matrix systems and reinforcing forms. However, fibre reinforced polymers (FRPs) dominate in the aerospace composite structures, and the typical manufacturing techniques for FRP composites will be presented next. In aerospace applications, the complete manufacturing of composite components can be broken down into four major steps: forming, machining, joining (or assembly), and then finishing, excluding the quality control activities along with the whole manufacturing process.

2.5.1 Forming Processes

Forming processes are those used to bring resins and various forms of fibre or fabric reinforcement together to produce the desired composite parts or final items. Illustrated by Baker et al. (2004), the forming process of composites orientates the fibres in the matrix with proper directions and proportions and it forms the shape of component to obtain the desired two- or three-dimensional mechanical properties, and it may also ensure that the fibres are distributed uniformly in the matrix without unacceptable voids or vacancies of fibres.

Mazumdar (2002) stated that all forming processes for composite parts can be divided into four basic steps, consisting of wetting/impregnation, lay-up, consolidation, and solidification, although each step could be accomplished by various techniques. Some of the detailed forming techniques commonly used for FRP composites are hand or automated lay-up, filament winding, resin film infusion (RFI), resin transfer moulding (RTM), vacuum-assisted RTM (VARTM), pultrusion, etc.

However, the laminating process is the primary manufacturing method for aircraft composite components. In this process, sheets of reinforcements, which are coated with resin pre-coated or freshly applied, are forced against the mould surface under the specific conditions of pressure, temperature, and time (Baker et al., 2004). Figure 2-14 illustrates the typical manufacturing procedures for laminate composites.

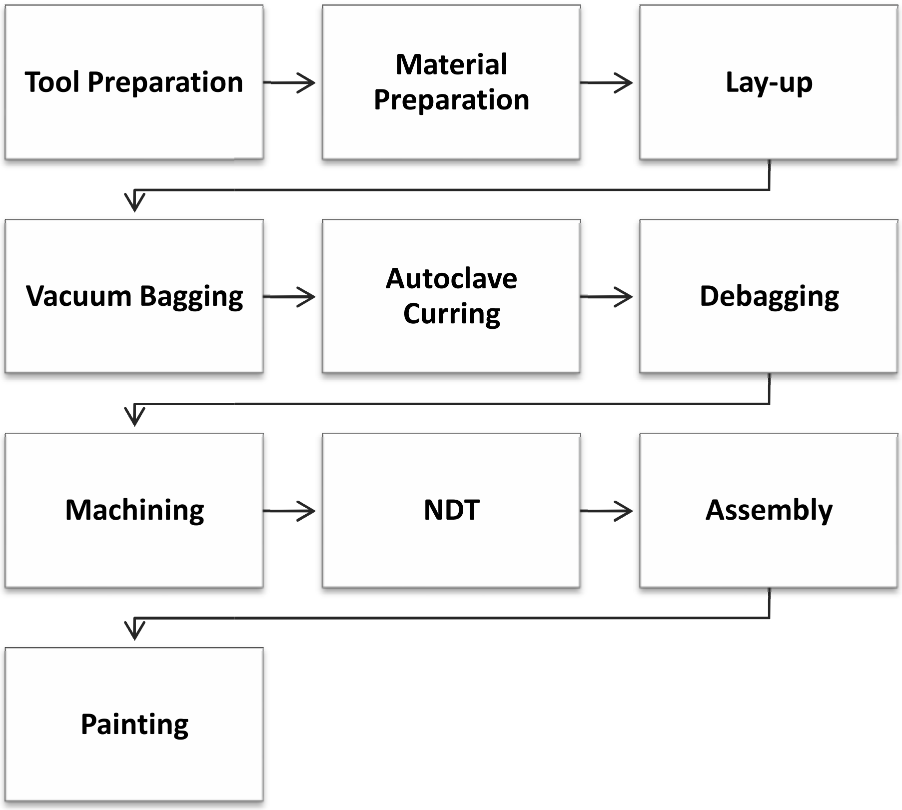


Figure 2–14: Flow Chart of Typical Manufacturing Processes for Laminate Composites

2.5.2 Machining Processes

It has been illustrated that composite materials offer the benefits of part integration in Figure 2-13. Part integration can reduce the amount of parts and thus it can minimize the requirements for machining operations, however the machining operations cannot be completely avoided (Mazumdar, 2002).

There are several types of machining operations, such as cutting, drilling, routing, trimming, sanding etc., and they are performed to achieve various objectives.

Cutting and drilling are two of the major machining operations. Water-jet cutting and laser cutting are two dominating cutting operations (Mazumdar, 2002), and the primary attractions of water-jet cutting are the negligible force on the work-piece and elimination of edge delamination (Baker et al., 2004). Drilling of panels for fastener installing is one of the most time consuming operations in aerospace manufacturing, and it usually needs carbide-tipped drilling tools which are different from those for metal cutting (Baker et al., 2004). Drilling is also operated to produce holes for various features, e.g. a passage for liquid (like oil) or wires (Mazumdar, 2002).

2.5.3 Joining and Finishing Processes

According to Baker et al. (2004), the airframe structures are basically an assembly of simple parts that are assembled together to produce a load transmission path, and the various parts, which include skins, stiffeners, frames and spars, are joined to form the major components such as wings, fuselage, and empennage.

It is a design criterion to reduce the number as well as complexity of joints, for joints and connections are usually the most weakest and most failure emanating points, and furthermore it can minimize the weight and cost (Mazumdar, 2002; Baker et al., 2004). Composite construction is able to create integrated parts and minimize the number of joints, however, it is still challenging to design and manufacture the joints with cost efficiency and structural efficiency and safety (Deo et al., 2001; Baker et al., 2004).

The joint types can be categorized into adhesively bonding, using polymeric adhesives, and mechanical fastening, using rivets or bolts (Mazumdar, 2002; Baker et al., 2004). In airframe construction, both types of joint are common in connecting composite laminates to other composite parts or metal parts.

Finishing usually refers to abrading, burring and painting for the surface that have the requirements of smoothness or corrosion/wear resistant.

2.5.4 Quality Control

Generally, quality control involves the testing and inspections that are carried out during all the stages of part fabrication and/or assembly. According to Baker et al. (2004), quality control for composites includes not only the validation of physical and mechanical properties of cured laminates, but also control of incoming materials and equipments, control of the process, and inspection for defects.

According to the Composite Materials Handbook published by DoD of US (2002), the following points should be specially controlled or monitored:

Material control generally includes the control of package, identification, storage conditions, storage and working life, acceptance and re-verification tests, and those that assure the materials meet the user/manufacturer's specifications or requirements. Tool, equipment and facility control, as well as environment control are vital in composites manufacturing.

Process control of composites involves both laying the material and its subsequent cure. During the laying process, all the plies should be laid in the mould with specified orientation, sequence and position, and the number of plies should meet requirements. The cure cycle must then be monitored to ensure that the heating rate, time at specified temperature, and cooling rate all comply with the engineering requirements. Pressure, vacuum, and temperature must be maintained within the prescribed tolerances and sequence. Some processes may require physical and mechanical tests to validate the processing, using test specimens.

After fabrication, it is required to inspect the composite parts not only for conformance requirements of dimension and workmanship but also for possible damage and defects, like micro-cracks, voids, inclusions and delaminations. The strict quality assurance policy of the aerospace industry enforces components to be inspected for defects using Non-Destructive Testing (NDT) technologies, and sometimes 100% inspection is required, especially for those in the primary structures (Baker et al., 2004). The two frequently used NDT methods for aerospace composite structures are ultrasonic inspection (ultrasonic thru-transmission C-scan and ultrasonic pulse echo A-scan) and X-ray radiography. Figure 2-15 shows one large NDT system, and a skin panel of horizontal stabilizer is lying on the testing bench. Figure 2-16 shows the NDT for a laminate composite part using the portable ultrasonic NDT system.

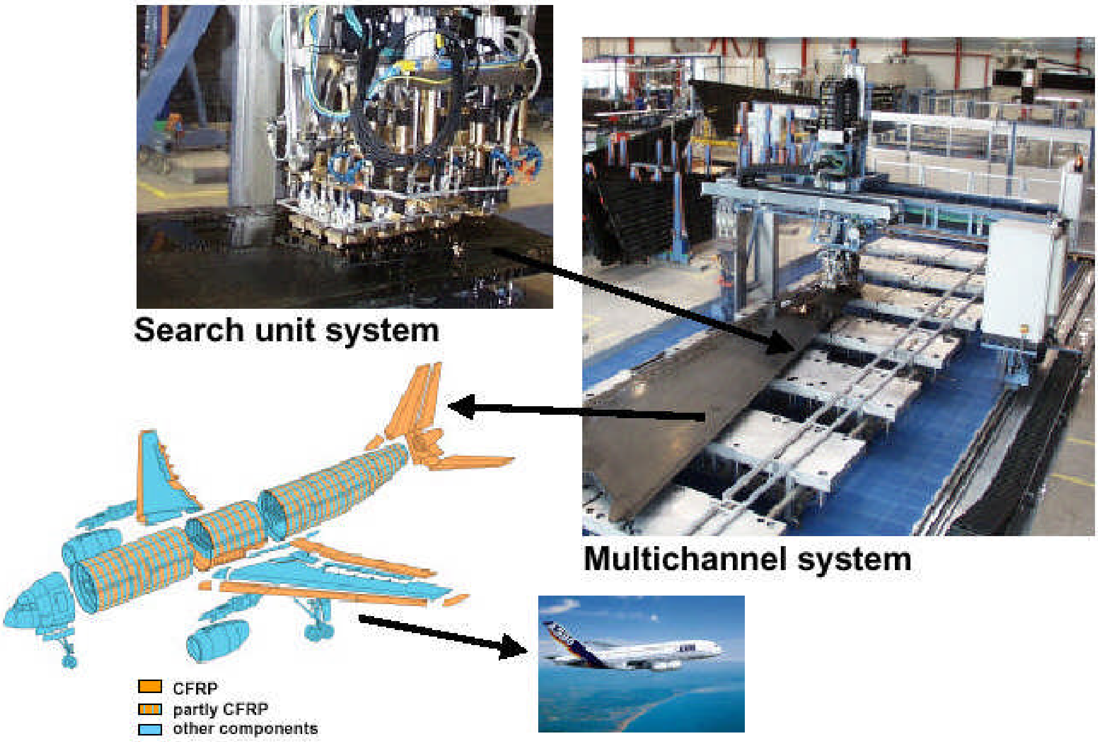


Figure 2–15: NDT for Large Skin Panel of Vertical Stabilizer (Guenter et al., 2003)

Figure 2–16: Portable Ultrasonic Inspection (Olympus NDT, 2010)

2.6 Cost Modelling for Composites

a) ACCEM

Northrop Corporation and U.S. Air force have developed a cost model for hand lay-up process that was published in the '*Advanced Composites Cost Estimating Manual*' (ACCEM) (Lorenzana et al., 1976). This model utilizes a computerized method to estimate the recurring costs, and it breaks the entire manufacture process of a composite part into a sequence of detailed operations and the labour time for performing each operation is calculated using Industrial Engineering Standards equations that are functions of part feature and complexity. The ACCEM model is well known for its reasonable results and it has been used and further developed by some companies. However, this model is limited to estimate the fabrication cost of individual composite parts and it does not include the quality inspection.

b) First-Order Model & Its Extended Models

A theoretical model has been developed by Gutowski et al. (1994) to estimate the processing time (human and machine) for the composite part fabrication.

The theoretical approach refers that the composite fabrication processes can be modelled as first-order basic steps. Firstly, these basic steps are modelled by dynamic equations, and then the step time can be summed to obtain the total time. It was also found that the estimated results fit well with the ACCEM model.

This theoretical model has been applied to develop other detailed models. A web-based system was built by a research group from MIT (Massachusetts Institute of Technology), and the system has the capacities of process time estimation, cost estimation of different composite fabrication processes and also assembly processes (Neoh, 1995; Boyer, 2001; Pas, 2001; Haffner, 2002). However, this system does not cover the quality inspection processes.

The PCAD (Process Cost Analysis Database), developed by the researchers from NASA/Boeing ATCAS initiative, is a process-based manufacturing and assembly cost modelling tool, and the first-order dynamic method was used to model the sequential manufacturing processes and the process time (Gutowski et al., 1995).

Barlow et al. (2002) used the first-order equations for modelling the labour cost of VARTM and RTM manufacturing process for aircraft composite parts, and it was found that the VARTM process needed 10% more labour time to fabricate a aircraft flap, compared with RTM. Using the first-order equations, Clayton and Howe (2005) have modelled the production process and cost of VARTM, RTM and cocure prepreg process, and they found that the fabrication cost of RTM was about 10% less than VARTM and cocure prepreg process, which need vacuum bagging and assembly. However, these two research just focused on the RTM and VARTM.

c) Knowledge – Based Models

A design decision support system was developed for cost estimation for composites manufacturing by Eaglesham (1998), through an intelligent method of searching and processing the existing cost data. However, the quality inspection has not been concerned in this research.

Barton (2002) has developed the Process Link software that has an ability of linking the geometric data that are automatically attracted from CAD model to the PCAD process modelling database. Furthermore, Choi et al. (2005) have created a knowledge-based engineering system with the visual basic application tool in CATIA V5 to estimate the manufacturing cost for composite structures. It has the capacity of capturing geometry and feature data from a CATIA model and it also uses the PCAD to carry out the process cost analysis. The quality inspection has not been mentioned in these two researches either.

With the knowledge-based methodology, an intelligent system has been explored by Shehab and Abdalla (2002) for manufacturing cost modelling for machined and injection moulded products. The system provides user material selection functions, CAD systems, as well as machine/process selection for machining components or mould design for moulded parts. The material selection module gives the user two options, whether specifying the material and properties by themselves or using the professional material selection system CMS (Cambridge Materials Selector). The assembly cost is also covered in the modelling system. Although this system has not covered composites manufacturing yet, the knowledge-based methodology can be applied in this research.

d) Modelling Software

Curran et al. (2008) used the SEER-DFM, a parametric cost estimating system from Galorath Inc., to make cost estimation for composite components as well as composite assemblies, and it is highlighted that although it can produce accurate cost estimation, the estimators need skills to calibrate the software within the specific cost environment of their companies.

Cheung et al. (2009) introduced the cost modelling software ‘Vanguard Studio’ and ‘ExtendSim’ in Rolls-Royce plc, and a composite fan blade as a case study is presented. Using the software, the manufacturing costs along with equipment and labour time are gained basing on dynamic process modelling, and the factory capacity analysis is applied to improve the efficiency of process and design.

e) Other Models

Tse (1992) illustrated a cost model for composite components, which is based on the design complexity and the complexity is measured by an information theory. The manufacturing processes were simulated through experiments of various types of aircraft stringers, and the manufacturing time of three different forming process, hand lay-up, hot drape forming and pultrusion, were compared for the stringers. However, this model has not included the quality inspection.

Alhajri (2008) conducted a research on various lifecycle stages of composite products, from development to recycling. The breakdown activities and the main cost drivers of each stage were highlighted, and a framework aiming to develop a whole lifecycle cost model for composite products was produced. This model just completed the framework for cost estimation.

2.7 Research Gap Analysis

It can be seen that several researchers and institutes have made efforts on cost modelling for composites manufacturing from the literature review. Most of the models were developed for various composites forming processes (manual and/or automatic lay-up, RTM, VARTM, etc.), and some of them can be used to estimate the assembly and tooling fabrication cost.

As a result, a little research effort has been done in cost modelling for composites manufacturing which take into consideration the following:

- Multiple types of composites forming process.
- Part fabrication and also assembly.
- Quality inspection, such as Non-Destructive Testing (NDT).

Quality inspection activities take a much more vital role in manufacturing of -aerospace components, compared to other industries. They are also time-consuming and investment sensitive, especially for the NDT of aerospace composites, as it has very strict inspection requirements and high inspection proportions, and usually it also needs large equipment with advanced systems. Hence, quality inspection is an important cost driver for composites manufacturing in aerospace industry.

It is essential to set up a cost model for composites manufacturing, in which the quality inspection costs is included. Hence, it has been made as the target area of this research.

2.8 Summary

Composite structures are increasingly used in aerospace area, and it is necessary to utilize cost estimation tools as early as possible in the design cycle, thus efficient decisions and optimizations can be made to reduce the product cost. CFRP is the most widely used and developed composite material for aerospace structures, due to its excellent high strength and low density, but the raw material and manufacturing cost of CFRP products is significantly higher than other main structural materials, like aluminium alloys. This makes the author focus the research on the CFRP manufacturing area.

The literature review indicates that some studies have been conducted on the topic of cost modelling for composites manufacturing. It is suggested by the gap analysis to develop a cost model covering the quality inspection costs.

3 RESEARCH METHODOLOGY

3.1 Introduction

As presented previously, the main research aim is to develop a cost model for aerospace composites manufacturing. Firstly, it is imperative to get a well knowledge of composites manufacturing, taking the complexity and multiple types of composites manufacturing processes into consideration. Furthermore, it is also be essential to capture the basic knowledge and skills to develop a cost model. Thus an extensive literature review along with industrial survey has been chosen as the best way to conduct this research, and then detailed work for developing and validating the model has been carried out.

3.2 Adopted Research Methodology

As illustrated in Figure 3-1, the adopted research methodology for cost modelling involves four main phases: understanding the context, data collection and analysis, model development and validation. The main aim, scheduled actions and outputs of each phase are introduced next.

Phase 1: Understanding the Context

This phase aims to obtain an integrated understanding of this research and its related fields. A searching for literature on the topics of cost modelling and composites manufacturing has been firstly conducted from books, journals, reports, theses, websites, etc. An intensive literature review was followed to realise the standard stages and activities of CFRP composites manufacturing and to identify the various cost drivers and cost estimation relationships. The final output of this phase comprised a literature review report, which was incorporated into Chapter 2.

Phase 2: Data Collection and Analysis

This phase is mainly to gather the necessary data for cost modelling. The required data, that covers materials, manufacturing processes, equipments and tooling of aerospace CFRPs, can be collected both from the literature and the industry. There are some literature and databases, which consist of necessary information for modelling the cost of CFRP composites. However, it is impossible to capture all the needed data from the literature and the supplementary data were obtained from the industry. Some questionnaire surveys and interviews of industrial experts were arranged in the industrial process. Otherwise, the quality inspection data of some composite components were collected from the industry to model the quality inspection cost. After data collection and analysis, a cost model structure and several data spreadsheets were presented.

Phase 3: Model Development

The Phase 3 is to output a cost modelling system combined with several databases, including material, process, equipment and tooling. Begin with the design of user interface, databases and cost estimation system, main functions of design attribute inputting, material selection, process planning and estimation result reporting were enabled in a user friendly environment. To implement the modelling system, some valuable ideas and techniques of programming were captured from the literature. Debugging of the system was also carried out when the construction work was finished.

Phase 4: Validation

Finally, a validation of the developed cost model was carried out through case studies and expert judgements. Some industrial components were used to validate the model in the case study stage. Moreover, some industrial experts were invited to attend a validation session of the developed model, from which some expert judgements for the model were gathered. With the case studies and expert judgements, the capacity and the reliability of the developed model were validated.

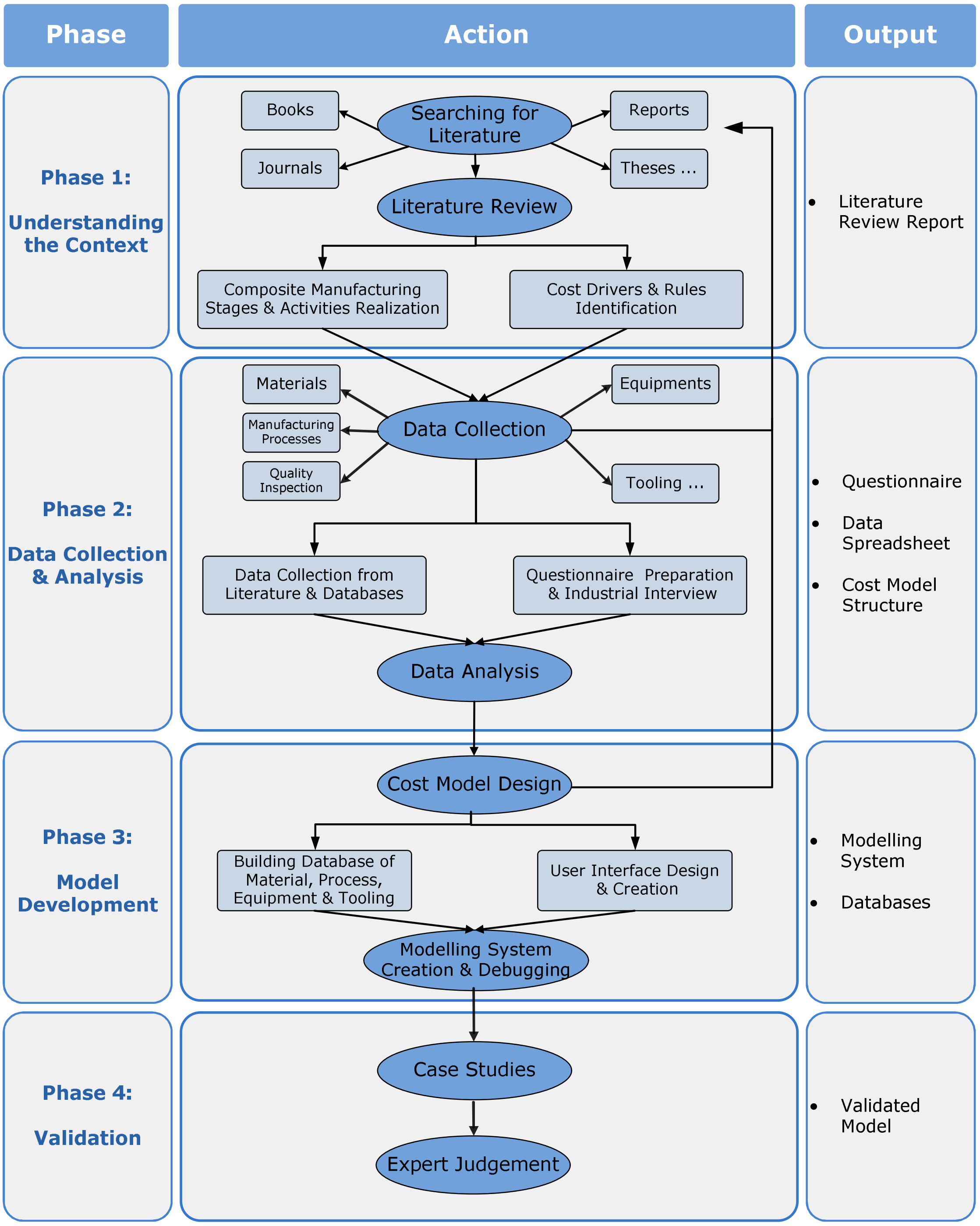


Figure 3–1: Research Methodology for Cost Modelling

3.3 Summary

This chapter introduced the adopted research methodology to develop a cost model for composites manufacturing, and a comprehensive literature review and an industrial survey have been conducted to develop the cost model. It also presented the main schedules to perform it and the main outputs of each phase in this chapter.

4 DEVELOPMENT OF THE COST MODEL

4.1 Introduction

The development approach of the proposed cost model will be introduced in this chapter. The approach can be divided into four primary phases, including conducting the industrial survey, identifying the general activities and cost drivers, developing the cost model and implementing the modelling system.

The gap analysis from literature review shows that the quality control cost should be included in the cost model. Hence, special attentions have been paid on the quality inspection in this research.

4.2 Industrial Survey

The industrial survey was carried out using closed questionnaire. This survey aims to help the researcher to identify cost drivers and collect industrial data for analysing the industrial average proportions of major cost drivers.

The survey was made among five manufacturing companies of aircraft components in China, and eight industrial experts were involved. All of the eight experts, including project managers, engineers and operators, have over 10 years of industrial experience. The questionnaire and the results were all sent by email. Furthermore, three of the eight experts were interviewed by telephone, and the interviews were recorded using the digital recorder. For confidential purpose, the company names and the expert names are not shown in this thesis, and code names were used in the necessary places.

4.2.1 Questionnaire Design

There are three main sections in the questionnaire (see Appendix A). The first section is designed to gather the general information of the interviewee and his/her company. Section 2 is to explore whether the interviewee has any cost estimation experience and to identify the cost drivers. The last section is set to collect the data of manufacturing cost of composites, and it was focused on the hand lay-up and autoclave curing process for CFRP composites.

The questionnaire was designed to be completed within one hour, and fifteen questions were set as a result. For example, the third question Q3 is to know his/her working experience and professional area, and the fifth question Q5 is to identify the key cost drivers which are set during the design stage, and the tenth question Q10 is to determine the average percentage of quality inspection cost in total manufacturing cost, as shown in Figure 4-1.

Q3. General information of you:

Your name (optioned):	
Your responsibility	
Total year of your working experience:	

Q5. For a composite component, which design attributes are the main factors of the manufacturing cost? (Multiple-choice)

A. Material Selection	B. Perimeter	C. Area
D. Thickness	E. Weight	F. Configuration
G. Flanges	H. Steps	I. Curvature
J. Tolerance	K. Surface Roughness	
L. Core	N. Stiffener	O. Requirements of NDT

Other *(please list them below)*:

Q10. From your experience, what percentage of the total manufacturing cost of a laminated CFRP component would be spent on the quality inspections? Please give a specific number, if applicable.

A. 0% - 5%	B. 6% - 10%	C. 11% - 15%
D. 16% - 20%	E. 21% - 25%	F. 26% - 30%

J. Not sure

Other %

Does it include the overhead cost of inspection equipments, tools, and supervising? ('Yes' or 'No')

Figure 4–1: Examples of Questionnaire

4.2.2 Survey Results and Discussion

The data from respondents are based on the individual experience of experts. The main survey results were summarised as follows and the proportions of major cost drivers were illustrated in Figure 4-2. In addition, it should be highlighted that some of the data is only applicable for aerospace industry and prepreg hand lay-up process of CFRPs, as the data are all from this area.

Key cost drivers of design attributes: material selection, geometric sizes (including thickness, area, perimeter and curvature), configurations, inspection standard and requirements, part weight, etc.

Key cost drivers of manufacturing: labour, equipment, tooling, automation, NDT, quality assurance, production volume, scrap rate, etc.

Material Cost: the raw materials and support materials take about 42 percent of the manufacturing cost, and the typical ratio of support material cost to raw material cost is 3 percent. The support materials mean the consumable material during production, mainly including vacuum bagging materials, release agents, and solvent. The typical scrap rate is 15 percent for carbon composite materials, and the typical reject rate is 5 percent for composite parts made by hand lay-up.

Labour Cost: the labour (direct and indirect) takes about 42 percent of the manufacturing cost. The indirect labour time is about 40 percent of the direct labour time.

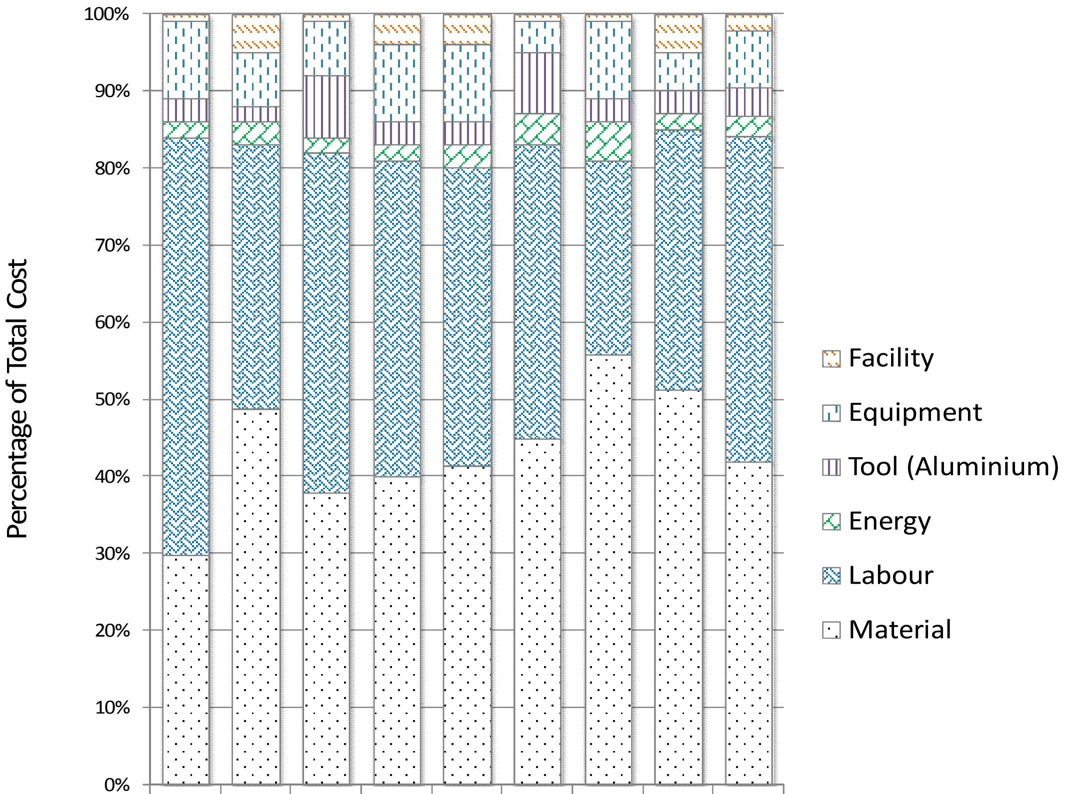
Energy Cost: it is about 3 percent of the total manufacturing cost. It seems to be a very high value, however the autoclave curing cycle and also other large equipments can consume large amount of energy in composites manufacturing.

Tooling Cost: different tooling materials will result the differences in material cost and fabrication cost. The survey indicated that special steel (like Invar) mould will be much more expensive than the mould made with aluminium alloy or other materials, and it may result in over 10 percent of the total manufacturing cost. The aluminium tooling takes about 4 percent of the total manufacturing cost.

Equipment Cost: the equipments take about 7 percent of the total manufacturing cost.

Facility Cost: it is about 2 percent of the total manufacturing cost.

Quality Inspection Cost: It takes about 6 percent of the total manufacturing cost. It should be mentioned that the quality inspection cost is estimated as an individual part, which means the above six types of cost (material, labour, energy, equipment, tooling, and facility) totally take 100 percent of the total cost, except for the quality inspection cost.



Interviewee	A	B	C	D	E	F	G	H	Geomean
Facility	1%	5%	1%	4%	4%	1%	1%	5%	2%
Equipment	10%	7%	7%	10%	10%	4%	10%	5%	7%
Tool (Aluminium)	3%	2%	8%	3%	3%	8%	3%	3%	4%
Energy	2%	3%	2%	2%	3%	4%	5%	2%	3%
Labour	54%	34%	44%	41%	39%	38%	25%	34%	42%
Material	30%	49%	38%	40%	41%	45%	56%	51%	42%

Note: $Geomean = \sqrt{A^2 + B^2 + C^2 + D^2 + \cdots + H^2}$

Figure 4–2: Breakdown of Composites Manufacturing Cost from Industrial Survey

4.3 Standard Activities and Cost Drivers

From the literature review and the industrial survey, a comprehensive knowledge of composites manufacturing and the key cost drivers were identified. That is the first step to set up the cost model. As a result, the major activities of composites manufacturing were summarised and the cost drivers of composites manufacturing were classified in the next subsections.

4.3.1 Standard Activities

It has been presented in Chapter 2 that there are four main stages, forming, machining, joining/assembly, and finishing, in composites manufacturing. Besides of the various fabrication and joining/assembly processes, the quality control activities, mainly including control of materials, equipments, tooling, manufacturing process, quality and defects of products, are covering the whole manufacturing cycle of composite components (see Figure 4-3). The general process flows of CFRP laminating are shown in Figure 2-14 (Chapter 2).

4.3.2 Cost Drivers

In Figure 4-4, the cost drivers of composites manufacturing are classified into five groups, design attributes, materials, production, investment and labour:

Design attributes - The design attributes are the main factors determined in the design stage, which have significant impact on the manufacturing cost. These attributes include the configuration, geometric sizes, weight, inspection requirements, material selection etc.

Materials - The material drivers are not only the raw materials (fibre or fibre preforms, resin, additives, prepreg, etc.) but also the support materials that are consumed during the processing cycle. Otherwise, the number of plies is an important factor which has influence on the lay-up time of preforms or prepregs.

Production - Production elements include various types of operations and the production volume in addition.

Investment - The cost drivers of investment can be identified as tooling, equipments and facilities.

Labour - The labour cost includes the direct labour cost for production as well as the indirect labour cost, e.g. maintenance, manufacturing engineering, quality assurance, and production management.

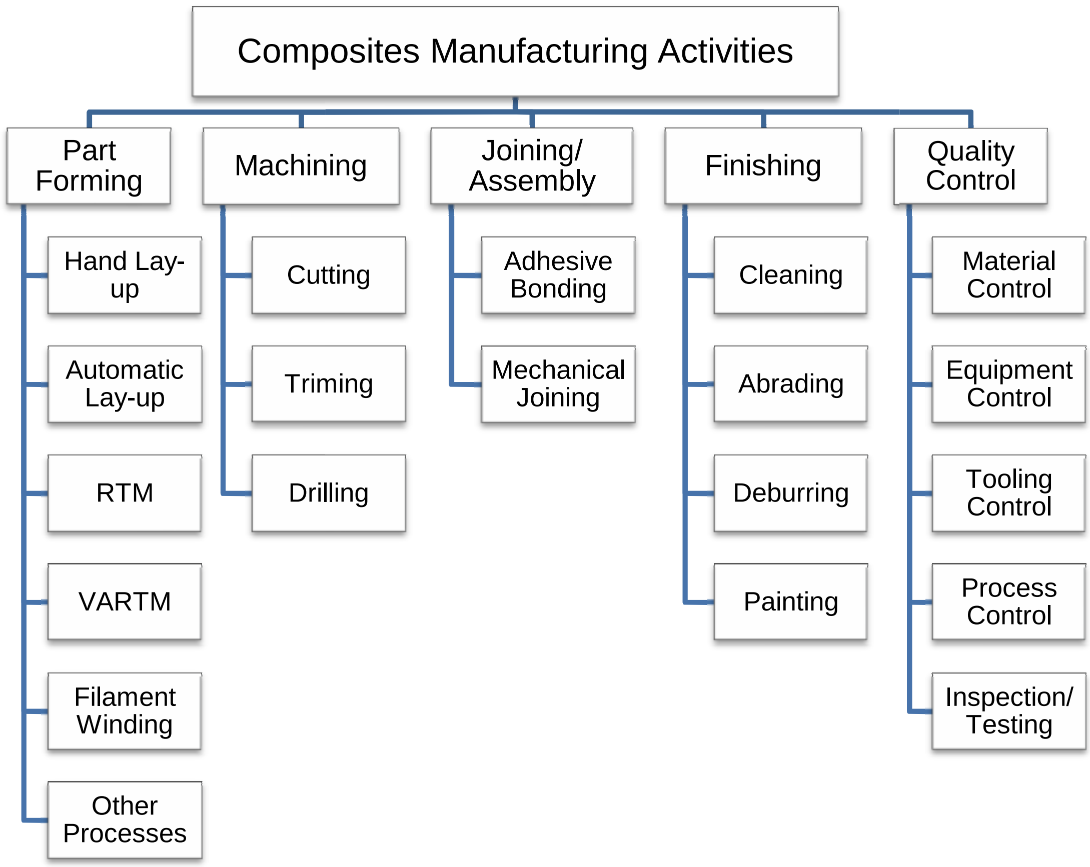


Figure 4–3: Composites Manufacturing Activities

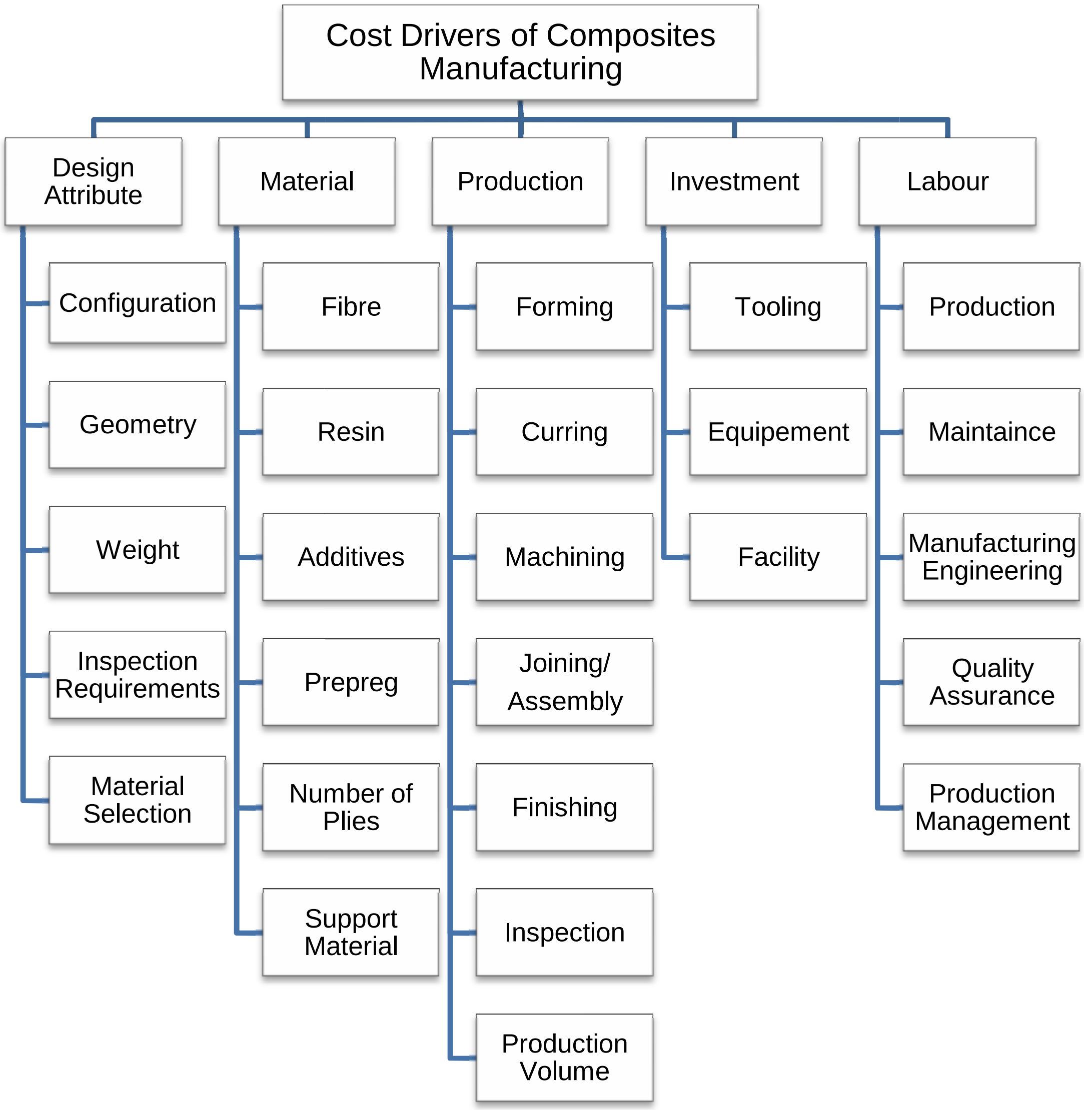


Figure 4–4: Cost Drivers of Composites Manufacturing

4.4 Development of the Cost Model

4.4.1 Overall Structure of the Cost Modelling System

The cost modelling system CMCE (Composites Manufacturing Cost Estimator) basically consists of a material selection module, a process planning module, a cost estimation module, a cost reporting module and a user friendly interface, as illustrated in Figure 4-5. Additionally, several cost databases (material, process, equipment and tooling) are combined with the selection and planning modules.

To make cost estimation, firstly, the user needs to capture the design attributes of composite components from the product models, including the material information and the necessary product features. Then within the cost modelling system environment, the design attributes should be inputted with several selections of material and processes, and the system will estimate the costs, including the material cost, labour cost, tooling and equipment cost, facility cost etc. The total manufacturing cost will be calculated as the sum of these various cost elements. Otherwise, the labour cost, tooling and equipment cost, facility cost incurred for quality inspection will be counted individually, and then the quality inspection cost can be estimated. Finally, a report with detailed cost results will be generated.

4.4.2 Cost Breakdown Structure and Estimation Equations

The manufacturing cost of composites consists of two main parts, the recurring cost and the non-recurring cost, and furthermore, the material cost, direct labour cost and energy cost are summed to get the recurring cost, while the indirect labour cost, equipment cost, tooling cost and facility cost contribute the non-recurring cost, as presented by Equation (4-1), (4-2) and (4-3). For each element, the estimation methods are presented in the following sections and Equation (4-4) to (4-21).

$$\begin{aligned} &Manufacturing\ Cost \\ &\qquad = \sum Recurring\ Cost + \sum Non\text{–}\ Recurring\ Cost \end{aligned} \tag{4-1}$$

$$\begin{aligned} &Recurring\ Cost \\ &\qquad = \sum Material\ Cost + \sum Direct\ Labour\ Cost \\ &\qquad + \sum Energy\ \ Cost \end{aligned} \tag{4-2}$$

$$\begin{aligned} &Non\text{–}\ Recurring\ Cost \\ &\qquad = \sum Indirect\ Labour\ Cost + \sum Equipment\ Cost \\ &\qquad + \sum Tooling\ Cost + \sum Facility\ Cost \end{aligned} \tag{4-3}$$

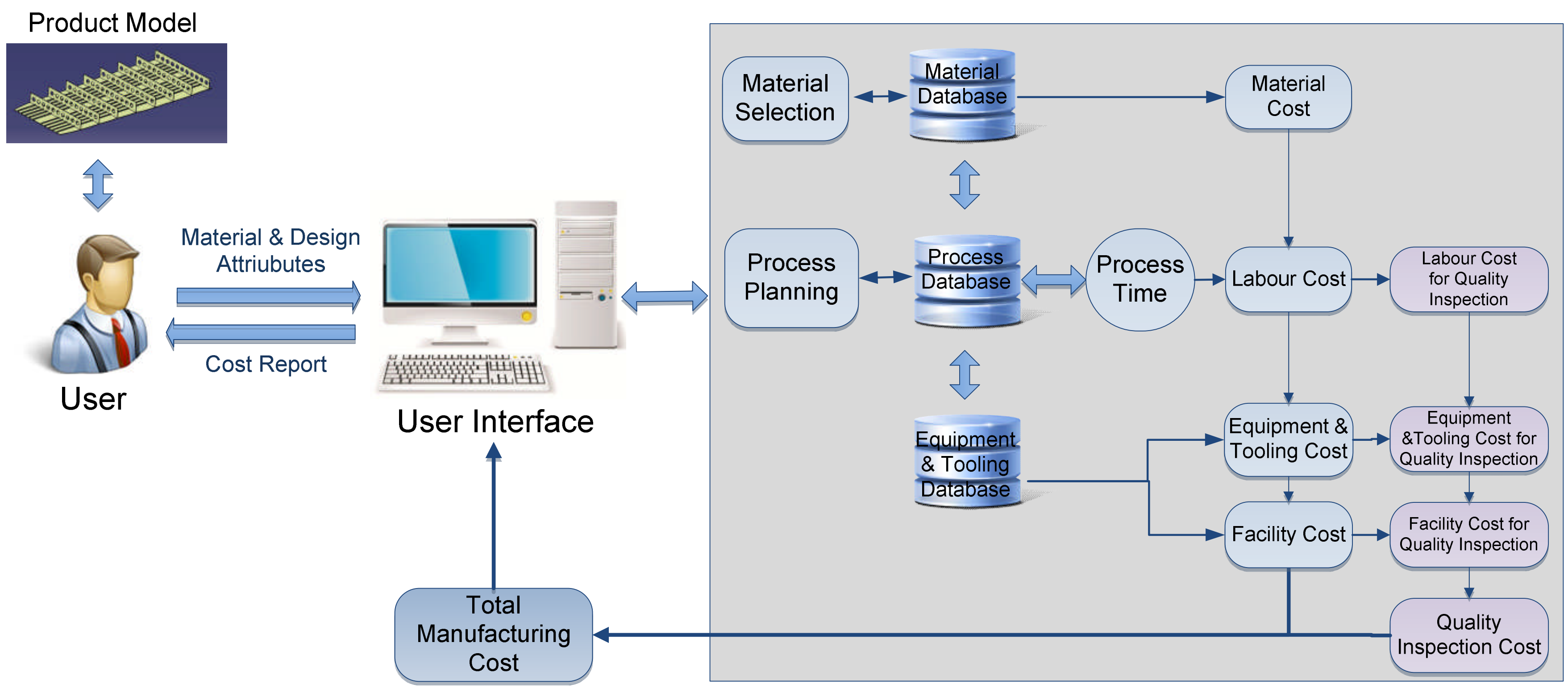


Figure 4–5: The System Structure for Cost Modelling for Composites Manufacturing

4.4.2.1 Material Cost

The materials used for composites manufacturing can be categorized into two major groups, the raw materials and the support materials. Hence, the material cost can be categorized into the raw material cost and the support material cost, as shown by Equation (4-4).

Although the raw material cost can be easily calculated using material weight multiplied by material unit price, the material scrap rate and the part reject rate should be taken into consideration in calculation of material weight, as shown by Equation (4-5). The typical material scrap rate for CFRP is 15% (industrial survey results), and the typical reject rate for hand lay-up is assumed to be 5%.

The support material cost is estimated using the raw material cost and the ratio of support material cost to raw material cost in this model as shown by Equation (4-6), since the support materials are usually various and it will be difficult to determine the detailed material list. The typical rate of support material cost to raw material cost for CFRP is 3 percent, which is from the industrial survey. The typical values are options for estimators, and they can be modified to be suitable for their companies' actual conditions.

$$Material\ Cost = \sum Raw\ Material\ Cost + \sum Support\ Material\ Cost \tag{4-4}$$

$$Raw\ Material\ Cost = \frac{Part\ Matl.Weight \times Matl.Unit\ Price}{(1 - Matl.Scrap\ Rate) \times (1 - Reject\ Rate)} \tag{4-5}$$

$$\begin{aligned} &Support\ Material\ Cost \\ &= Raw\ Matl.Cost \times \left(\frac{Sup.Matl.Cost}{Raw\ Matl.Cost}\right) Rate \end{aligned} \tag{4-6}$$

4.4.2.2 Direct Labour Cost

The direct labour cost for one part is presented by Equation (4-7), and it also takes the part reject rate into consideration. The direct labour time for a specific process can be estimated by the process time multiplied by the number of operators for this process.

$$Direct\ Labour\ Cost = \frac{Direct\ Labour\ Time \times Labour\ Rate}{(1 - Reject\ Rate) \times No._{parts/run}} \tag{4-7}$$

Where:

$No._{parts/run}$ = the quantity of parts for single run.

$$Direct\ Labour\ Time = No._{operators} \times Process\ Time \tag{4-8}$$

Where:

$No._{operators}$ = the number of operators for a specific operation.

How to estimate the process time accurately is vital for the estimation of labour cost. The MIT equations (Neoh, 1995; Pas, 2001; Haffner, 2002) are widely used for time estimation, see Equation (4-9) to (4-13). These equations have been applied in this model. Each equation is applicable for different operations, for example Equation (4-9) is used for equipment, tool or material setup and Equation (4-13) is used for prepreg lay-up.

As mentioned previously, the MIT model and equations (Neoh, 1995; Pas, 2001; Haffner, 2002) have not covered the NDT process. Hence, the estimation method for inspection time of NDT has been developed, and the approach will be presented later in Section 4.4.5.

$$T_p = T_{setup} + No._{parts/run} \times No._{operations/run} \times T_{delay} \tag{4-9}$$

Where:

T_p = the process time per run, min.

T_{setup} = the set up time of equipment or operation, min.

T_{delay} = the delay time between parts or operations, min.

$No._{parts/run}$ = the quantity of parts for single run.

$No._{operations/run}$ = the number of operations for single run.

$$T_p = T_{setup} + No._{parts/run} \times No._{operations/run} \times \left(T_{delay} + \sqrt{\left(\frac{V_b}{V_a}\right)^2 + \frac{2T_aV_b}{V_a}} \right) \tag{4-10}$$

Where:

V_a = the velocity constant of a specific operation, m/min. or m^2/min.

V_b - the variable, such as the perimeter or area, m or m^2.

T_a = the time constant of a specific operation, min.

$$T_p = T_{setup} + No._{parts/run} \times No._{operations/run} \times \left(T_{delay} + \frac{V_b}{V_a} \right) \tag{4-11}$$

$$T_p = T_{setup} + No._{parts/run} \times No._{operations/run} \times \left(T_{delay} + \sqrt{\left(\frac{V_b}{V_a}\right)^2 + \frac{2T_aV_b}{V_a}} \right) \times V_c \tag{4-12}$$

Where:

V_c - the variable, such as the proportion of area that needs abrading.

$$T_{layup} = T_{setup} + No._{parts/run} \times No._{operations/run} \times No._{plies} \times \left(T_{delay} + T_{sg} \times \sqrt{\left(\frac{A_{sg}}{V_{sg}T_{sg}} + 1\right)^2 - 1} + T_a \times \sqrt{\left(\frac{A_{db}}{V_{db}T_a} + 1\right)^2 - 1} \right) \quad (4\text{-}13)$$

Where:

$No._{plies}$ = the number of plies.

T_{layup} = the layup time, min.

T_{sg} = the time constant, min.

T_a = the time constant, min.

V_{sg} = the steady layup velocity for single curve, m/min. or m^2/min.

V_{db} = the steady layup velocity for double curve, m/min. or m^2/min.

A_{sg} = the ply length or area of single curve, m or m^2.

A_{db} = the ply length or area of double curve, m or m^2.

4.4.2.3 Indirect Labour Cost

The indirect labour cost can be calculated using Equation (4-14). However, the indirect labour time is difficult to be determined, as the related activities do not always happen. From the industrial survey, the typical rate of indirect labour time to direct labour time for aerospace industry is 40 percent. This rate can be used to estimate the indirect labour time, if the direct labour time has been estimated accurately. On the other hand, this rate may be not exact for some companies. Taking this factor into consideration, the value of 40 percent is preset as a reference and it can be modified by the estimators themselves in this model.

$$Indirect\ Labour\ Cost = \frac{Indirect\ Labour\ Time \times Labour\ Rate}{(1 - Reject\ Rate) \times No._{rarts/run}} \tag{4-14}$$

$$Indirect\ Labour\ Time = Direct\ Labour\ Time\ \times \left(\frac{Indirect\ Labour\ Time}{Direct\ Labour\ Time}\right) Rate \tag{4-15}$$

4.4.2.4 Energy Cost

Song et al. (2009) studied the lifecycle energy of composites, and the energy consumption rate is 39 kWh/ kg (141.3 MJ/kg) for reinforced composites manufacturing that are made by the autoclave process, according to their research. The total 141.3 MJ/kg is the sum of three values, 21.9 MJ/kg for autoclave moulding, 61.5 MJ/kg for additive values, and 57.9 MJ/kg for remaining values. Hence, the energy consumption rate is assumed as 40 kWh/ kg and the energy price is assumed as £ 0.1/kWh for CFRP manufacturing process in this model. The energy cost can be estimated using Equation (4-16), and the material scrap rate and part reject rate have been counted into it.

$$Energy\ Cost = \frac{Part\ Weight \times Energy\ Consump.Rate \times Energy\ Price}{(1 - Matl.Scrap\ Rate) \times (1 - Reject\ Rate)} \tag{4-16}$$

Since the energy consumption rate is estimated by unit weight of composites, this estimation method is more suitable for the large production volumes. It will be not accurate for the small production quantities of one batch, and therefore it can be estimated by the consumption rate of unit time and related process time instead. For the second approach, it needs to collect the data of energy consumption rate of unit time from the industry. However, there is little research on this topic and it can be made one future work.

4.4.2.5 Equipment, Tooling and Facility Cost

Equipment, tooling and facility all belong to the investment in composites manufacturing. The cost of their depreciation can be estimated using the cost rate of unit time/cycle multiplied by the related process time, as shown by Equation (4-17) to (4-21).

$$Equipment\ Cost = \frac{Equip.Time \times Equip.Cost\ Rate}{(1 - Reject\ Rate) \times No._{parts/run}} \tag{4-17}$$

$$Equipment\ Cost\ Rate = \frac{Equip.\ Investment}{Equip.\ Life \times Equip.Annual\ Available\ Time} \tag{4-18}$$

$$Tooling\ Cost = \frac{Tooling\ Investment}{(1 - Reject\ Rate) \times No._{parts/mould} \times Tooling\ Life\ Cycles} \tag{4-19}$$

Where:

$No._{parts/mould}$ = the quantity of parts in one mould.

$$Facility\ Cost = \frac{Process\ Time \times Facility\ Cost\ Rate}{(1 - Reject\ Rate) \times No._{parts/run}} \tag{4-20}$$

$$Facility\ Cost\ Rate = \frac{Facility\ Investment}{Facility\ Life \times Facility\ Annual\ Available\ Time} \tag{4-21}$$

4.4.2.6 Quality Inspection Cost

The quality inspection cost mainly includes the direct labour cost, indirect labour cost, equipment cost and facility cost which are incurred for NDT, and it can be calculated using Equation 4-22. The breakdown costs can be estimated using the equations in previous sections, and the time estimation for NDT will be stated in Section 4.4.5.

$$
\begin{aligned}
&Quality\ Inspection\ Cost \\
&\qquad = (Direct\ Labour\ Cost)_{NDT} \\
&\qquad + (Indirect\ Labour\ Cost)_{NDT} \\
&\qquad + (Equipment\ Cost)_{NDT} + (Facility\ Cost)_{NDT}
\end{aligned}
\tag{4-22}
$$

4.4.3 Material Database

To develop a user friendly model, it is necessary to build a material database, which can help the estimators with material selection. In this thesis, the materials, which are mainly the carbon prepregs, were collected both from the existing databases and from the industry. Boyer (2001) had collected some carbon prepregs in his thesis, and they were taken as part of the material database in this thesis. Some more materials were collected from Company A, an aircraft component manufacturer in China.

The required information is the cured ply thickness, density and unit price for material cost estimation, and some other data, like the resin content, typical cure temperature and time, were also collected (see Table 4-1). The price has been converted to British pounds from the previous currency, and the exchange rates are 1 USD = 0.694 GBP (the average rate of 2001) and 1 CNY = 0.096 GBP (the average rate of the first half year of 2010), according to the historical data from Oanda (2010). However, the material price will be quite different for various countries and the purchase quantity also has dramatic influences on the unit price. Hence, the unit prices listed in the Table 4-1 should be taken as reference.

Table 4-1: Summary of Material Data for the Cost Modelling System

No.	Material ID	Material Class	Material Name	Supplier	Fibre	Resin	Resin Content	Cure Temp.	Cure Time/ min.	Width/ mm	Cured Thick./ mm	Density /gsm	Price £/kg	Price Year
1	CP2H1NB1122	Car bon Wove n Fabric/Epoxy	NB-1122	HEXCEL	Schwebel 282 Plain Weave Carbon 3K		34%	170°C		1,270		197.0	160	2001
2	CP2H1NB1450	Car bon Wove n Fabric/Epoxy	NB-1450	HEXCEL	Schwebel 433 Fabric Carbon 3K		34%	124°C		1,270		285.0	143	2001
3	CP2H1AW3705	Car bon Wove n Fabric/Epoxy	AW370-5H/3501-6	HEXCEL	5H Satin Weave Carbon 6K	3501-6	42%	176°C		1,245	0.360	370.0	66	2001
4	CP2H1AW3708	Car bon Wove n Fabric/Epoxy	AW370-8H/3501-6	HEXCEL	8H Satin Weave Carbon 6K	3501-6	42%	176°C		1,245	0.360	370.0	111	2001
5	CP2H1AW193P	Car bon Wove n Fabric/Epoxy	AW193-PW/3501-6	HEXCEL	Plain Weave Carbon 6K	3501-6	42%	176°C		1,245	0.200	193.0	106	2001
6	CP1H1NCT303	Carbon UD Tape/Epoxy	NCT-303	HEXCEL	AS4 Carbon 3K		34%	135°C		305		150.0	35	2001
7	CP1H1NCT112	Carbon UD Tape/Epoxy	NCT-1122	HEXCEL	AS4 Carbon 6K		34%	180°C		305		250.0	35	2001
8	CP1H1AS4350	Carbon UD Tape/Epoxy	AS4/3501-6 UD	HEXCEL	AS4 Carbon 6K	3501-6	36%	176°C		305	0.130	150.0	69	2001
9	CP1C1T30012	Carbon UD Tape/Epoxy	T300-12K/CYCOM970	CYTEC	T300-12K	CYCOM 970	38%	177°C	120		0.203	306.0	110	2010
10	CP1C1PWCT3A	Carbon Woven Fabric/Epoxy	PWC-T300-3K/CYCOM970	CYTEC	T300, 3K-70-PW	CYCOM 970	40%	177°C	120		0.216	322.0	140	2010
11	CP1H1T300F5A	Carbon UD Tape/Epoxy	T300/F593-12	HEXCEL	T300	F593	38%	180°C	120		0.155	234.0	110	2010
12	CP1H1W3T28A	Car bon Wove n Fabric/Epoxy	W3T-282/F593-1	HEXCEL	T300, 3K-70-PW	F593	44%	180°C	120		0.234	345.0	140	2010
13	CP1H1W3T28B	Car bon Wove n Fabric/Epoxy	W3T-282/F593-18	HEXCEL	T300, 3K-70-PW	F593	40%	180°C	120		0.216	322.0	140	2010

Note: The material data of No.1 to No.8 are taken from Boyer's BSc Thesis (2001), and the material data of No.9 to No.13 are collected from Company A. The exchange rates are 1 USD = 0.694 GBP (the average rate of 2001) and 1 CNY = 0.096 GBP (the average rate of the first half year of 2010), according to the historical data from Oanda (2010).

4.4.4 Process Planning

In this research project, the component manufacturing process was divided into eight main processes: tool preparation, material preparation, lay-up, vacuum bagging, autoclave setup, cure cycle, finishing, and quality inspection. Table 4-2 shows the detailed manufacturing process for hand lay-up, and the standard operations are mainly refer to the MIT models (Pas, 2001; Haffner, 2002), except for the quality inspection. For quality inspection, it was just limited to the portable ultrasonic inspection, and other types of NDT processes are not available in this thesis, which could be added in the future.

Table 4-2: Process Planning for Hand Lay-up Process

Main Process	Sub Process
A. Tool Preparation	1. Clean tool surface
	2. Setup tool
	3. Apply release agent
	4. Apply barrier film
B. Material Preparation	5. Setup prepreg
	6. Cut prepreg
	7. Cut bleeder
	8. Cut breather
	9. Cut vacuum bag
C. Lay-up	10. Lay-up
	11. Debulk
	12. Remove compaction bag
D. Vacuum Bagging	13. Apply bleeder
	14. Apply breather
	15. Apply cork dams
	16. Apply Sealant tapes
	17. Apply vacuum bag
	18. Connect vacuum line
	19. Apply vacuum
	20. Check seals
	21. Disconnect vacuum lines
	22. Apply peal plies
	23. Install caul plate

Table 4-2: Process Planning for Hand Lay-up Process (Continued)

<table>
<tr><th>Main Process</th><th colspan="2">Sub Process</th></tr>
<tr><td rowspan="6">E. Autoclave Setup</td><td colspan="2">24. Transfer to autoclave</td></tr>
<tr><td colspan="2">25. Connect vacuum lines</td></tr>
<tr><td colspan="2">26. Connect thermocouple</td></tr>
<tr><td colspan="2">27. Apply vacuum</td></tr>
<tr><td colspan="2">28. Check seal</td></tr>
<tr><td colspan="2">29. Setup autoclave</td></tr>
<tr><td rowspan="4">F. Cure Cycle</td><td colspan="2">30. Start autoclave</td></tr>
<tr><td colspan="2">31. Disconnect vacuum line</td></tr>
<tr><td colspan="2">32. Disconnect thermocouple</td></tr>
<tr><td colspan="2">33. Unload part</td></tr>
<tr><td rowspan="7">G. Finishing</td><td colspan="2">34. Remove bagging</td></tr>
<tr><td colspan="2">35. Demold part</td></tr>
<tr><td colspan="2">36. Clean part</td></tr>
<tr><td colspan="2">37. Abrade part</td></tr>
<tr><td colspan="2">38. Trim part</td></tr>
<tr><td colspan="2">39. Deflash part</td></tr>
<tr><td colspan="2">40. Deburr part</td></tr>
<tr><td rowspan="4">H. Quality Inspection</td><td rowspan="4">41. Portable Ultrasonic Inspection</td><td>a. Clean part</td></tr>
<tr><td>b. Setup equipment</td></tr>
<tr><td>c. Inspection</td></tr>
<tr><td>d. Clean part</td></tr>
</table>

4.4.5 Time Estimation for Non-Destructive Testing

Although the MIT model is applied for process time estimation, it is still necessary to determine a time estimation method for non-destructive testing (NDT), according to the statement of Section 4.4.2.2. The determining approach will be presented in this section.

The general process of portable ultrasonic inspection was shown in Table 4-2, and it includes part cleaning (before and after inspection), equipment setup and inspection. The cleaning time can be estimated by Equation (4-10), in which: V_b is the surface area to be cleaned and T_{setup} = 2.56 min., T_{delay} = 0.5 min., V_a =

0.32045 m^2/min., and T_a = 7.77 min. (Neoh, 1995). The setup time of portable ultrasonic C-Scan equipment can be estimated by Equation (4-9), in which: T_{setup} = 7 min., and T_{delay} = 0 min. (data from Company A). The inspection time is mainly determined by the inspection area and the configuration complexity of components to be inspected, and that means there are two variables for inspection time, so Equation (4-12) was used for NDT process in this thesis.

For NDT, the number of parts for single run is generally one, and the inspection is a continuous process for single component, so delay time is zero. The setup time in Equation (4-12) is the time between two runs (parts), and it is 2 minutes averagely for portable ultrasonic inspection (data from Company A). The inspection area A_i can be treated as the variable V_b, and the complexity of component configuration K can be treated as the variable V_c. K is the ratio of inspection area divided by maximum projected area of specific component, and the maximum projected area should be the maximum value of projected areas from different positions. Then the constants of V_a and T_a should be determined next.

It is required to collect the industrial data of inspection time of composite components to achieve that. Then the researcher contacted Company A, and the data of six composite components were collected (Table 4-3). Data analysis was conducted to get the constant values in Equation (4-12). The constants were finally determined as: V_a = 0.03044 m^2/min. and T_a = 88.8 min (T_{setup} = 2 min. and T_{delay} = 0 min., as analysed in previous paragraph).

Table 4-3: Data for NDT Time Estimation

Component	A_i	A_p	K	T_i - Estimated	T_i - Calculated
A	0.379	0.288	1.32	60	62
B	0.502	0.458	1.10	60	64
C	1.121	0.437	2.57	210	228
D	1.397	1.178	1.19	120	120
E	2.500	2.500	1.00	150	146
F	13.430	4.873	2.76	1440	1440

$\mathbf{A_i}$ - The area of required inspecting surface.

$\mathbf{A_p}$ - The maximum projected area of component.

K - $K = A_i / A_p$. K refers to the configuration complexity of component.

$\mathbf{T_i}$ - Estimated or calculated inspection time of NDT, excluding the setup time (T_{setup}=2 *min.)*. The estimated values are collected from Company A, and the calculated values are the calculation results using Equation (4-12).

4.5 System Scenario and Implementation

The CMCE system was developed using Microsoft Office Excel VBA. It consists of four user windows: Design Attribute Input, Material Database, Material Cost Estimation and Process Planning, besides of the Start Interface and the Cost Report. The CMCE system will be demonstrated in Section 5.2.2 (Chapter 5).

The general estimation flow of CMCE system is shown in Figure 4-6. In general, the system enables the user to select or add different materials and make process planning for the components. Firstly, the user needs to collect the material, configuration and geometric information from the component model and input them into the CMCE system, and then the material cost can be estimated according to the above inputs. The next step is planning the manufacturing process, not only fabrication operations but also NDT, for the component and adding further information, like tooling and equipment investment, labour rate etc. When the above actions have been completed and the inputs have been confirmed, the times (e.g. process time and labour time) and the various costs, including the direct and indirect labour cost, energy cost, equipment cost, facility cost, equipment cost, tooling cost, recurring cost, non-recurring cost and the total manufacturing cost, will be estimated by the system. Furthermore, the incurred costs for NDT, including the equipment cost, facility cost, direct labour cost and indirect labour cost, will be summed up to get the quality inspection cost. Then the final manufacturing cost report of the component will be produced and spread to the user. Then, the user can analyse the estimation results and re-estimate it by changing some of the parameters if necessary.

4.6 Summary

The development approach of proposed cost model was introduced in this chapter. Firstly, an industrial survey was carried out, and the survey results were analysed to help the researcher to identify the cost drivers and gather data. Secondly, the general activities and cost drivers of composites manufacturing were identified through the literature review and industrial survey. Thirdly, the cost model was developed, and the CERs of each key cost drivers were identified. Moreover, the process of data collection and analysis for model development was introduced. Finally, the scenario and implementation of the modelling system CMCE were presented.

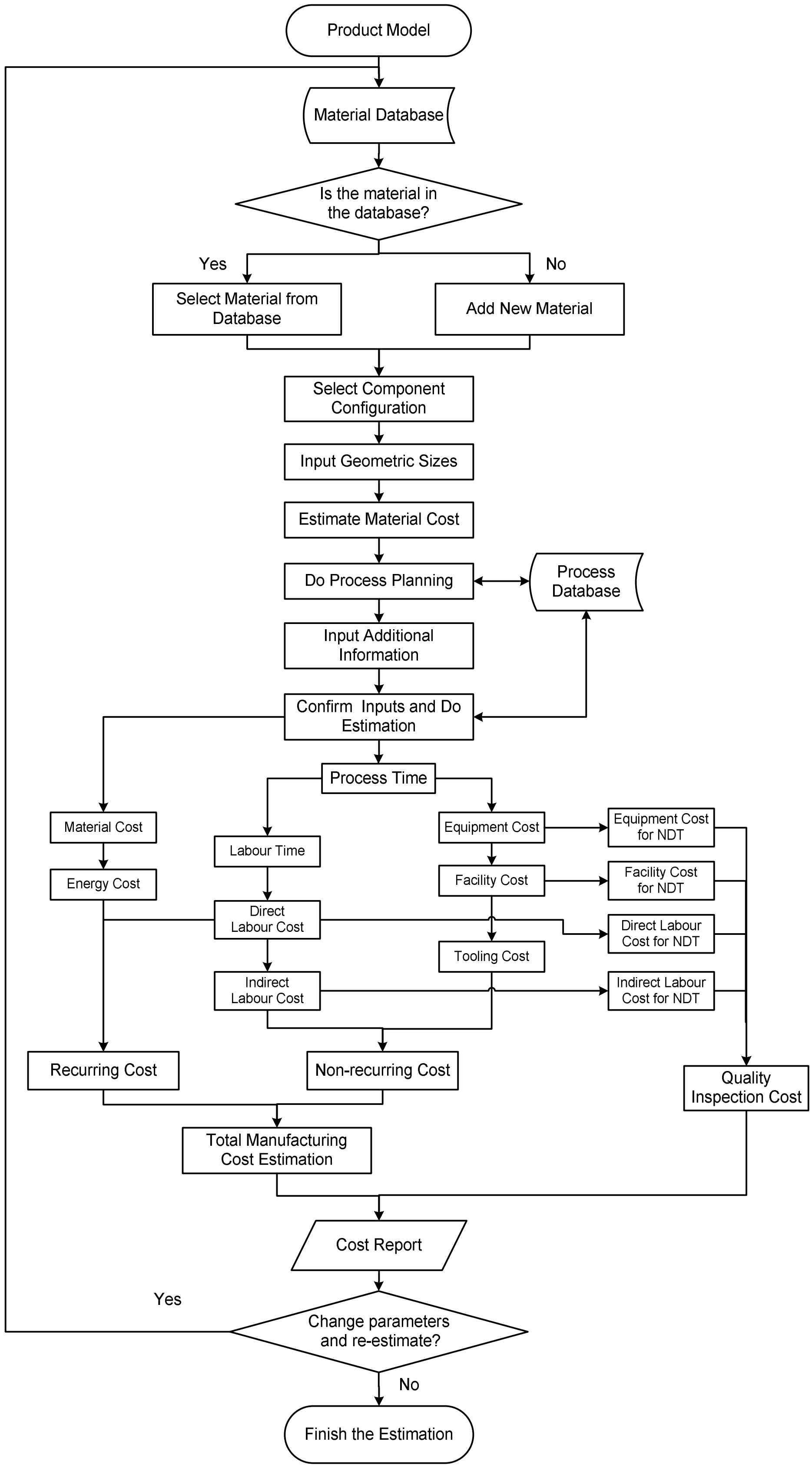


Figure 4–6: Estimation Flow of CMCE

5 VALIDATION OF THE COST MODEL

5.1 Introduction

This chapter focuses on the validation process of the developed cost model both through several case studies and expert judgements. The case studies were cost estimations of some components from aerospace industry, and then the estimation results were analysed and compared with the industrial estimated values. To get evaluations for the model, a validation session was also arranged with some experts that had engineering experiences of aircraft design or manufacturing. With the case study results and experts' feedbacks, the capacity and reliability of CMCE were discussed.

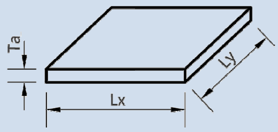
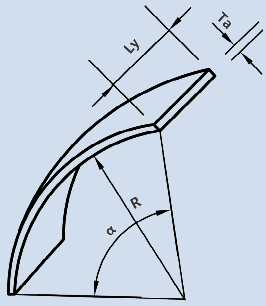
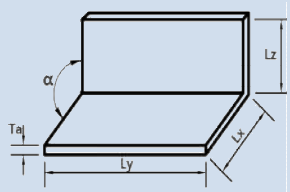
5.2 Case Studies

The case studies were carried out in Company A (an aircraft component manufacturer in China). Firstly, the CMCE system was provided to two engineers, and they used it to estimate the manufacturing cost of different composite parts. Then, the estimation results produced by CMCE system were compared with the cost estimated by the engineers themselves.

5.2.1 Summary of the Inputs of Case Studies

Three cases of different shapes were considered for validation studies. The first component for validation case studies is a flat panel, without any stiffener. The second component is a single curved skin panel, and the third case is six straight L-profile stringers. These three shapes of component are common in aerospace industry, and the two engineers have chosen them to validate the capacity and reliability of CMCE system. The main inputs of each component were listed in Table 5-1.

Table 5-1: Summary of the Details of Case Studies

	Case 1	Case 2	Case 3
Part Drawing:	Flat Panel 	Skin Panel 	L Stringer 
Dimension:	T_a = 3 mm, L_x = 600 mm, L_y = 2000 mm.	T_a = 2.5 mm, L_y =1000mm, R = 1500 mm, α = 50°.	T_a = 3.5 mm, L_x = 50 mm, L_y = 750 mm, L_z = 100mm, α = 90°.
Material:	UD carbon prepregs, T300-12K/CYCOM970	Woven carbon prepregs, PWC-T300-3K/CYCOM970	UD carbon prepregs, T300-12K/CYCOM970
Unit Price	£ 200 /kg	£ 200 /kg	£ 200 /kg
Part Weight	5.34 kg	4.63 kg	0.59 kg
Scrap rate	3 %	15 %	45 %
No. of Plies	14	11	17
Support Material Cost to Raw Material Cost Rate - 3 %			
Reject Rate:	1 %	5 %	5 %
Quantity:	1 part/batch	1 part/batch	6 parts/batch
Direct Labour Rate: £ 10 /hour			
Indirect Labour Rate: £ 12 /hour; Indirect/direct labour time rate - 40 %.			
Mould:	£ 10000; 1 part/mould; life -500 cycles.	£ 20000; 1 part/mould; life -500 cycles.	£ 20000; 6 parts/mould; life -500 cycles.
Autoclave: £ 500,000; Life - 10 years; 200 days/year, 16 hours/day.			
Portable Ultrasonic C-Scanner: £ 120,000; Life - 10 years; 240 days/year, 6 hours/day.			
Facility: £ 1,000,000; Life - 30 years; 240 days/year, 16 hours/day.			
Energy: Consumption rate - 40 kWh/kg; Energy price - £ 0.1 /kWh.			

5.2.2 Demonstration of the Estimation Process of Case Studies

The estimation process of case studies, using CMCE system, will be presented in this section, taking Case 2 for example.

Firstly, the estimator enters the ‘Start Interface’ of CMCE in Microsoft Excel system, as shown in Figure 5-1. The ‘Start Interface’ shows the general information of CMCE system, including the language selection options. Two languages were considered, English and Chinese. The Chinese language has been chosen due to the sponsoring company of this project. By clicking the ‘Start’ button, the estimator can begin the cost estimation.

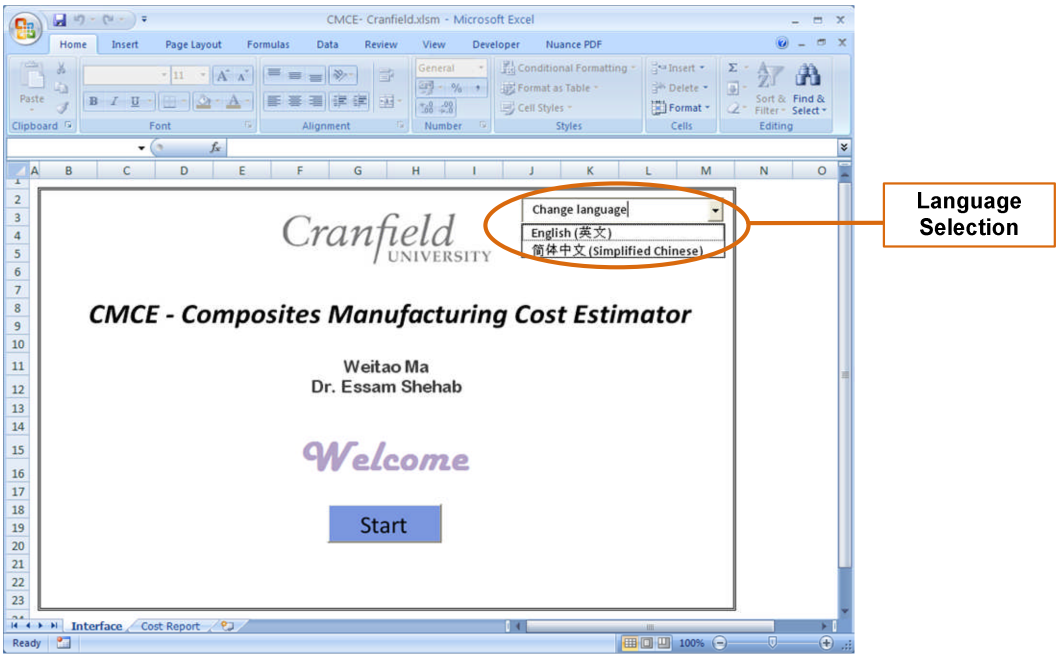


Figure 5–1: Start Interface of CMCE

Secondly, the estimator inputs the necessary design information, including the material, part configuration and geometric sizes, in the user window of Design Attribute Input, as shown in Figure 5-2. In Case 2, the estimator selected an existing prepreg from the material database, after viewing the material information in material database (see Figure 5-3).

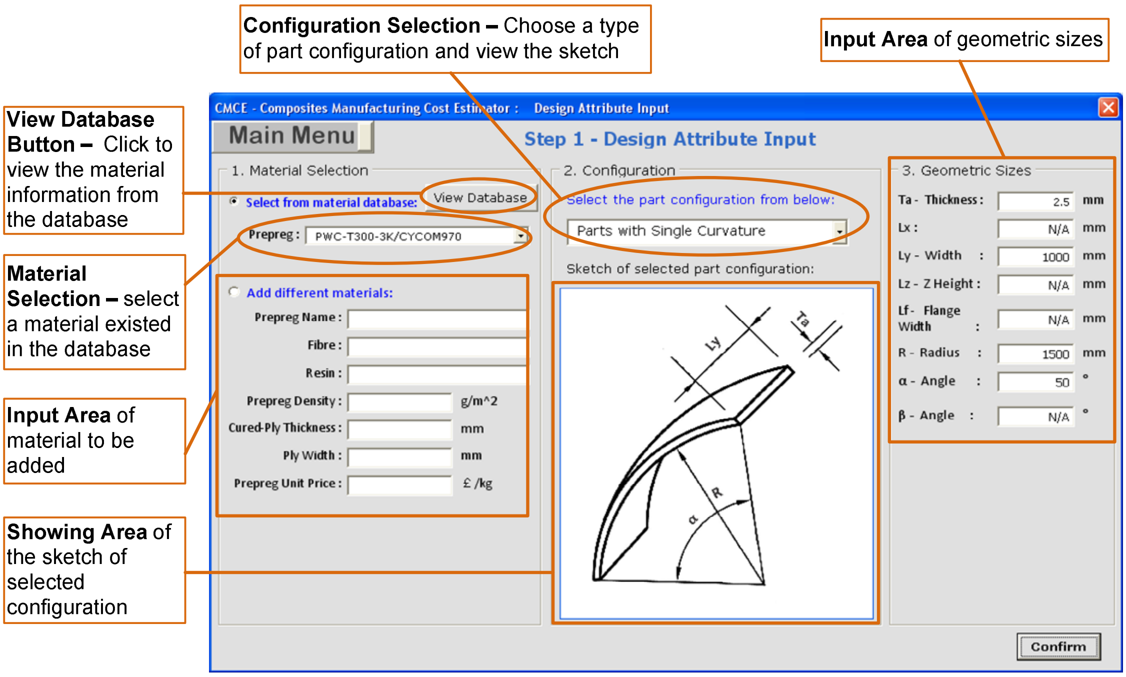


Figure 5–2: Design Attribute Input

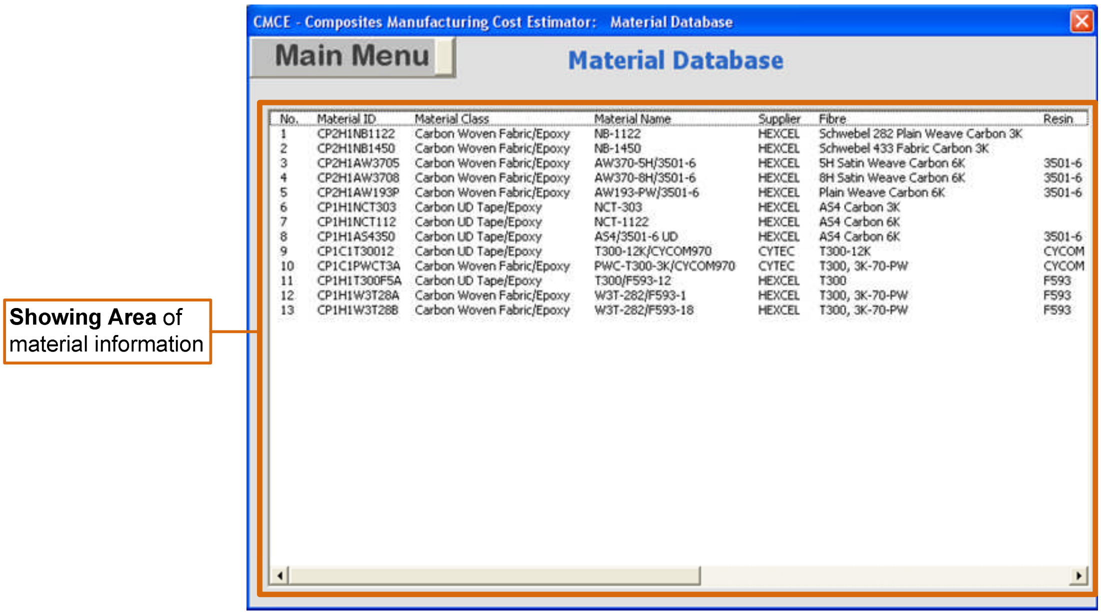


Figure 5–3: Material Database in CMCE System

Thirdly, the material cost estimation can be carried out when the inputs of material and geometric sizes are confirmed, as shown in Figure 5-4. The unit price of selected material, the calculation result of part weight and the pre-set values of material scrap rate, the part reject rate and the support material cost to raw material cost rate are firstly shown to the estimator. When the pre-set values are confirmed or modified, the material costs will be calculated and the results will be shown to the estimator.

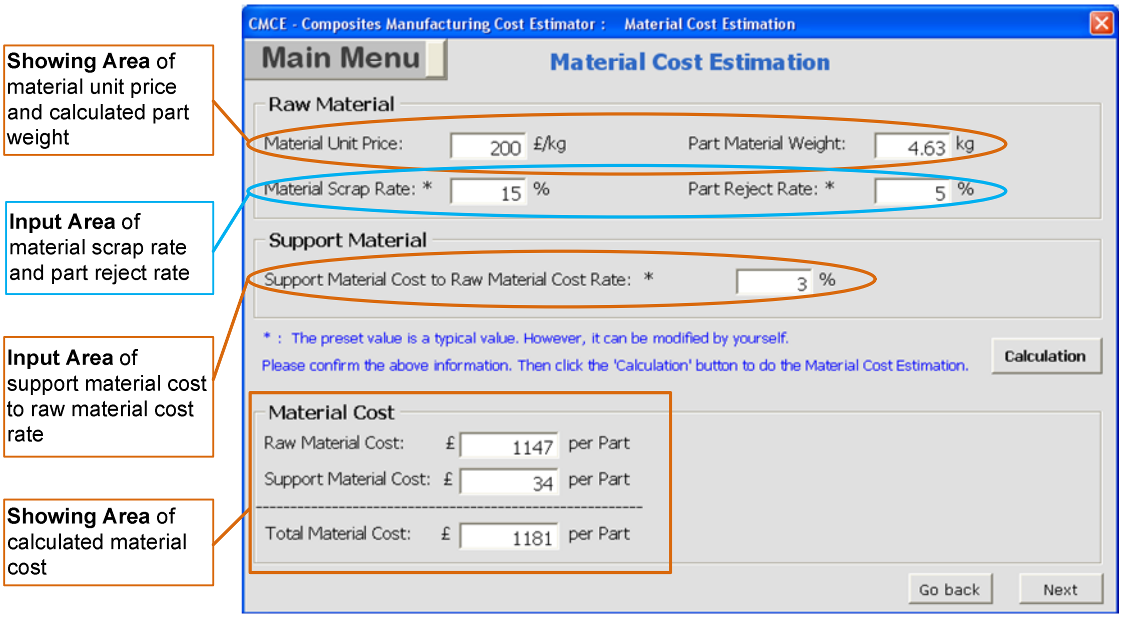


Figure 5–4: Material Cost Estimation

Fourthly, it is necessary to perform the process planning before the final cost estimation, as shown in Figure 5-5. The 'Process Planning' window provides the estimators the typical process plan of composites manufacturing and lets them input the cost information of equipment, tooling, facility, production quantity, labour rate, energy rate etc. The estimator can make his/her own plan by choosing or not choosing a specific process, according to the actual components. When the process plan and the inputs of necessary information have been completed, the estimator can click the ‘Estimate’ button to perform the calculation and to view the final cost report.

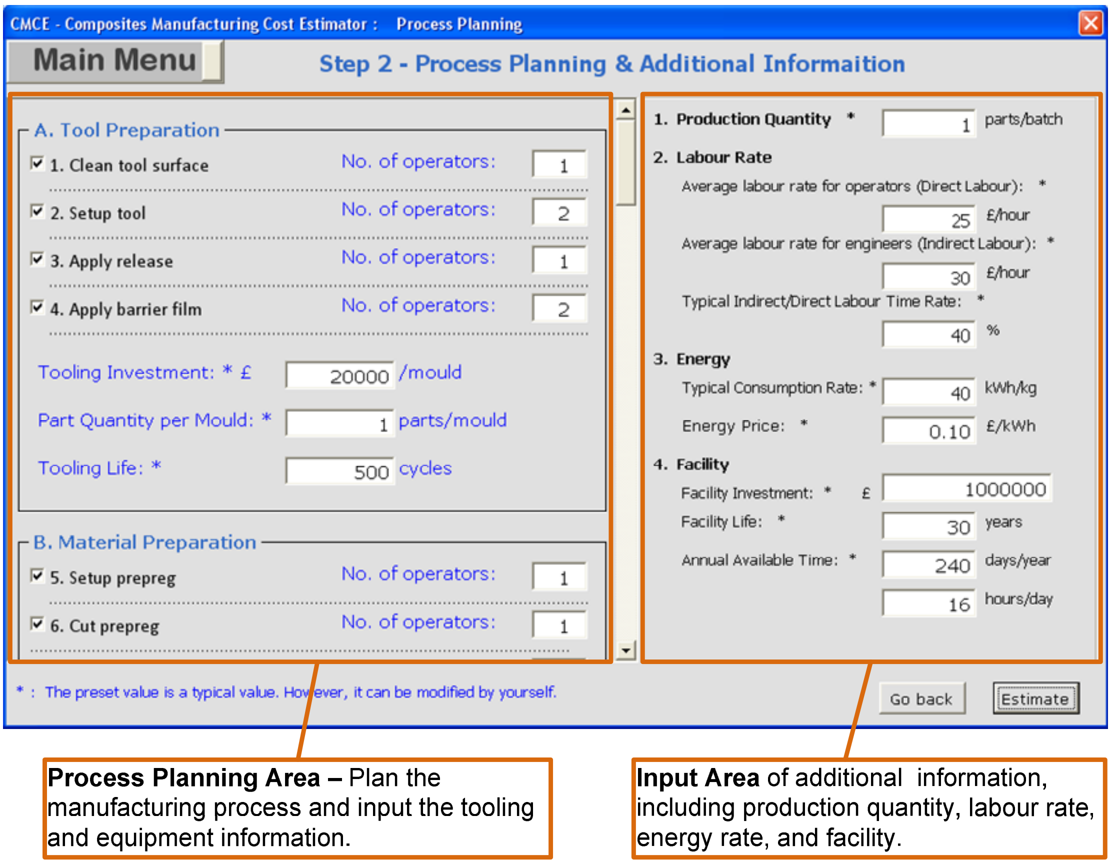


Figure 5–5: Process Planning

Finally, the estimated results of various cost will be summarised and shown in an excel spreadsheet, as shown in Figure 5-6. The content of cost report will mainly include the detail information of each cost element, the breakdown of total manufacturing cost, the summary of time estimation results and breakdown, and the estimation results and analysis of the non-destructive inspection cost.

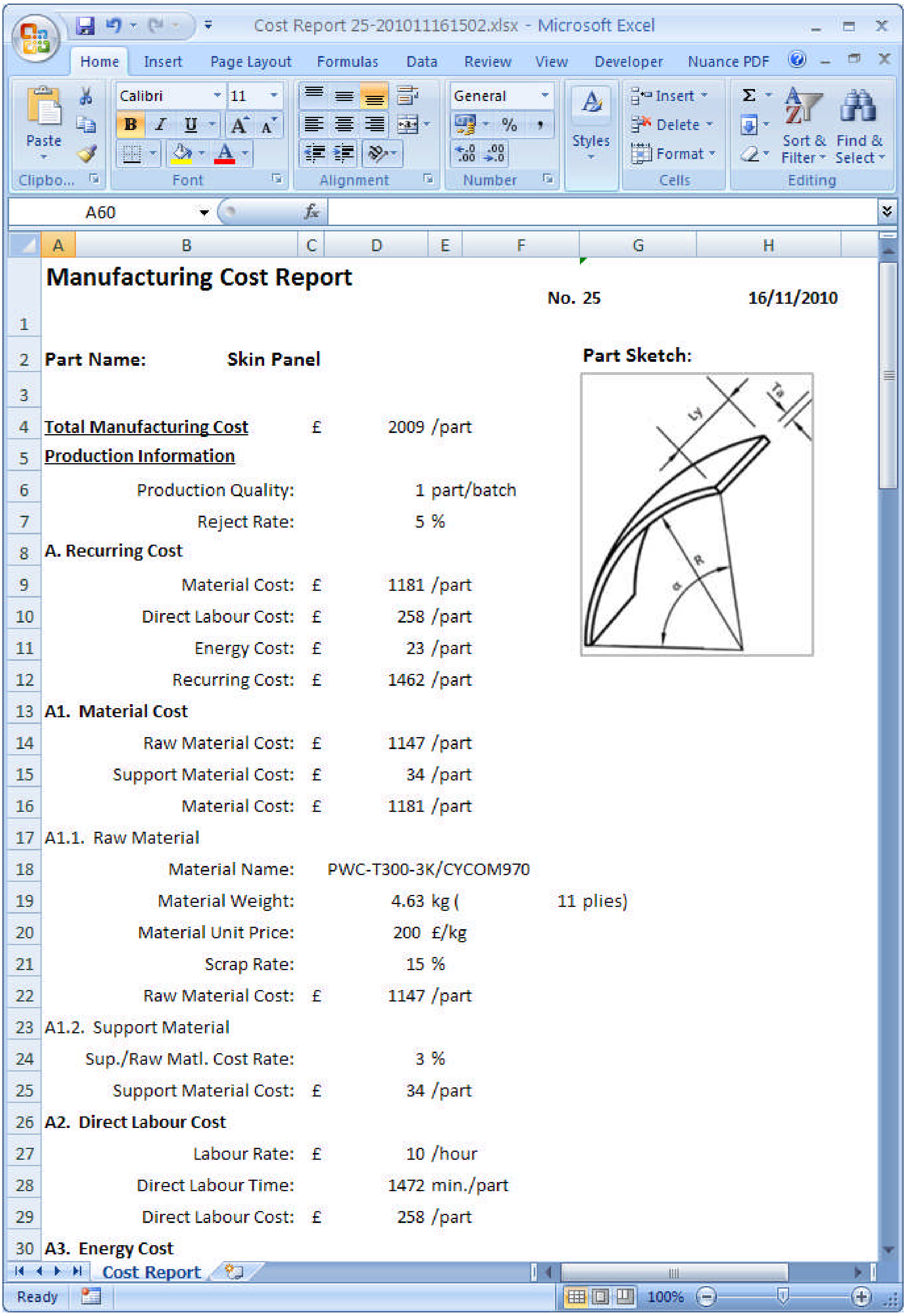


Figure 5–6: Example of Cost Report

5.2.3 Analysis of the Cost Estimation Results

As a consequence, the time estimation results from the developed system were summarised in Figure 5-7 and Table 5-2, while the cost estimation results from the developed system were illustrated in Figure 5-8 and Table 5-3.

From the case studies, the material and labour represent the majority of total manufacturing cost of composite components, which is the same as the industrial survey results by questionnaire. Particularly, the material took 51% to 59% and the direct and indirect labour took 19% to 26%, and it seems that the proportions of labour cost are lower and the proportions of material cost are higher than some other’s research results. However, that is because of the lower labour rate and higher raw material price in China. Otherwise, the quality inspection cost took about 5% to 8% of the total manufacturing cost, and it mainly included the direct and indirect labour cost, equipment cost and facility cost occurred during the NDT inspections.

The lay-up, vacuum bagging and quality inspection were the most time consuming processes in the studies, besides the autoclave setup and cure cycle. The increased number of plies will significantly result in the time increasing of prepreg lay-up, and the proportion of cure cycle will have significant decreasing when produce multiple parts for one batch, compared with one part for one batch. Otherwise, the higher complexity of configuration will result longer process time of lay-up and quality inspection.

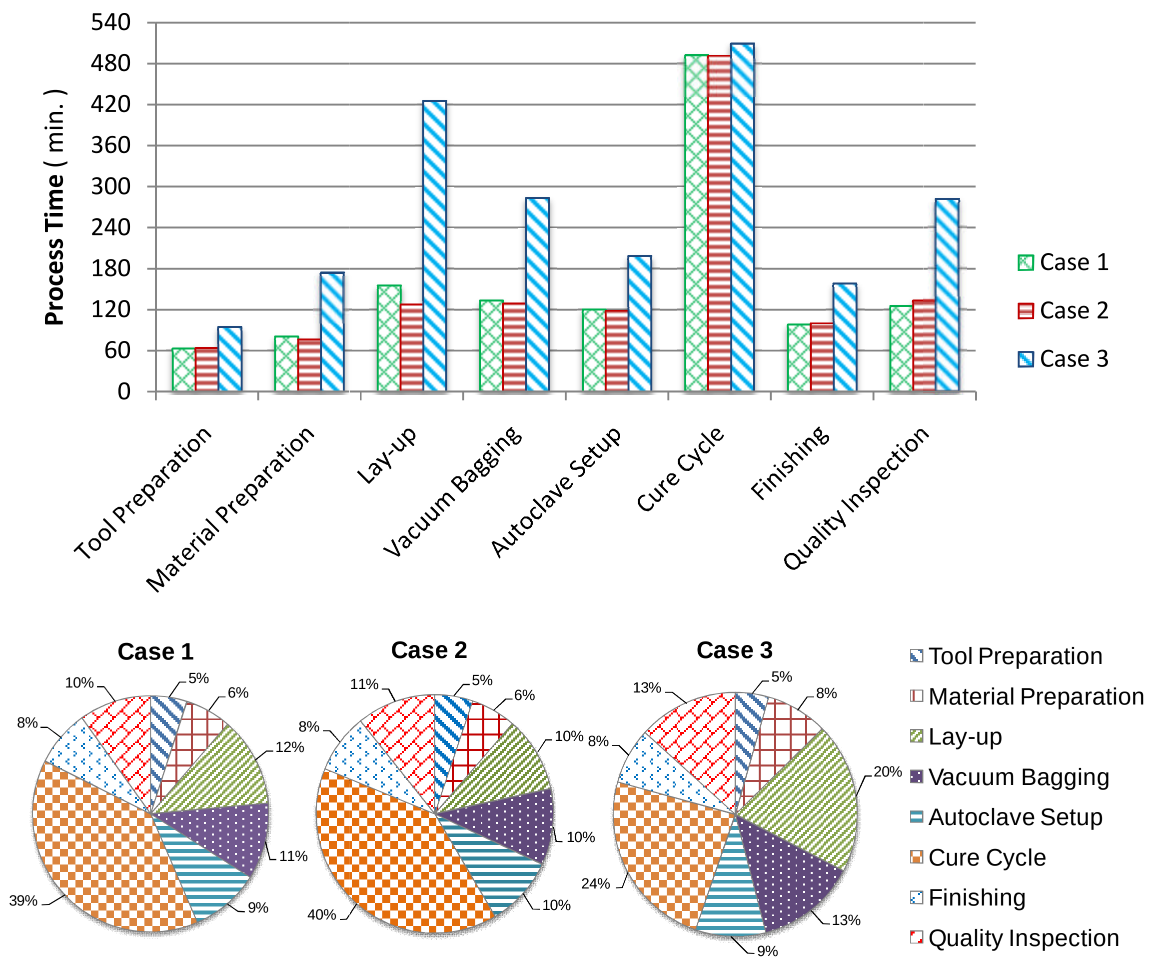


Figure 5–7: Process Time Breakdown of Case Studies (Batch Time)

Table 5-2: Summary of Time Estimation Results of Case Studies

	Case 1	Case 2	Case 3	
	1 part	1 part	6 parts	1 part
NDT Process Time	2.1 h	2.2 h	4.7 h	0.8 h
Direct NDT Labour Time	3.7 h	3.9 h	8.6 h	1.4 h
Total Process Time	21.1 h	20.7 h	35.4 h	5.9 h
Total Direct Labour Time	25.1 h	24.5 h	45.3 h	7.6 h

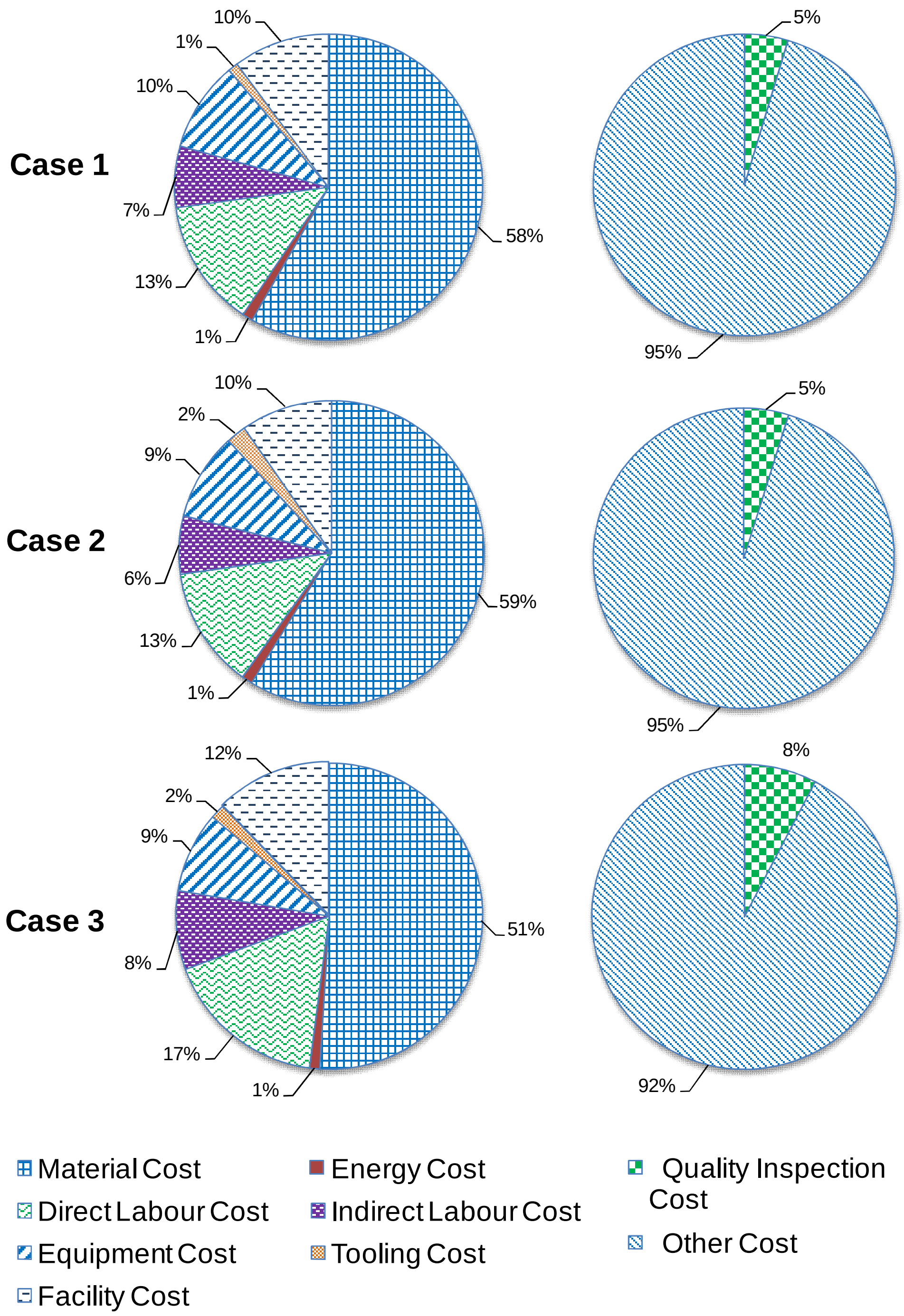


Figure 5–8: Cost Breakdown of Case Studies (per part)

Table 5-3: Summary of Cost Estimation Results of Case Studies (per part)

	Case 1	Case 2	Case 3
Material Cost	£ 1102	£ 1181	£ 233
Energy Cost	£ 21	£ 23	£ 5
Direct Labour Cost	£ 254	£ 258	£ 79
Indirect Labour Cost	£ 122	£ 124	£ 38
Equipment Cost	£ 179	£ 186	£ 39
Tooling Cost	£ 20	£ 42	£ 7
Facility Cost	£ 192	£ 195	£ 56
Total Manufacturing Cost	**£ 1890**	**£ 2009**	**£ 457**
Quality Inspection Cost	£ 88	£ 97	£ 35

5.2.4 Estimation Results Comparison

After the estimation using CMCE system, the engineers compared the final results with their own estimation values. With comparisons, they found that the CMCE results were 9% to 14% higher than their values, as shown in Table 5-4, and they thought that the CMCE results were in the reliable range.

The engineers also discussed about the possible reasons of higher results. They believed that the inaccurate facility investment might result in this at first, as it is too high for the facility cost taking over 10% of the total cost. However, it seems quite difficult to identify the exact investment of related facilities. The researcher assumed £ 1,000,000 as a reference value for facility investment, and the facility cost rate is £ 9 per hour for 30 years life and available time of 240 days per year and 16 hours per day. The engineers then pointed out that this rate could be reasonable for large components and batch productions and the proportion would be decreased. In their opinions, the cost rate is reasonable and the small sizes of components and small production quantity of each batch was one of the reasons which caused the high proportion of facility cost in the case studies.

Table 5-4: Comparison of Manufacturing Cost Estimated by CMCE and Industrial Experts

	Case 1	**Case 2**	**Case 3**
CMCE - Cost A	£ 1890	£ 2009	£ 457
Industrial Expert - Cost B	£ 1700	£ 1850	£ 400
Cost A/Cost B × 100%	111 %	109 %	114 %

5.3 Expert Judgement

In this section, the developed model was validated through expert judgement, and some professional opinions and suggestions were collected. A validation session was arranged by the researcher, and four experts were invited to attend the session. One of them is an aircraft design engineer and the rest three experts are aircraft manufacturing engineers, as shown in Table 5-5.

Table 5-5: General Information of the Experts

Expert	**Job Title**	**Background**	**Year of Experience**
A	Design Engineer	Aircraft Design	7
B	Manufacturing Engineer	Aircraft Assembly	7
C	Manufacturing Engineer	Aircraft Material	6
D	Manufacturing Engineer	Aircraft Tooling	4

The validation session lasted for 90 minutes, and it was recorded by a digital recorder for gathering the expert judgements. At the beginning of the session, a general introduction of the developed model and CMCE system was presented, and the system was shown to the experts through the estimation process of Case 2 (Section 5.2). The experts also used the system by themselves, and then they had a discussion about it. Their opinions were summarised as follows:

- The system is user friendly and not too complex. Expert A commented that, ‘it just needs a few minutes to get practice before using it’.

- The model gives the user some flexibility, like the material can be selected from the database or added by the users, and the pre-set values can be modified by the users too.

- The model includes the quality inspection besides of the part fabrication processes, which makes the cost more complete.

- The model helped them with understanding the manufacturing process of composites, as it has combined with the process planning, and the final report can also help them with identifying the key cost drivers.

- The model is just available for the components that are made by hand lay-up process until now, and the experts believed that it had the capacity of extending for other processes.

- Further improvements: the cost report should contain the number of plies and highlight the total manufacturing cost (this point has been implied in the improved system); expanding the databases and processes.

In general, the experts gave the CMCE system positive valuations and they thought that the engineers would benefit from using the system. Some of the expert suggestions have been implied and the cost report has been improved.

Otherwise, the database information of CMCE system is still not plentiful, so one future work is to add more information to the material, process, equipment and tooling databases.

5.4 Summary

The validation process of developed model was presented in this chapter. Three cases were studied in the aerospace industry, and a validation session with four experts was carried out and some valuable judgements were gathered. As a consequence, the model has the capacity to estimate the manufacturing cost for composite components, and the engineers can also benefit from using it.

6 DISCUSSION AND CONCLUSIONS

6.1 Introduction

A cost model for composites manufacturing was developed and the proposed modelling system has been validated both through case studies and expert judgements. The planned aim and objectives will be discussed and the main conclusions will be summarised in this chapter. Furthermore, the contribution and limitations of this research and the recommended future work will be stated.

6.2 Discussion

It has been presented that this research aimed to develop a cost model for aerospace CFRP composites, which would help designers and cost engineers to estimate the manufacturing cost in the early development stages. To achieve that, several objectives were set, which were to: (1) recognise the standard manufacturing stages and activities of CFRP components, (2) identify the cost drivers of composites manufacturing, (3) identify the cost estimation relationships, (4) develop a cost model that can assist designers and engineers with manufacturing cost estimation for CFRP components, and (5) validate the developed cost model through case studies and expert judgements.

6.2.1 Achievement of Objectives

The first two objectives aim to set up the framework of proposed cost model, and they were achieved mainly through an integrated literature review, which includes papers, theses, books, reports and articles of related topics, and partly through the industrial survey. As discussed in Chapter 4, there are four main stages in composites manufacturing: forming, machining, joining/assembly and finishing, besides of quality control. The major activities of each stage were summarised and the cost drivers of composites manufacturing were classified and shown in section 4.3.

The framework of proposed model has been developed, as the result of achievements of first two objectives. The total manufacturing cost of composites was divided into the recurring cost and the non-recurring cost at the first level, and furthermore it was broken down into seven main parts: material cost, direct labour cost, energy cost, indirect labour cost, equipment cost, tooling cost, and facility cost. For each part, the cost estimation relationships were identified, partly from the literatures and partly from the analysis of industrial data, and the third objective was achieved in this stage.

According to the framework, a modelling system CMCE was developed, and it basically consists of a material selection module, a process planning module, a cost estimation module and a cost reporting module, besides of the material database and process database. In CMCE system, a report of detailed cost results will be generated after inputting the design and manufacturing information. Therefore, the fourth objective has been achieved.

Three case studies and a validation session with four industrial experts were carried out to achieve the fifth objective. Three CFRP components were studied in aerospace industry, and it was believed that the estimation results of CMCE were in the reliable range, compared to the industrial estimation values. Some judgements were gathered from the experts and some of the suggestions were implied to improve the model. Hence, it has been validated that this model has the capacity of estimating the manufacturing cost for CFRP composites.

6.2.2 Cost Modelling for Composites Manufacturing

It has been discussed that cost modelling and estimation are indispensible to assistant designers to develop composite parts with more price competitiveness, and this should be carried out as earlier as possible. However, it is difficult to make estimations accurately as there is quite limited information in the early design stages. Hence, a modelling system, which could provide material selection and process planning, will be efficient and convenient for designers and engineers, like CMCE system developed in this thesis.

The first step is to identify the standard stages and activities and the main cost drivers for the model development, and a comprehensive literature review and an industrial survey were carried out in order to achieve that in this research. It has been realised that there are four main stages, forming, machining, joining/assembly and finishing in composites manufacturing, besides of the quality control activities. The main cost drivers of composites manufacturing are the configuration, geometric sizes, weight, inspection requirements, raw materials, support materials, number of plies, production volume, tooling, equipments, facilities, manufacturing engineering, quality assurance, maintenance, production management etc. These cost drivers were broadly divided into five groups, design attributes, materials, production, investment and labour in this thesis.

With the identification of cost drivers and standard activities, the total manufacturing cost of composites were broken down into material cost, direct labour cost, energy cost, indirect labour cost, equipment cost, tooling cost and facility cost, and the first three costs are the recurring cost while the rest are the non-recurring cost. The CERs of each cost element was then identified, and the process time was regarded as a basic variable in cost estimation of labour, equipments and facility. The MIT equations, which were widely used for time estimation for composites manufacturing, were implied in this model. However, the estimation equation for quality inspection was determined through the analysis of industrial data, as the MIT equations have not covered the quality inspections. As a consequence, the framework of proposed model has been set up.

According to the framework, the system was developed with VBA in the Microsoft Office Excel system, and it consists of a user friendly interface, a cost estimation module and a cost reporting module, besides of the material selection and process planning modules. To implement the selection and planning functions, the material and process data were collected from the literature and industry to build the material and process databases. In this system, the design attributes should be inputted with several steps of material selection and process planning, and then the manufacturing cost will be estimated, including the material cost, labour cost, energy cost, equipment cost, tooling cost, facility cost etc. Detailed cost results will be summarised in a cost report and spread to the user for analysis. Thereafter, some further decisions or design optimization could be made.

To validate the model, three cases of composite components were studied and a validation session with several industrial experts was carried out. According to the validation results, the model has the capacity of manufacturing cost estimation and process time estimation for CFRP composites that are made by hand lay-up and autoclave processes.

6.3 Contribution to Knowledge

In summary, the main contribution of this research is the approach of modelling the manufacturing cost for CFRP composite components, including the component fabrication cost and the quality inspection cost. It provides a way to build a cost modelling system, which combines several modules: material selection, process planning, cost estimation and cost reporting. Moreover, an approach to estimate the cost of non-destructive testing has been developed in this research.

This new model can not only help the engineers to estimate the cost but also help the designers to understand the manufacturing cost, then efficient decisions and/or design optimizations can be made.

6.4 Conclusions

In conclusion, a validated cost modelling system for composites manufacturing was developed and the developing approach was introduced in this thesis. The system enables the user to estimate the manufacturing cost and process time, and it also has the capacity of selecting the material and manufacturing process. It can help designers realise the impact of design changes on the manufacturing cost in the early design stages.

Moreover, the research results could be summarised as follows:

- Process planning can efficiently help estimators to understand the manufacturing process.
- Time estimation is vital for manufacturing cost estimation and the time can be accurately estimated by using process planning.
- Quality control activities are time consuming and investment sensitive in composites manufacturing, especially for aerospace industry.
- Material and labour take the majority of the total manufacturing cost of CFRP components.
- The lay-up, vacuum bagging and quality inspection are the most time consuming processes, besides of the autoclave setup and cure cycle, for the hand lay-up and autoclave process.

6.5 Research Limitations

This model can be applied for cost modelling for composites manufacturing, which covers not only the part fabrication but also the quality inspection. However, it is limited to the prepreg hand lay-up and autoclave laminating process and the NDT process is limited to the portable ultrasonic inspection now, because the data collected for cost estimation are limited to these processes.

Since the aerospace industry is the target area in this thesis, most of the data collected to develop the model were from this area and the industrial survey was also conducted in the aerospace companies. Therefore, the model will not be applicable for other industries unless some specific modifications and calibrations are made.

Moreover, CFRP composites are focused in this research, as it plays the most important role in the aerospace industry. However, the developed framework also has the capacity of cost modelling for other types of fibre reinforced polymer matrix composites, such as GFRPs.

6.6 Future Work

As presented previously, the developed model is focused on the prepreg hand lay-up process and portable ultrasonic inspection at present. However, the approach and framework introduced in this thesis can be applied to improve the model.

The recommended future work can be summarised as follows:

- **Manufacturing process for composites:** add more forming processes, such as RTM, automatic tape Lay-up; add adhesive joining and mechanical assembly processes; add more NDT processes, such as automatic ultrasonic inspection and X-ray inspection.

- **Part Configurations:** there are only a few types of part configuration available in the model, and the configuration variety can be expanded using the methods developed by the MIT research group or other methods.

- **Energy Cost Estimation:** collect and analyse the energy consumption rate of unit time from industry, since it will be more accurate to estimate the energy cost using the consumption rate of unit time and related process time for small production quantities of one batch, as discussed in Section 4.4.2.4.

- **Material database:** there are about thirteen kinds of carbon prepreg in the present database, and it is necessary to add more materials into the database and make the material information plentiful. It would be better to collect the material information from industry, because of the information is usually outdated in the existing databases.

6.7 Summary

In this chapter, it was reviewed that a cost modelling system had been developed and validated, and the research aim and objectives had been achieved. The developing approach of the cost modelling system was discussed and this approach is the main contribution to knowledge. The research results were concluded, and the research limitations and recommended future work were also discussed.

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APPENDICES

Appendix A Questionnaire

Questionnaire

For MSc thesis entitled:

Cost Modelling for Manufacturing of Aerospace Composites

August 2010

Research Student: Weitao Ma

Introduction

This questionnaire aims to gather the manufacturing data of aerospace composites that will allow the researcher to develop a cost model. The model can help engineers with cost estimating and modelling for composite components. The research will be temporarily limited to the prepreg hand lay-up and autoclave curing process and CFRP (Carbon Fibre Reinforced Plastic) composites.

Thanks for taking part in the research. The analysis results of manufacturing cost of composites, such as the cost breakdown and cost drivers, will benefit you and your company. The result can be sent to you if required.

The gathered data will be processed under the confidential protection. The original records will be destroyed when the thesis is completed and not be spread to any other organization or person.

Contact E-mail: walt.ma@cranfield.ac.uk

Note: Please write the letter of your choice(s) (e.g. A, B, or C …) or your answer in the box below the question.

Section 1: General Information

Q1. Name of your company?

Q2. Which type of composite product manufacturer is your company?

A. Raw material/perform manufacturer

B. Equipment manufacturer

C. Composite component manufacturer

D. Other

Note: If other, please type it above.

Q3. General information of you:

Your name (optioned):	
Your responsibility :	
Total year of your working experience:	

Section 2: Cost Estimation

Q4. Have you ever been involved in any cost estimation issues? ('Yes' or 'No')

Q5. For a composite component, which design attributes are the main factors of the manufacturing cost? (Multiple-choice)

A. Material Selection B. Perimeter C. Area

D. Thickness E. Weight F. Configuration

G. Flanges H. Steps I. Curvature

J. Tolerance K. Surface Roughness

L. Core N. Stiffener O. Requirements of NDT

Other *(please list them below)*:

Q6. For a composite component, which manufacturing factors have significant influence on the product cost? (Multiple-choice)

A. Production Volume B. Productivity C. Automation

D. Equipment E. Tooling F. Support Materials

G. Manufacturing Engineering H. Management

I. Quality Assurance J. NDT K. Scrap Rate

Other *(please list them below)*:

Section 3: Laminating Process

Q7. From your experience, what percentage of the total manufacturing cost of a laminated CFRP component would be spent on the raw material cost? Please give a specific number, if applicable.

A. 0% - 5%　B. 6% - 10%　C. 11% - 15%

D. 16% - 20%　E. 21% - 25%　F. 26% - 30%

G. 31% - 35%　H. 36% - 40%　I. 41% - 50%

J. Not sure

Other %

Does it include the cost of scraps ? ('Yes' or 'No')

The data is from:

a) Personal experience　b) Historical data

c) Enterprise Statistics　d) Literature

Q8. From your experience, what is the average percentage of scraps, for CFRP components manufactured by prepreg hand lay-up and autoclave curing process? Please give a specific number, if applicable.

A. 0% - 5%　B. 6% - 10%　C. 11% - 15%

D. 16% - 20%　E. 21% - 25%　F. 26% - 30%

G. Not sure

Other %

The data is from:

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q9. From your experience, how much support material (e.g. vacuum bagging materials, release agents, solvent and so on) would be spent for one unit (e.g. one thousand dollars) laminated CFRP components? Please give a specific number, if applicable.

A. < $ 5 (5 ‰) B. $ 5 - 10 (5‰ - 1%)

C. $ 11 - 30 (1% - 3%) D. $ 31 - 50 (3% - 5%)

E. Not sure

Other %

The data is from:

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q10. From your experience, what percentage of the total manufacturing cost of a laminated CFRP component would be spent on the quality inspections? Please give a specific number, if applicable.

A. 0% - 5% B. 6% - 10% C. 11% - 15%

D. 16% - 20% E. 21% - 25% F. 26% - 30%

J. Not sure

Other %

Does it include the overhead cost of inspection equipments, tools, and supervising? (‘Yes’ or ‘No’)

The data is from:

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q11. From your experience, how much energy would be spent for one unit (e.g. one thousand dollars) laminated CFRP components? Please give a specific number, if applicable.

A. < $ 10 (1%) B. $ 10 - 30 (1% - 3%)

C. $ 31 - 50 (3% - 5%) D. $ 51 - 70 (5% - 7%)

E. Not sure

Other %

The data is from:

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q12. From your experience, what ratio is it for indirect labour time divided by direct production labour time (the indirect labour time refers to the labour time for planning, manufacturing engineering, quality administration etc.)? Please give a specific number, if applicable.

A. 0% - 10% B. 10% - 30% C. 31% - 50%

C. 51% - 70% D. 71% - 90% E. 91% - 110%

F. 111% - 130% G. 131% - 150% H. 151% - 200%

I. Not sure

Other %

The data is from:

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q13. From your experience, what percentage of the total cost of a laminated CFRP component would be spent on the mould by different materials? Please give a specific number, if applicable.

1) Aluminium Mould :

A. 0% - 5% B. 5% - 10% C. 11% - 15% D. Not sure

Other %

2) Common Steel Mould:

A. 0% - 5% B. 5% - 10% C. 11% - 15% D. Not sure

Other %

3) Special Steel Mould:

A. 0% - 5% B. 5% - 10% C. 11% - 15% D. Not sure

Other ☐ %

4) Composites Mould:

☐

A. 0% - 5% B. 5% - 10% C. 11% - 15% D. Not sure

Other ☐ %

The data is from:

☐

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q14. From your experience, what percentage of the total manufacturing cost of a laminated CFRP component would be spent on the equipments (e.g. machines, instruments and tools)? Please give a specific number, if applicable.

☐

A. 0% - 2% B. 3 % - 5% C. 6% - 8% D. 9% - 11%

E. 12% - 14% F. 15% - 17% G. 18% - 20% G. Not sure

Other ☐ %

The data is from:

☐

a) Personal experience b) Historical data

c) Enterprise Statistics d) Literature

Q15. From your experience, what percentage of the total manufacturing cost of a laminated CFRP component would be spent on the investment of facilities (e.g. plant, laboratory and office, but excluding the related maintenance labour cost)? Please give a specific number, if applicable.

A. 0% - 2%   B. 3 % - 5%   C. 6% - 8%   D. 9% - 11%

E. 12% - 14%   F. 15% - 17%   G. 18% - 20%   G. Not sure

Other %

The data is from:

a) Personal experience   b) Historical data

c) Enterprise Statistics   d) Literature

This is the end of questionnaire.
Thanks a lot for your patience and valuable time.
Contact e-mail is listed on page II.

Appendix B Conference Paper

Manufacturing Cost Modelling for Aerospace Composite Applications

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Abstract

The application of composites has been increasing dramatically in aerospace structures recently, for example, composites have contributed over 50 percent of the structure mass of large transport airplanes. However, the further usage has been restricted because of the high material and manufacturing costs. Hence, it is essential to utilize cost estimation tools for accurate cost estimation in the early design stages, and then efficient decisions and design optimizations could be made to reduce the cost of composite products. A cost modelling system has been developed for aerospace CFRP composites, which can help designers and cost engineers to estimate the manufacturing cost in early development stages. The system consists of several modules: material selection, process planning, cost estimation, cost reporting and a user friendly interface. Moreover, the selection and planning modules are combined with databases, including material and process.

Keywords: *Cost Modelling, Aerospace, Composite Material, CFRP, NDT.*

1 Introduction

Composites, especially fibre reinforced plastics (FRPs), have been extensively applied in the aerospace industry since 1960s, owing to their excellent low density and high strength and stiffness. Now, aerospace has grown to be the most important market of advanced composites. Composites have contributed over 50% of the structural mass of large transport aircrafts, such as Boeing 787 and Airbus 350XWB.

Although composites have distinct advantages in comparison with conventional metals, their further applications have been restricted by the high material and manufacturing cost. Hence, cost engineering techniques have led to assist the designers and engineers with accurate cost estimation aiming to produce composite structures with reasonable affordability. Undoubtedly, it is much more efficient to reduce the cost in the early design stages rather than in the production stages, as more than 70% of the manufacturing cost has been set during the design phase [1]. However, compared to the mature metals, there is quite less knowledge and information available for composites cost estimation, due to the more complex techniques and the shorter history of application. Hence, plenty of research efforts

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have been contributed to the cost engineering for composites, especially in the aerospace area.

2 Related Research

Northrop Corporation [2] developed a cost model ACCEM for hand lay-up process. This model utilizes a computerized method to estimate the recurring costs, and it breaks the entire manufacture process a sequence of detailed operations and the labour time for performing each operation is calculated using Industrial Engineering Standards equations that are functions of part feature and complexity.

A theoretical model has been developed by Gutowski et al. [3] to estimate the processing time (human and machine) for the composites fabrication. The theoretical approach refers that the composite fabrication processes can be modelled as first-order basic steps. Firstly, these basic steps are modelled by dynamic equations, and then the step time can be summed to obtain the total time.

Moreover, the above theoretical model has been applied to develop other detailed models. A web-based system was built by a MIT research group [4], and it has the capacities of process time and cost estimation for different fabrication and assembly processes. The PCAD developed by NASA/Boeing ATCAS initiative [5] is a process-based modelling tool for manufacturing and assembly cost, and the first-order dynamic method was used to model the sequential processes and the process time. Barlow et al. [6] used the first-order equations for modelling the labour cost of VARTM and RTM manufacturing process for aircraft composite parts. Clayton and Howe [7] modelled the production process and cost of VARTM, RTM and cocure prepreg process using the first-order equations.

Choi et al. [8] created a knowledge-based system with the VB tool in CATIA V5 to estimate the manufacturing cost for composite structures, and it can capture geometry and feature data from a CATIA model and it also uses the PCAD for the process cost analysis. Curran et al. [9] used the Galorath SEER-DFM to make cost estimation for composite components as well as composite assemblies.

Shehab and Abdalla [10] explored an intelligent system with knowledge-based methodology for manufacturing cost modelling for machined and injection moulded products. The system provides material selection functions, CAD systems, as well as machine/process selection. The material selection module gives the user two options, whether specifying the material and properties by themselves or using the professional material selection system CMS (Cambridge Materials Selector).

However, a little effort has been done in the cost modelling for quality inspection. Quality inspection activities are time-consuming and investment sensitive, especially for the NDT of aerospace composites, as it has very strict inspection requirements and high inspection proportions, and it usually needs large equipments with advanced systems. Hence, quality inspection is an important cost driver for composites manufacturing in aerospace industry. It is essential to set up a cost model for composites manufacturing, in which the quality inspection costs is included, and it has been made as the target area of this research.

3 Methodology

This research aims to develop a cost modelling system for aerospace composites manufacturing. An industrial survey was carried out in five aerospace companies in China. The industrial survey helped the authors to indentify the standard activities and cost drivers of aerospace composites manufacturing. A number of data were collected from these companies to analyse the manufacturing cost of aerospace composites, and then a cost modelling system was developed. To validate the developed system, several composite components were studied and a validation session was carried out in one of the aerospace companies.

4 Cost Modelling System for Composites Manufacturing

4.1 The Developed Cost Modelling System

The developed cost modelling system, CMCE (Composites Manufacturing Cost Estimator), basically consists of a material selection module, a process planning module, a cost estimation module, a cost reporting module and a user friendly interface, as illustrated in Figure 1. Additionally, several cost databases (material, process, equipment and tooling) are combined with the selection and planning modules.

The CMCE system was developed using Microsoft Office Excel VBA. The system mainly consists of four user windows: Design Attribute Input, Material Database, Material Cost Estimation and Process Planning, besides of the Start Interface and the Cost Report.

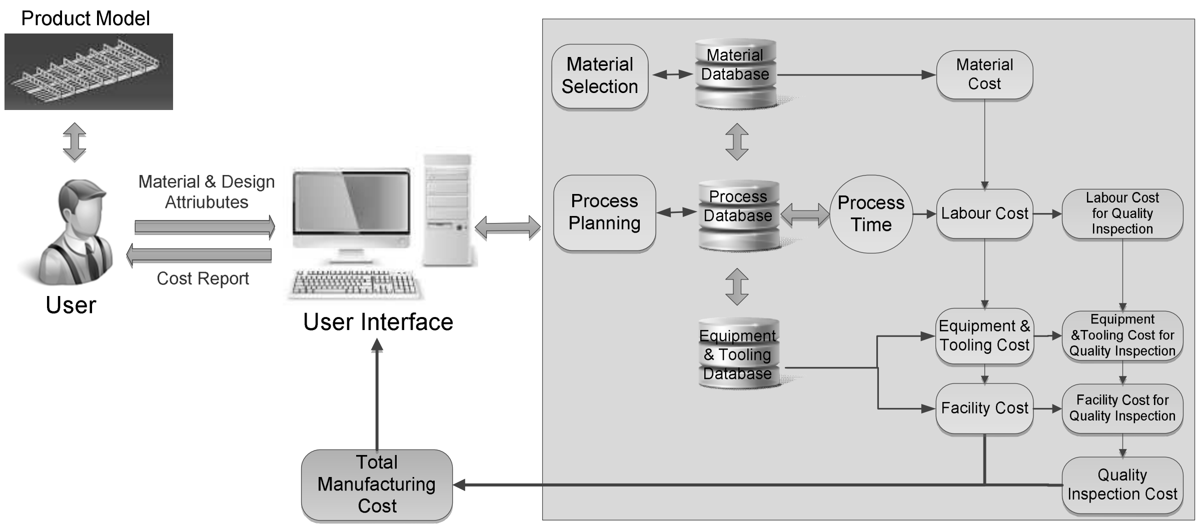

Figure 1: The Overall Structure of CMCE System

The system prompts the user to input the design attributes of composite components, including the material information and the necessary product features. For material selection, the user can select the material from the database or add different materials by themselves. The process planning allows the user to select the detailed manufacturing processes and input additional production information, such as the tooling and equipment investment and the labour rate. Then the system will estimate the various costs, including the material cost, labour cost, tooling and equipment cost, facility cost etc. The total manufacturing cost will be calculated as the sum of these various cost elements. Otherwise, the labour cost, tooling and equipment cost, facility cost incurred for quality inspection will be counted individually, and the quality inspection cost can be estimated. Then a final report with detailed cost results will be generated. The user can analyse the estimation results and re-estimate it by changing some of the parameters if necessary.

4.2 Standard Activities and Cost Drivers of Composites Manufacturing

Figure 2 shows the main activities of composites manufacturing. There are four main stages: forming, machining, joining/ assembly, and finishing. Besides of the various fabrication and joining/assembly processes, the quality control activities, mainly including control of materials, equipments, tooling, manufacturing process, quality and defects of products, are covering the whole manufacturing cycle of composite components.

The cost drivers of composites manufacturing are classified into five groups: design attributes, materials, production, investment and labour. The design attributes are the factors determined in the design stage, including the configuration, geometric sizes, weight, inspection requirements, material selection etc. The material drivers are not only the raw materials (fibre or fibre preforms, resin, additives, prepreg, etc.) but also the support materials that are consumed during the processing cycle. Otherwise, the number of layers is an important factor which has influence on the lay-up time of preforms or prepregs. Production drivers include various types of operations and the production volume. The cost drivers of investment can be identified as tooling, equipments and facilities. The labour cost includes the direct labour cost for production as well as the indirect labour cost, e.g. maintenance, manufacturing engineering, quality assurance and production management.

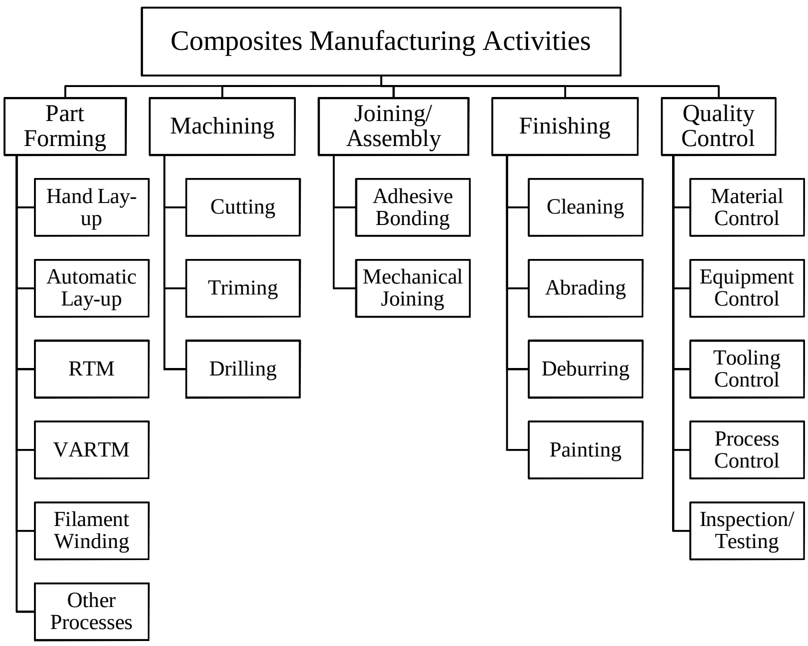

Figure 2: Composites Manufacturing Activities

4.3 Cost Breakdown and Cost Estimation

The manufacturing cost of composites consists of the raw and support material cost, direct and indirect labour cost, energy cost, equipment cost, tooling cost and facility cost, as presented by Eq. (1). The estimation methods of each cost element have been identified. For example, Eq. (2) presents the estimation of direct labour cost for a specific operation.

$$\begin{aligned} Manufacturing\ Cost \\ &= (\textstyle\sum Raw\ Material\ Cost + \sum Support\ Material\ Cost) \\ &+ (\textstyle\sum Direct\ Labour\ Cost + \sum Indirect\ Labour\ Cost) \\ &+ \textstyle\sum Energy\ \ Cost + \sum Equipment\ Cost + \sum Tooling\ Cost \\ &+ \textstyle\sum Facility\ Cost \end{aligned} \quad (1)$$

$$Direct\ Labour\ Cost = \frac{No._{operators} \times Process\ Time \times Labour\ Rate}{(1 - Reject\ Rate) \times No._{parts/Run}} \quad (2)$$

Where:

No. $_{operators}$ *= the number of operators for a specific operation..*

No. $_{parts/run}$ *= the quantity of parts for single run.*

4.3.1 Process Time Estimation

The process time is a key variable for the cost estimations of direct/indirect labour, equipment and facility. It has been reviewed that the MIT equations were widely used for the time estimation of composites manufacturing and they have also been applied in this model.

However, the MIT equations have not covered the NDT process. Hence, the time estimation method for NDT has been determined in this research. There are two frequently used NDT methods for aerospace composite structures, which are Ultrasonic Inspection (ultrasonic thru-transmission C-Scan or ultrasonic pulse echo A-Scan) and X-Ray Radiography, and the inspection equipments can be portable systems or large automatic systems. However, the Portable Ultrasonic C-Scan process has been taken as the research target at first.

Equation (3) [11] has been applied for Portable Ultrasonic C-Scan inspection, where the part configuration complexity K is treated as the variable V_c, and the constants in Eq. (3) were determined through the inspection data analysis of several industrial composite components. The estimated inspection time doesn't include the part cleaning (before and after inspection) and equipment setup (calibration and testing), which are treated as separated operations.

$$T = T_{setup} + No._{parts/run} \times No._{operations/run} \times \left(T_{delay} + \sqrt{\left(\frac{V_b}{V_a}\right)^2 + \frac{2T_aV_b}{V_a}} \right) \times V_c \quad (3)$$

For Portable Ultrasonic C-Scan, where:

V_b *= The surface area of required inspecting surface (*A_i*).*

V_c = K =Inspection Area/Maximum projected area, the configuration complexity of component.

T_{setup} = 2 min.

T_{delay} = 0 min.

V_a = 0.03044 m^2/min.

T_a = 88.8 min.

5 Case Studies for Validation

To validate the developed system, three different CFRP components were studied in one aerospace company. The components for case studies are all made by prepreg hand lay-up and autoclave curing process, and the Portable Ultrasonic C-Scan has been chosen for NDT.

Figure 3 shows the cost estimation results of a single curved skin panel (see Figure 4), one of the case studies, from the CMCE system. From the case studies, it found that the material and labour represented the majority of total manufacturing cost. It should be highlighted that the case studies were carried out in a Chinese company and the high material price and low labour rate resulted the high proportions of material cost and low proportions of labour cost. It also found that the lay-up, vacuum bagging and quality inspection were the most time consuming processes in the case studies, besides of the autoclave setup and cure cycle. The increased number of plies will significantly result in the time increasing of prepreg lay-up, and the higher complexity of configuration will result longer process time of lay-up and quality inspection.

Moreover, the total manufacturing costs estimated by the CMCE system were compared with the actual costs, as shown in Figure 5.

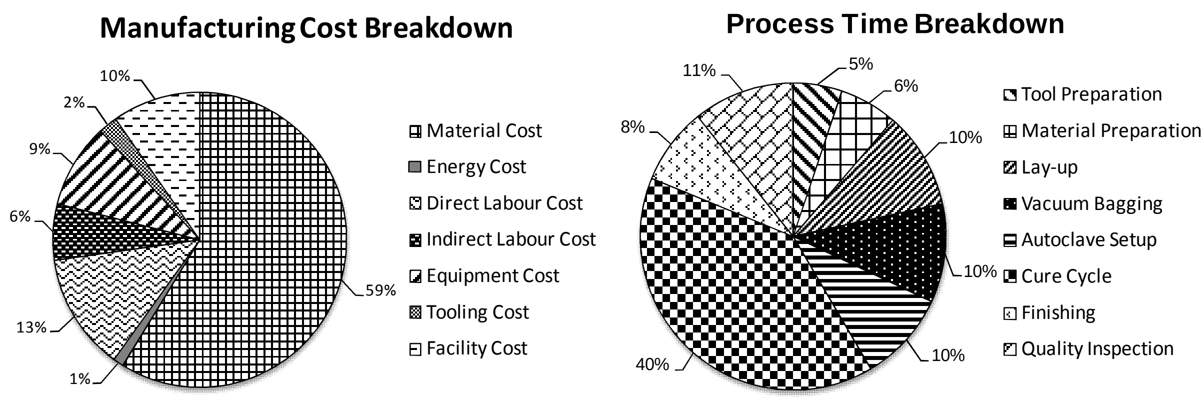

Figure 3: Cost and Process Breakdowns of Case Study (Hand Lay-up, CFRP)

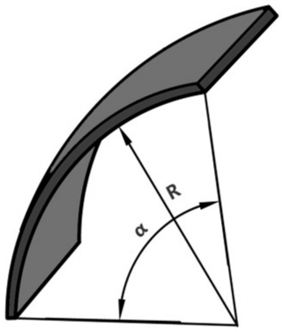

Figure 4: Sketch of Skin Panel

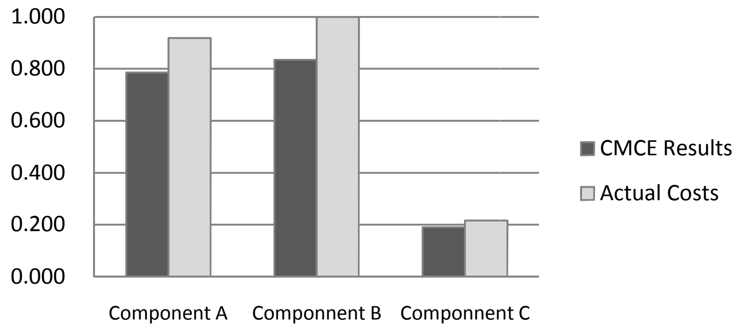

Figure 5: Comparison of CMCE Estimation Results and Actual Cost

6 Conclusions

In conclusion, a cost modelling system for composites manufacturing was developed in this research. The system enables the user to estimate the manufacturing cost and process time for aerospace CFRP components, and it also has the capacity of selecting the material and manufacturing process. It can help designers realize the impact of design changes on the manufacturing cost in the early design stages. It found that the process planning can efficiently help estimators with manufacturing process understanding and accurate time estimation. It also found that the quality control activities are time consuming and investment sensitive in composites manufacturing.

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