Cranfield University

Tienan Zhao

Acquisition Cost Estimating Methodology for Aircraft Conceptual Design

School of Engineering

MSc by Research Thesis

Cranfield University

School of Engineering

MSc by Research Thesis

Academic Year 2008-2009

Tienan Zhao

Acquisition Cost Estimating Methodology for Aircraft Conceptual Design

Supervisor: Pro. John P. Fielding

January 2009

Acknowledgement

Here I would like to thank all people who helped me to accomplish this research in last 10 months. I will not be able to finish this work without their assistances.

First and foremost, I would like to appreciate my supervisor Prof. J. P. Fielding for his guidance and supporting with patience and kindness. He inducted me into a completely new and interesting area I never experienced before; and enlightened me with his professional experience and knowledge about everything of aircraft throughout the research.

Also, I would like to thank Mrs. Kath Tipping, Dr. Xiang Zhang, Dr. Shijun Guo, Dr. Huamin Jia, Dr. Stephen O T Ogaji, Mr. Rob Brink and Mr. Bin Wang for their superb collaboration during my research.

Finally, I would like to thank my families for their support on my study in Cranfield University. They are my wife Changqing Sun and my 8-month-old daughter Ziqing Zhao. This thesis is also a gift for Ziqing as she was born after I leave for UK and consequently I haven’t seen her by eyes till now.

Abstract

Key words: Aircraft, Conceptual Design, Acquisition Cost, Cost Estimating, Analogy, Parametric, Regression

The research was conducted in the light of a training programme which will train a total of 150 engineers of AVIC I in Cranfield University during a period of 3 years.

Cost has become an essential driver to aircraft design, as well as performances due to either the limited defence budget or competitive airline market. Consequently, knowing the possible cost prior to making actual expenditure will help managers to make proper decisions and allocate resources efficiently, and designers to optimize their work. Existing aircraft cost estimating models are outdated and mainly based on a database including both military and civil aircraft with various missions. This research concentrated on commercial jet aircraft and was to develop a suitable acquisition cost estimating methodology for conceptual design from a commercial aircraft manufacturer's perspective.

The literature reviewing took a comprehensive overview of some widely-applied cost estimating methods: Analogy, Parametric, Bottom-up, Feature-based costing, Activity-based costing (ABC), Expert judgement, and etc. Some practical cost models were also reviewed to learn the application of cost estimating in the aerospace industry. Then, analogy and parametric approaches were selected to perform the methodology development considering the limited data available at the conceptual design phase.

An investigation was deployed to identify the actual problems in practice. The results helped to recognize the needs of industry. Also, the preparation works for development are presented to understand the environment.

With subjective judgement and statistical techniques, a series of cost estimating relationships (CERs) were achieved, in which some historic explanatory parameters remained or were eliminated, and some new ones introduced. Size of aircraft became another variable besides weight. As to engines, all developed explanatory variables have been revealed in prior researches. The validation of CERs proves that they can provide reliable cost estimates with high accuracy and can be applied to conceptual design. In addition, a case study was conducted using a baseline aircraft defined in the group design project (GDP) and presents cost forecasting for the proposed aircraft.

At last, discussion and conclusion presents an overview of the research. A framework for cost estimating system can be educed. Also, the future work is proposed for in-depth research.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Acronyms

ABC - Activity-Based Costing
AI - Artificial Intelligence
AMPR - Aeronautical Manufacturers Planning Report
APU - Auxiliary Power Unit
ARCO - Aircraft Resources Control Office during the World War II
AVIC I - China Aviation Industry Corporation I ()
BPR - Bypass Ratio
CACC - Commercial Aircraft Corporation of China ()
CAD - Computer Aided Design
CE-C - Cost Estimating for Commercial
CE-E - Cost Estimating for Engineering
CEF - Cost Escalation Factor
CER - Cost Estimating Relationships
CERC - Cost Estimating Rationale Capture
DCAA - Defense Contract Audit Agency
DESCEM - DEcision support for the Selection of Cost Estimation Methods
DFM - Design For Manufacturing
DFA - Design For Assembly
DFC - Design For Cost
DOC - Direct Operating Cost
DoD - Department of Defence
EJ - Expert Judgements
FUCE - FUnction-based Cost Estimating
GDP - Group Design Project
IPT - Integrated Product Team
LCC - Life Cycle Cost
MHR - Man-Hours in Research
MKS - the Meter, Kilogram, and/or Second system of units
MTOM - Maximum Take-Off Mass
NN - Neural Networks
OEM - Operational Empty Mass
OLSR - Ordinary Least-Squares Regression

PCA - Principal Component Analysis
PLSR - Partial Least Square Regression
PPI - Producer Price Indices
RDT&E - Research, Design, Test and Evaluation
RTO - the NATO Research and Technology Organisation
SFC - Specific fuel consumption
SPC - Statistical Process Control
VIP - Importance of variable in projection
WBS - Working Breakdown Structure

Notations

C_{ac} - Acquisition cost of unit aircraft

C_{af} - Airframe cost

C_{avi} - Avionics cost of unit aircraft

$C_{avi\text{-}d}$ - System design cost of avionics

$C_{avi\text{-}hd}$ - Hardware cost of avionics

$C_{avi\text{-}i}$ - Installation cost of avionics

$C_{avi\text{-}sw}$ - Software cost of avionics

$C_{avi\text{-}hb}$ - Cost of base avionics kit

C_{ENG} – Engine Cost

C_{eng} - Acquisition cost of unit engine

$C_{eng\text{-}sample}$ - Acquisition cost of unit sample engine

C_{FLY} - Flyaway cost of unit aircraft

C_{lab} - Labour cost

C_{inv} - Investment cost

C_{MAN} - Manufacturing cost of a programme (recurring cost)

C_{mat} - Material cost

C_{mis} - Miscellaneous cost of unit aircraft

C_{oh} - Overhead cost

C_{P} - Acquisition cost of a programme

C_{qc} - Quality control cost

$C_{RDT\&E}$ - Development cost of a programme (nonrecurring cost)

C_{stru} - Airframe structure cost of unit aircraft

C_{U} - Acquisition cost of unit aircraft

f_{diff} - Adjustment factors for difficulty

f_{lab} - Adjustment factors for labour rate

f_{mat} - Adjustment factors for material

f_{oh} - Adjustment factors for overhead

f_{tech} - Adjustment factors for technology

$F_{avi\text{-}diff}$ - Difficulty judgement factor of avionics

$F_{avi\text{-}d}$ - Judgement factor for avionics design

$F_{avi\text{-}i}$ - Judgement factor avionics installation

$F_{avi\text{-}pro}$ - Proportion factor of avionics to base kit

$F_{avi\text{-}sw}$ - Judgement factor for avionics software
F_{CAD} - Judgement factor of computer aided design
F_{inv} - Adjustment factor of investment
F_m - Judgement factor of material types
F_{mis} - Ratio judgement factor of miscellaneous systems to structure
F_{oh} - Judgement factor of overhead cost
F_{tech} - Judgement factor of technology
F_u - Normalized material utilization factor
F_{diff} - Difficulty judgement factor
F_{cad} - CAD judgement factor
F_{tech} - Technology judgement factor
F_{mat} - Advanced material judgement factor.
MHR_{eng} - Engineering man-hour per unit aircraft
MHR_{manu} - Manufacturing man-hour per unit aircraft
N - Total production number of one programme
N_{rdte} - Production number for RDT&E
P_u - Profit of each aircraft
P - the total profit of a programme.
$Price_{al}$ - the average price of aluminium alloy
P_U - Profit of unit aircraft.
Q^2 - Cumulated index of global model in PLSR
R^2 - Coefficient of Determination
R^2Y - Cumulated index of dependent variable
R^2X - Cumulated index of independent variables
R_{eng} - Engineering labour rate
R_{man} - Manufacturing labour rate
V_{max} - Maximum speed
W_{ampr} - AMPR weight

1 Introduction

This chapter is to introduce the background of this research. The structure of the whole thesis will be described as well to present an overview for readers.

1.1 Background

The research carried by this thesis is a part of a training programme built up in the light of preparation for developing a large commercial aircraft (80-150 seats) in China, which will train a total of 150 engineers from China Aviation Industry Corporation I (AVIC I) during 3 years (50 for each year) in Cranfield University.

This research is employed for the conceptual design, as the first step of the 3-year research programme aiming to establish a systemic methodology of cost estimating for aircraft design.

A group design project (GDP) is carried out to develop a baseline aircraft at the same time of this research. And it is presented as case study in this thesis.

1.2 Industrial Sponsor

China Aviation Industry Corporation I (AVIC I) is the largest state-owned aerospace company which has been committing to developing and manufacturing fighter, bomber, trainer, transport aircraft, missile, and engine etc for more than 50 years.

Recent years, AVIC I has became a main supplier for commercials by providing parts, components and assemblies to many international companies around the world, such as Boeing, Airbus, Bombardier, etc.

AVIC I is one principal shareholder of Commercial Aircraft Corporation of China (CACC) who is founded to develop large commercial transport at Shanghai in May, 2008.

1.3 Need for Research

Cost is always the most sensitive and critical factor in any business activity. How well a company can survival in current competitive economic environment depends on its financial functions and performances, i.e., its ability of controlling cost (Asiedu, 1998).

Performance was the only focus of aircraft design in past decades. However, other factors must be involved at design phase to trade-off in order to meet customers' requirements, especially affordability requirement. Thus, acquisition cost becomes vital for operators as buying cost and one part of operating cost (Fielding, 1999).

To develop an advanced and competitive (not only on performance but also on cost) civil aircraft in order to take shares from current and future global market, which is already occupied by many successful and mature products (for instance, B737 family and A320 family in 150-seat class), the design should be defined seriously and systematically from the very beginning to the completeness, taking account of technology, performance, environment, capacity, capability, and the most important issue for both users and producers - cost (including direct operating cost for customers and development & manufacturing cost for manufacturers themselves).

At the aircraft conceptual design phase, various alternative concepts are to be compared for choosing a final decision. Being aware of cost of each concept certainly will help to make decisions and optimize following design, especially when the majority of life cycle cost is determined at this stage. Thus, cost estimating approaches are required by both managers and engineers at the beginning of a new programme.

1.4 Research Aim

The aim of this research is to identify a suitable acquisition cost estimating methodology for aircraft conceptual design stage.

With the cost estimating model, a systemic framework of cost estimating is able to be built up by performing a complete cost estimating process, to be applied to the practice of aerospace industry in China within a cost-driven environment. Then a sound cost estimating system can be established, based on the learning and understanding obtained during this research programme.

At last, some measures for cost reduction are to be discussed on the basis of achieved cost estimating model.

1.5 Structure of the Thesis

Chapter 1 introduces the background, the needs, and the aim of this research as well as showing the thesis structure. The industrial sponsor is introduced as well. Chapter 2 reviews and surveys the cost estimating methodologies and techniques developed in past decades, on which the research is based. Chapter 3 highlights the objectives and methodologies used in the research. Chapter 4 presents an investigation of cost estimating of aerospace industry in Asia, which will concentrate the research on needs of practice. The preparation works for methodology development are depicted in Chapter 5.

In Chapter 6, some cost models for aircraft conceptual design are derived using analogy estimating approach. A framework of analogy cost estimating system is presented as well. Besides that, parametric cost models are developed in Chapter 7, including a whole aircraft model and component model from manufacturers’ perspective.

The acquisition cost of baseline aircraft defined in GDP is estimated in Chapter 8, with methodologies developed in Chapter 6 and 7.

Finally, overall discussions and conclusions are presented in Chapter 9. Also, future works are expected for further research.

2 Literature Review

This chapter will present a comprehensive review of cost estimating and the methodologies developed in past decades for the research.

2.1 Overview of Cost Estimating

Cost estimating is to "accurately approximate the probable resources required to produce a work activity or a work output based on information available or that can be collected at the time" (Stewart, 1995). And it is one aspect of cost engineering while the others concern with cost control, business planning and management science (Roy, 2003).

Within a competitive global climate, aerospace industry is increasingly identifying factors such as cost, performance, schedule, and quality in order to satisfy customers' requirements about affordability, i.e. reducing aircraft acquisition cost, during recent years (Kundu, 2003; Crosby et al, 2003). Nowadays, design is to satisfy both realistic user requirements and affordability (Apgar, 2001). And cost already became an important design variable on an equal level with traditional performance variables (Marx, 1995). Decision makers or project managers do rely on it at early stage, regardless of its inaccuracy (Zack, 2007).

2.1.1 Role of Cost Estimating

There is a continuously growing demand to develop cost estimates for management supporting, programme, and engineering; and get estimating done as fast as possible (Young, 2008). The motivation to estimate costs is to assist decision making, cost management and budgeting in business (Asiedu, 1998; Apgar, 2004; Evans, 2006). It is crucial for the success of product (Sandberg et al, 2005) and important to achieve competitiveness for industries (Roy, 2007).

Cost estimation is required to use cost as initial tool in design (Koelle, 1994). And it also enables the designers to make decisions by finding the best cost-function trade-offs during the conceptual design phase (Duverlie et al, 1999; Crosby et al, 2003; Cavalieri, 2004); allow both designers and manufacturing engineers to make more competitive decisions within a design process that integrated Design For Manufacturing (DFM), Design For Assembly (DFA), and Design For Cost (DFC) as illustrated below (Curran, 2002).

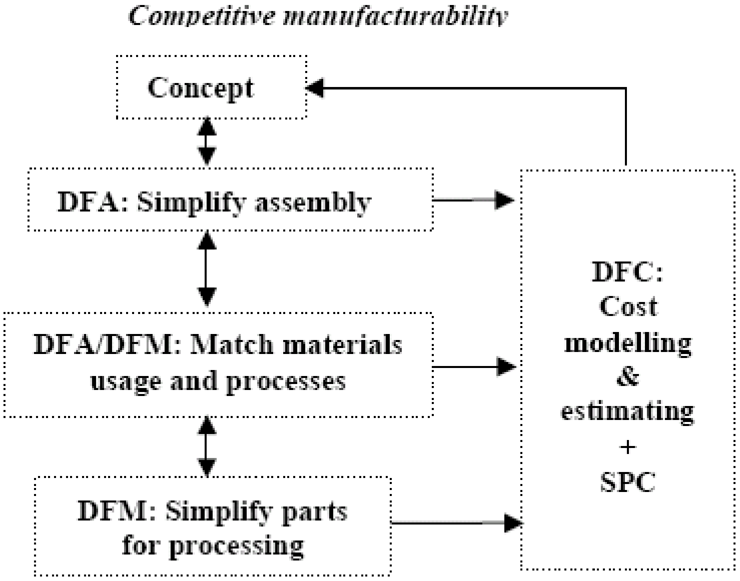


Figure 2.1 – Design Process linking DFA, DFM and DFC (Curran, 2002)

where DFA stands for Design For Assembly, DFC Design For Cost, DFM Design For Manufacture, and SPC Statistical Process Control.

Awareness of the potential cost prior to the work is undertaken surely provides an opportunity to optimise design to minimize costs or to decide a profitable price to customers (Evans, 2006). Cost estimating already became a truly powerful, creditable, and useful function of organizations or business activities (Stewart, 1995), a focal point for design and operational strategies as well as a key agenda for managerial policies and business decisions (Niazi et al, 2006).

2.1.2 Cost Estimating in Aircraft Design

Aircraft cost estimating is a combination of science, art and politics. It is hard to obtain actual cost data of historic aircraft which will support new aircraft perfectly because there always are some particular things for them, e.g. technology (Raymer, 2006).

There are many reasons to emphasize cost during the design phase. The most important one is that 70-80 percent of the life cycle cost of a product is determined during the early design phase (Pahl, 1996; Ou-Yang and Lin, 1997; Rehman, 1998; Forsberg and

Kelvesjö, 1999; Gayretli, 1999; Murman, 2001; Koonce, 2003; Castagne, 2004; Cavalieri, 2004). With respect to aircraft, a recognized fact is that around 65 per cent of total life cycle cost is determined within the conceptual design phase and 85 per cent by preliminary design (Roskam, 1990; Willcox, 2004; Raju, 2003; Choi, 2007).

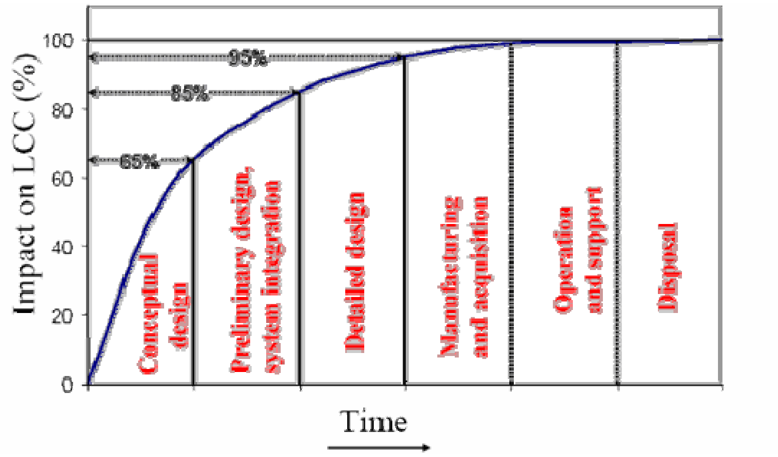


Figure 2.2 - Impact of Aircraft programme phases on Life Cycle Cost (Roskam, 1990)

A similar figure can be found in Hamaker's presentation (2006) as shown below.

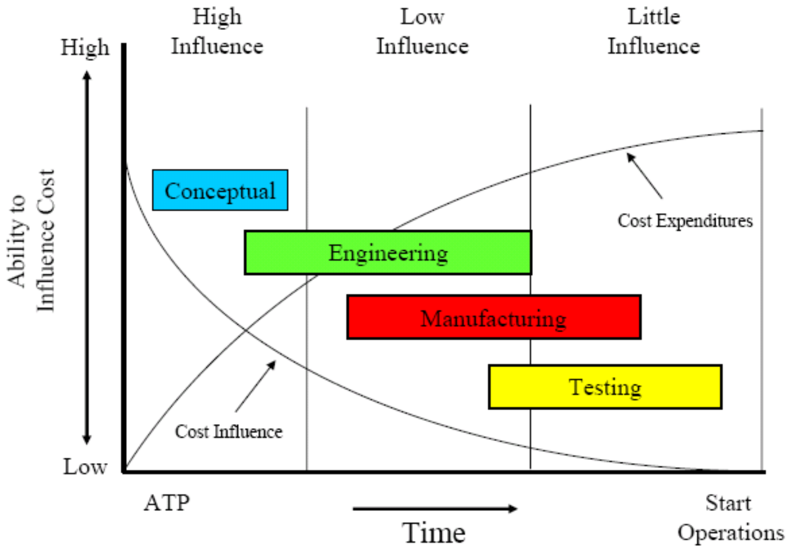


Figure 2.3 – Early Design Choices Affect Ability to Influence Costs (Hamaker, 2006)

Many other similar figures can be found in works of other authors (figure 2.4 to 2.7).

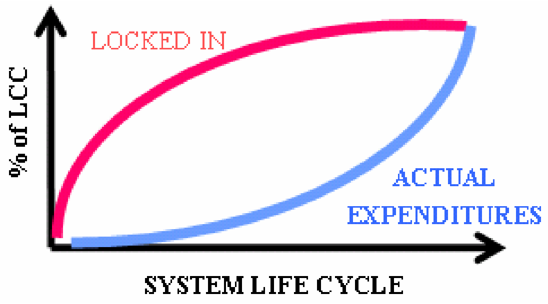


Figure 2.4 – LCC and Actual Cost Determination (Kankey, 2007)

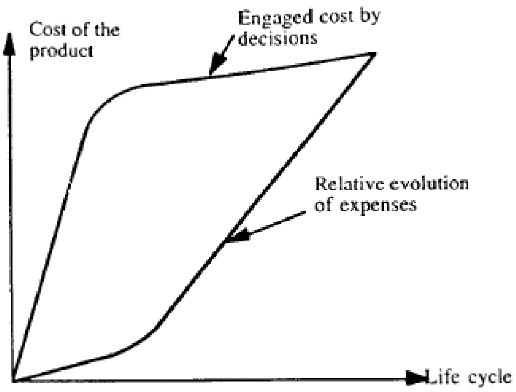


Figure 2.5 – Example of expense and the engagement of costs (Duverlie et al, 1999)

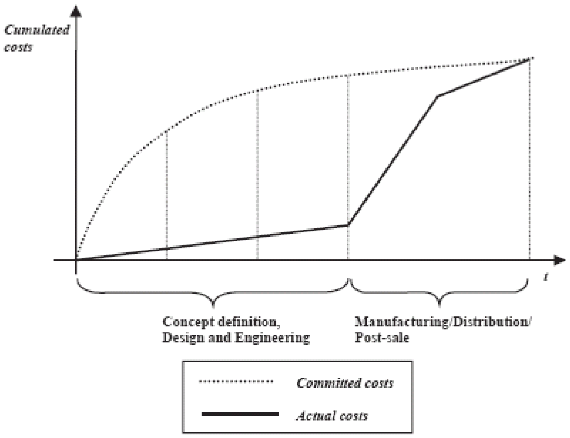


Figure 2.6 – Committed costs and actual costs along the Product life cycle (Cavalieri, 2004)

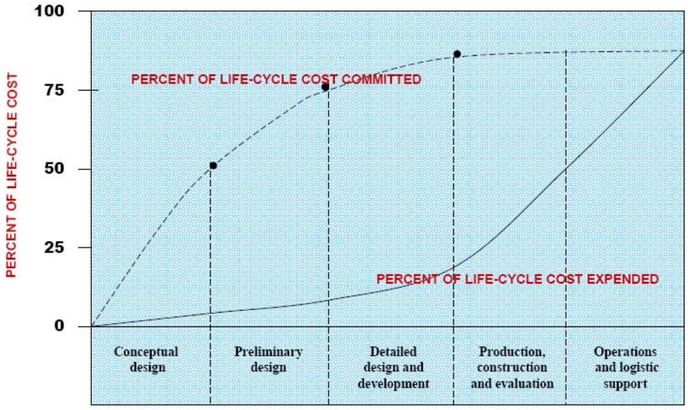


Figure 2.7 – Cost Leverage through the Life Cycle (Hamaker, 2006)

The outcome of aircraft conceptual design is the understanding of feasibility involving various concepts and a prediction of the most possible configuration in current environments with respect to technology and business considerations (Jenkinson, 1999); any later modification of these features will be difficult and costly.

Therefore, designers primarily concern the relationship between cost data and design decisions (Asiedu, 1998). However, it is restricted by the limited information and consequently, the cost estimating methodology for conceptual design becomes essential.

2.2 Approaches of Cost Estimating

There are many approaches for estimating cost of programme. In fact, the cost estimating methodology of a project is usually a combination of methods used in particular area or stage of life cycle (RTO, 2007), just like Kaplan said: “one cost system is not enough” (2001). Any estimates obtained from one approach need to be crosschecked by others. Otherwise, the methods vary with different stages of a product’s lifespan. For instance, Watson et al (2004) incorporate analogous, parametric, and ratio estimating for their “PRO-COST EST” model; and Marx (1995) integrates “bottom up” and “top down” approaches for a hierarchical life cycle costing model.

In an overview of cost estimating, Niazi et al (2006) categorize all cost estimating methods into qualitative and quantitative techniques, which also are highlighted by Roy et al (2003), after reviewing many literatures. The former consists of intuitive and analogical techniques while the latter is subdivide into parametric and analytical techniques. Evans (2006) reveals that there is no consistent classification for cost estimating methods with a similar literature review and then identify 10 methods, which are discussed frequently in many other authors’ researches (Stewart, 1995; Asiedu, 1998; Richey, 2003; Roy, 2003; Cavalieri, 2004; NASA, 2004; Gates, 2006; RTO, 2007), using Web Grid III application.

- Parametric cost estimates
- Neural Networks
- Expert Judgement(roundtable cost estimating)
- Function Costing
- Feature Costing
- Group Technology estimating
- Case-Based Reasoning
- Knowledge-Based Systems
- Generative Costing
- Activity-Based Costing (ABC)

Similarly, Evans (2006) sorts all these methods into two top level: transparent and black box by the intuition of reasoning behind methods; and furthermore the former one includes analogical method (Group Technology estimating, Case-Based Reasoning, and Knowledge-Based Systems) and detail method (Function and Feature costing as attribute-based methods while Activity-based costing and Generative costing as accumulation methods) and "black box" comprises Expert Judgement, Neural Networks, and Parametric Methods. Duverlie et al (1999) offers their option about categorising: intuitive method, analogical method, parametric method, and analytical method.

In this section, some of aforementioned methods are introduced considering the possible suitability in aerospace industry as well as the relativity to aircraft acquisition cost.

2.2.1 Analogy Cost Estimating

Analogy cost estimating is using past similar cases to estimate costs of a new programme by comparing the proposed programme with one or more analogous existing recent programme with accurate cost and technical data to find the reasonable comparative relationships (Watson et al, 2004; Gates, 2006; Niazi et al, 2006; RTO, 2007). It depends on the similarity or differentiation of the prior programme to the new one (Cavalieri, 2004; Curran and Raghunathan, 2004; Shishko, 2004) with the ground assumption that no new programme is a totally new one since "most new programmes originate or are evolved from already existing or simply represent a new combination of existing components." (RTO, 2007)

Analogy estimating is suitable for state-of-the-art products since there are so many innovation and immature technologies in these kinds of programmes with limited historical data and experiences (Gates, 2006; Roy, 2003).

Typically, it is used when numerous like programme and technical definition are available for both proper selection and adjustment of comparable cost data (NASA, 2004) in conceptual design stage (Crosby et al, 2003). At that time, there is no sufficient historical data to develop a statistically valid parametric estimating model; or no enough available information, time, or resources to conduct an engineering estimate (Shishko, 2004).

The analogy system relies on the opinions of experts heavily for adjustment factors generated subjectively by them (NASA, 2004; Shishko, 2004) due to the shortage of supporting historical data, so that risk and uncertainty are introduced as well. This is one of its weaknesses (Asiedu, 1998) although subjective expert judgement is must at then.

However, estimating by analogy is reasonably fast, cheap, and easy to change (Gates, 2006); and does not require detail information. To derive reliable estimates, analogous method requires identifying both the similarity for comparing and differences in order to define adjustment factors (Roy, 2003; Curran and Raghunathan, 2004; NASA, 2004).

For an innovative product without historical cases, analogous estimating may be the most suitable approach for its ability of accepting unknown information (Duverlie et al, 1999). Smith et al (1997) support this advantage for neural networks in their research as well.

After cost estimates have been produced with analogy approach, the chosen products or projects for analogy, the adjustment factors, the considerations during the process, and the cost estimates must be documented (DoD, 1992) for preserving knowledge, tracing back and possible future application. All information stored will be preserved as collective knowledge even the experts are not available (Duverlie et al, 1999). That is one of the advantages of analogical methodology.

It also can be particularly regarded as case based reasoning (Duverlie et al, 1999; Roy, 2003), which attempts to connect the source cases and the target new projects in order to obtain solution from past experience; and is being improved by using computer aided techniques, so called Artificial Intelligence (AI) or Neural Networks (NN). The computer application can store all cost data, learn the impact of related features to cost occurred in past cases (Roy, 2003; Curran and Raghunathan, 2004; Niazi et al, 2006), and then chooses the most suitable situations for the new product and adapts a solution based on what it learned from past (Roy, 2003). It is the most important and exciting feature of Neural Networks that their capacity is able to infer from stored knowledge the solutions to new problems that they have never been told before, just like the learning ability of human brain (De Cos et al, 2008).

Analogy cost estimating, or neural networks, is a black-box approach because the results are often uninterpretable and offer little insight to estimators or other involved people. However, it can support the designers or engineers with an additional information source to choose assembly system for cost optimization at design stage (Shtub, 1993).

2.2.2 Parametric Cost Estimating

2.2.2.1 Overview

“Parametric estimating is the process of estimating cost by mathematical equations that relate cost to one or more physical or performance variables associated with the item being estimated” (Stewart, 1995).

Another definition describes the parametric cost estimating as “A technique employing one or more Cost Estimating Relationships (CERs) and associated mathematical relationships and logic. The technique is used to measure and/or estimate the cost associated with the development, manufacture, or modification of a specified end item. The measurement is based on the technical, physical, or other end item characteristics.”(DoD, 1995)

Asiedu (1998) describes parametric cost estimating approach as a statistical methods that “correlate costs and technical information with parameters describing the system and results in sets of formulae”. And these equations or formulas, or called CERs, illuminate how and how much a product’s physical characteristics and programmatic properties affect its cost and timeline (Duverlie et al, 1999; RTO, 2007) and are then applied to deduce from past and current example data to predict the cost of future programmes (Dean, 1995).

These physical or performance variables are sometimes known as “cost drivers” (Apgar, 2004; Cavalieri, 2004; Niazi et al, 2006). Typically, they should be measurable attributes (Dean, 1995) and then may be manufacturing complexity, design familiarity, weight, and performance, etc (Asiedu, 1998). Rand Corporation has done a lot of works in their studies or researches primarily for military acquisition in decades (Levenson, 1966; Levenson, 1972; Nelson, 1974; Large, 1976; Birkler, 1982; Hess, 1987; Palmer, 1992; Fox, 2004).

It was first introduced to predict the manufacturing cost of aircraft during the World War II primarily using learning curve theory suggested in 1936 by T. P. Wright in the early years, until Rand Corporation expanding it in 1950s (DoD, 1995).

As parametric estimating method is often used in the earlier phases of definition when little information is available (Stewart, 1995; Koonce, 2003; Niazi et al, 2006), it should be another possible solution satisfying this research. It is also suitable for technology-driven programmes through simplifying the complex new technologies by identifying, validating and maintaining (Kwak, 2005). However, Duverlie et al (1999) believe that it is useful only if used with other approaches to form a combination methodology.

Tan et al (2008) describes that parametric costing method is sometimes called the Function costing method; but in Evans' classification (2006), function costing is distinct form parametric costing.

Joseph Hamaker thinks that parametric method is the only estimating technique in a project before detailed information is available (Stewart, 1995). However, looking back to the previous section, it can be seen that analogy method is another option although it is rough and dependent on subjective opinions, especially when quick results are required.

Parametric costing method can be used in detailed design, production and operation stages as well, either as a method to perform independent check and validation or the primary method for selected cost elements (Stewart, 1995; Kwak, 2005).

2.2.2.2 Development

A general process of developing CERs is illustrated by Forsberg and Kelvesjö (1999):

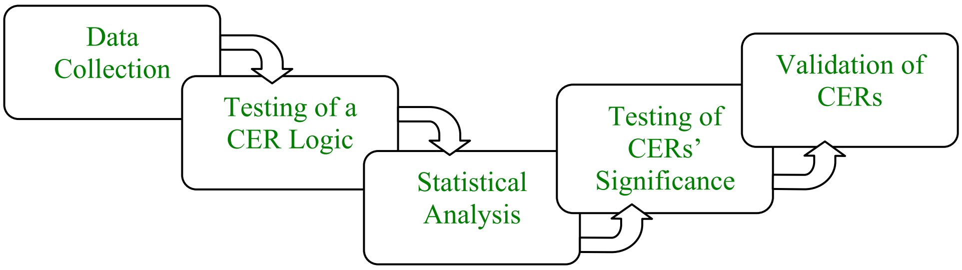


Figure 2.8 – A General Process of Developing CERs (Forsberg and Kelvesjö, 1999)

Parametric cost estimating needs historical data to develop the CERs. That is the reason why it is also called statistical estimating. The database of estimating will decide the accuracy and reliability of results.

2.2.2.3 Ground Rules and Assumptions

Ground rules and assumptions are to present a common and comparable platform for cost estimating, not only for parametric approach but also others. The rules will define the scope of estimating, and the assumptions can suppose unknown information and then make estimating possible although the assumptions are not correct. For instance, the base year of dollar, the electronic formats of documents, the objective area, the cost classification, and etc (Peffley, 1996).

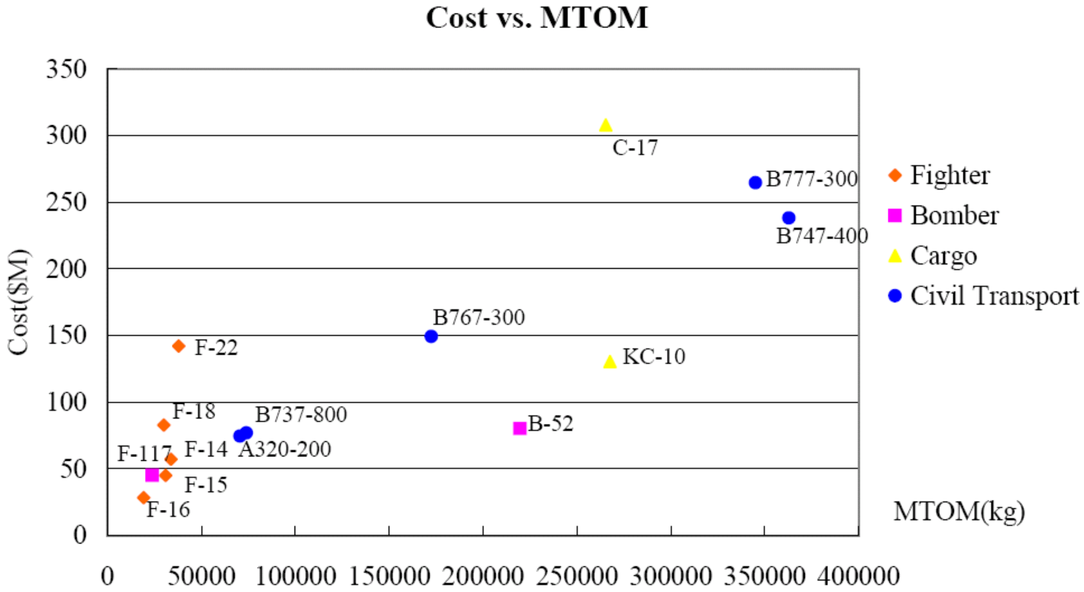
As Stewart (1995) explained, proper ground rules and assumptions are able to avoid many pitfalls that will cause inaccurate or mislead estimating. He also highlight that Working Breakdown Structure (WBS) is the first, vital and indispensable step in cost estimating because it will provide a solid framework as the base on which the estimate can be built. However, WBS requires detail information so that it is not suitable for conceptual design.

2.2.2.4 Database

Database establishment is the first activity for developing CERs (Forsberg and Kelvesjö, 1999). Collected data will quantify determined drivers (Curran, 2002). Dean (1995) highlights that collection and utility of a cost database in parametric cost estimating will lead to considerable saving in total cost.

Size is the first requirement to database. Too few samples or observations will consequently reduce the reliability and accuracy of the CERs because data of several cases can not represent the general trend hidden behind most products. Due to the particularity of aircraft, limited samples can be collected. However, it can be offset by mathematical techniques which can produce satisfied results based on a small size database (Li et al, 2007).

Another requirement to database is the homogeny, or comparability. In Rand’s first model, all sample aircraft are mixed together without grouping them by classes or missions (Levenson, 1966; Large, 1976). It is difficult to find logical relationship between a light fighter like F-16 and a giant bomber like B52 as shown in figure below



Data Source: http://www.aerospaceweb.org/aircraft/

Figure 2.9 - Groups of Aircraft Samples

Therefore, normalization becomes necessary and must to make the data from different sources comparable. As Large (1976) stated, cost data should be normalized to avoid the uncertain cases which will increase or reduce the costs by accident. That is also addressed by Forsberg and Kelvesjö (1999): adjustments to the raw data are required to achieve reasonably consistent and comparable data.

In general, the data in a database needs to be normalized with respect to time (Large, 1976; Cyr, 1994). For instance, Large uses 1959 as a watershed year to separates data samples while Cyr uses 1969. In addition, Large et al (1976) also group the sample aircraft by type, age, speed, weight, and etc in their research, to meet the homogeneous requirement. Considering the disparity of volume between military and civil aircraft, it is easy to understand the importance of homogeny.

Although it is time consuming and hard to keep all CERs upgraded, parametric costing will provide a rapid estimate once all data is available (Asiedu, 1998). Database maintenance is also vital for accurate estimates since environment never stop changing.

2.2.2.5 Explanatory Variables/Parameters

There are independent and dependent variables in parametric cost estimating. Hatry (1966) point outs that selection of variables, both dependent and independent, is one of the major problems during the development of CERs.

Normally, dependent variables are monetary costs in dollar or other forms such as in labour-hour. On the other hand, independent variables are the parameters in CERs, such as weight and speed (Large, 1976; Roskam, 1990; Burns, 1994; Raymer, 2006).

At the early years of aircraft cost estimating, weight was the main characteristic as aluminium is the main material of aircraft. Most of the structural component cost equations are based on weight (Marx, 1995). For instance, the ARCO (Aircraft Resources Control Office during the World War II) factor ensured the ability of estimating manufacturing hours per unit weight of airframe by weight and production volume (Large, 1976). The similar viewpoint can be found in Cyr's research (1994).

However, with the progressing of technology, cost estimators felt that those two variables can not explanatorily represent new technology such as new materials, utilization of computer, fly-by-wire and etc. According to Curran (2005), the minimal weight of components does not result in minimal direct operating cost because of manufacturing cost. More characteristics need to be added into cost estimating in order to represent the new trends.

According to Large (1976), there are three criteria for new aircraft characteristics:

- Able to provide consistently accurate cost estimates combined with existing weight;
- Related to aircraft cost logically, and;
- Can be defined before commencing actual design, e g can be determined in conceptual design.

Except that two main characteristics of aircraft, more other parameters (such as range, climb rate, thrust and aspect ratio) are possible to be introduced into the cost model to improve accuracy (Large, 1976). But till now, the third explanatory variable is just production number, which can be seen in existing aircraft CERs (Roskam, 1990; Burns, 1994, Raymer, 2006). The main reason is that the cost elements that can not be explained by weight and speed are not able to be explained by other independent variables; however, it is beneficial to examine the CERs of updated database and improved technology in engineering and manufacturing (Large, 1976).

Peffley (1996) depicts that choosing parameters are based on past estimating experience and suggestions from data suppliers. Cyr (1994) presents detail descriptions of variables that drive cost: quantity, weight, culture (the category), complexity, generation (the similarity between a product and its derivation or successor), and time (including the inflation, technology progress, and etc.).

With respect to propulsion of aircraft, thrust, quantity produced, weight, SFC, turbine inlet temperature, and Mach number may be the parameters that engine cost is related; alternatively, engine cost can be input directly as a procured system (Marx, 1995). But weight will not be used as a design input variable by any engine manufacturers when estimating cost (Peffley, 1996).

2.2.2.6 Mathematic Techniques

Regression, especially multi regression, is a statistical approach which helps to find hidden correlations. It is the analytical technique used to derive the relationships between cost and parameters (Large, 1976; Ditto, 1985; Smith et al, 1997; Duverlie et al, 1999); and linear regression with logarithmic values of input data is performed in NASA's study (Peffley, 1996), which is shown below and Duverlie et al (1999) also support this structure:

$$Y=m\,X^{b}$$

where Y stands for predicted cost, m the coefficient, X technical parameter(s) and b slope of the regression curve.

Cyr (1994) uses a different multiple regression equation that includes 5 independent variables with different mathematical correlations based on a large database including several cultures like vehicles, ships, aircraft, missiles, and spacecraft, totally 253 data point.

$$\text{COST} = 0.0000172\ Q^{0.5773}\ W^{0.6569}\ 58.95^{C}\ 1.0291^{Y}\ 0.4483^{G}$$

where Q is the total quantity, W unit dry weight, C culture, Y year of initial operational capability, and G generation.

Partial square-lease regression is another useful statistical technique, which is first introduced in 1980s, that can be applied to predict dependent variable with small size data (Li et al, 2007). Possibly, it will fit this research since the number of active civil aircraft types is limited.

Hamilton (1968) recommends partial derivative technique for sensitivity study of a cost estimating model, which will indicate how and how much one dollar change of a variable will affect the dependent cost estimate.

2.2.2.7 CERs

In many literatures, the CERs developed for various purpose have similar mathematical expressions that are all exponential equations ($Y=\alpha X1^{\beta1}X2^{\beta2}X3^{\beta3}$); and the variable are mainly airframe weight and maximum speed while costs are divided into engineering, tooling, manufacturing, testing, quality control, and etc (Large, 1976; Roskam, 1990; Burns, 1994; Peffley, 1996). Sometimes time is introduced as an explanatory element, however it has to be removed if the proper assumption about how time can represent costs could not be found (Large, 1976). Also, only when comprehensive testing has indicated stability and accuracy over the expected range of forecasting requirements can a cost estimating model be used in reality (Cyr, 1994).

Some coefficients exist in developed CERs to represent complexity, technology, and other special considerations; for example, judgement factors for difficulty, CAD capability, material, and observable performance appear in CERs developed by Roskam (1990) while factors to account for advanced technology features, advanced material, security requirements, and escalation are observed in Burns' parametric equations (1994). They are mainly based on expert judgement subjectively.

2.2.2.8 Summary

Smith et al (1997) prefer parametric approach in cases that appropriate CERs are able to be identified because regression approach will provide better accuracy, variability, easier model establishment, and model examination.

As Hatry (1966) states, the advantages of parametric cost estimating are:

- Rapid cost estimation
- Less man-hours required to prepare the estimates
- Relatively objective
- Provide consistent and reproducible estimates
- Potential predictive accuracy improvement

There are also disadvantages associated with advantages mentioned above.

- Past practices are reflected in the equations
- Tendency to over-simplify
- Too much visibility of estimation method
- Does not eliminate prediction uncertainty
- Statistics questionable when extrapolating

A satisfied database must be available for deriving parametric relationships through statistic techniques. However, it is not always available; thus, some data are predicted to build up the cost model and then uncertainty is introduced (Duverlie et al, 1999). To avoid errors, historic data has to be normalized carefully (Scanlan, 2002).

Also, parametric method has limited resolution and cannot be used beyond the range where they have been validated (Scanlan, 2002). For example, the equation developed in 1980s can not used to predict the cost of current aircraft unless it is validated considering state of the art technologies.

Another drawback of parametric estimating is that it can not suit estimating the cost of products with new technologies (Asiedu, 1998) because there is no historical data for them.

Anyway, with limited information at early stages, parametric approach has its merit, and is the preferred approach for developing cost estimates until actual cost data are available (DoD, 1992).

2.2.3 Feature-based Cost Estimating

Feature-based costing is to estimate the costs associated with certain cost related features in a product; and these features are design related or process oriented (Niazi et al, 2006). For instance, material of product is a design feature while a cut-out is a process feature that needs to consider particular process. In Watson's (2004) Pro-Cost EST procurement cost model, all out-contracted parts are classified into families by features such as material, process, treatment, and etc.

Features of products should be considered in early design because they will affect manufacturing cost largely if a special machine is required by distinct processes (Ou-Yang and Lin, 1997). Mauchand et al (2008) develop a cost estimating tool for conceptual design phase using features of products in production integrated with manufacturing expert knowledge system.

Tammineni and Scanlan (2007) illustrate a knowledge-based cost modelling system that is based on manufacturing features with basic knowledge libraries of material, work locations, and processes tree objects, aiming to provide detailed cost information and manufacturing knowledge to designers to make them understood the implications of their design decisions on cost.

A cost model is built by Curran (2005) to optimize the cost of a skin panel in structure design, considering material, fabrication and assembly costs based on features like the distance between stringers, number of frames, the thickness of stringer and skin, and the stress. The results of this model claimed that the minimum weight will not represent the minimal DOC due to impact of manufacturing on acquisition cost.

However, feature-based costing requires detail information of parts, which will be available only after preliminary design; so it is not suitable for this research.

2.2.4 Activity-Based Costing (ABC)

Activity-Based Costing is a new approach introduced in 1980s as a complementarity to existing cost systems because the environment are gradually changing and becoming competitive, and traditional volume-based cost systems are not suitable for changing production situation due to the arbitrary allocation of overhead costs (Stewart, 1995; Andrade, 1999).

Traditional cost systems treat overhead costs on a labour-hour base which is developed from real labour-hour occurred in production. Consequently, they allocate indirect costs according to the volume, batch, and complexity, i.e. low volume, small batch and low complexity products will be allocated a small percentage of the total overhead and vice versa (Stewart, 1995; Andrade, 1999). However, Activity-Based Costing traces costs to products' consumption of each activity or process, including the overhead; and as the consequence, it will improve the traditional cost accounting (Stewart, 1995; Asiedu, 1998). It is "a powerful tool for industrial marketing decision makers", especially for pricing based on its recognition that costs may vary with some other measure if not volume traditionally (Lere, 2000)

Activity-based costing still needs detail information of products and product-related activities. Applying ABC to design, all activities in design can be categorized and associated resources can be assigned to form an accurate estimate in the light of assisting decision making (Stewart, 1995). The overhead inclusion is the distinction of ABC from generative cost estimating (Evans, 2006).

ABC's accuracy depends on the reliability of estimated times for a new product (Niazi et al, 2006). In general, it will be more accurate and consistent (Andrade, 1999).

2.2.5 Engineering Approach

Engineering approach is also called 'bottom up' or detailed method because it generates the cost estimates from the lowest level, for instance, task or work package (Asiedu, 1998), in the work breakdown structure (WBS) of a programme (RTO, 2007). Pugh (2004) highlights that it is inclined to underestimate the final cost due to activities can not be included in WBS.

This method is very information-intensive (Curran and Raghunathan, 2004), and is the most time consuming and costly approach (Asiedu, 1998). As the rewards, it will produce the most accurate estimates (Asiedu, 1998) on the ground of enough information.

Normally, it is applied when detailed design data is available so that it is often used in production stage (Crosby et al, 2003; RTO, 2007) after design is frozen and released. And it is time consuming and expensive also. As Stewart et al (1995) mentioned, the time of developing an accurate and reliable cost estimate will account for 8% of the total time required by a project using existing technologies. The percentage will reach 18% if the project involves high technology.

2.2.6 Expert Judgements

Rush and Roy (2001) believe that expert judgement is not a cost estimating technique; however, it can be found in most cost estimating approaches and sometimes is the only choice due to insufficient information.

In analogy approach, the adjustment factor generally is defined by experts with their professional knowledge in this domain although a subjective judgement will "negate the credibility of the estimate" (RTO, 2007). De Cos et al (2008) attempt to develop an easy and automatic parametric approach for estimating aerospace components costs without expert involvement but then expertise will be transferred into the cost model.

Cost estimating is a subjective process (Roy, 2002). Zack (2007) believes that the cost estimators' knowledge, experience, and judgment are more important than, at least equivalent to, the cost database information. And Beltramo (1988) suggests integrating subjectivity into founded cost models because they may not be appropriate 100 per cent for intended cases at the time due to the distinct conditions and technology advance.

Dalkey (1969) introduces Delphi method to use group information more efficiently with controlled feedbacks while RTO (2007) states that Delphi technique can provide collective suggestions; however Rush and Roy (2001) think that the expertises can be improved by researching the rationale underlying the judgement. For instance, artificial intelligence can learn that from past cases.

Roy et al (2003) develop a CERC (Cost Estimating Rationale Capture) tool on cost estimating knowledge and assumptions to capture the underlying rationale for future review or reference; which also helps to train the neural network or artificial intelligence with captured learning.

2.3 AS-IS Cost Models

Rand Corporation developed many aircraft cost models mainly for acquisition of military aircraft. Raymer (2006) gives some modified Rand cost estimating equations in his book. In fact, many cost models are based on Rand's achievements (Fielding, 1999) so that they are quite similar in form. For instance, Roskam (1990) presents a series of cost estimating equations for RDT&E, production, and operation stages, mainly using AMPR weight, maximum speed, and programme volume as the explanatory variables. A similar model is given by Burns (1994) with the same variables but somewhat different judgement factors. The exponents of variables are quite similar and even the same.

In Roskam

$$MHR=0.0396*W_{ampr}^{0.791}*V_{max}^{1.526}*N_{rdte}^{0.183}*F_{diff}*F_{cad}$$

In Burns

$$MHR=0.0660*W_{ampr}^{0.796}*V_{max}^{1.538}*N_{rdte}^{0.183}*F_{tech}*F_{mat}$$

where MHR stands for man-hours in research, W_{ampr} AMPR weight, V_{max} maximum speed, N_{rdte} production number for RDT&E, F_{diff} difficulty judgement factor, F_{cad} CAD judgement factor, F_{tech} technology judgement factor, and F_{mat} advanced material judgement factor.

In another recent model developed by Curran and Raghunathan (2004), the weight and part account were found the primary parameters for fabrication cost of components, while part account and fastener account for assembly cost in a sample case; both of them present the genetic causal cost theory to be integrated into the early design. Castagne's model (2004) considers thickness, length and area of parts for fabrication while rivet number for assembly. A similar work is done by Price et al (2006), which presents comparison between two configurations using optimizations for weight and DOC, and highlights that integrating design, manufacturing and cost will help to trade-off for final decision.

Kundu (2002) develop a rapid cost model for conceptual design, which studies some cost drivers that the designers need to trade-off for decision making, including geometry, functionality, technical specification, size, material selection, manufacturing processes, structural design concept, and man-hour rates (Kundu, 2002; Crosby et al, 2003). Watson et al (2004) provide "PRO-COST EST" model for part procurement in aerospace, which establishes a costing framework based on part commodity varying with degrees of input data. Curran et al (2005) also develop a manufacturing cost model by connecting cost elements and technical parameters for aircraft conceptual design phase.

Kaufmann (2008) depicts a cost/weight optimization model for aircraft composite structure design through optimizing direct operating cost evaluated considering manufacturing cost, non-destructive testing cost, and lifetime fuel consumption cost based on weight of structure.

$$DOC=\alpha_1*C_{manu} +\alpha_2 *C_{ndt,prod} + N*\alpha_3*C_{ndt,\ serv} +p*W$$

where, C_{manu} stands for manufacturing cost, Cndt,prod and Cndt, serv are non-destructive testing costs in production and service respectively, p is a weight penalty and W is the weight of structure. The coefficient α_i introduces depreciation, overhead cost and other adjustments, and N is the number of periodical inspections during the lifetime of aircraft.

To improve existing life cycle cost models that mainly focus on design and manufacturing, Sandberg et al (2005) introduce manufacturing and manufacturing following activities into conceptual design evaluation.

Hicks (2002) uses standard components to predict costs for mechanical systems with cost equations in early design phase. All components are divided into three classes: standard selected, standard designed, and bespoke designed.

Tan et al (2007) present an object-oriented life cycle cost model for an integrated wing of aircraft, which identifies objects, related features, and the corresponding operations within a honeycomb cell like framework that provides answers to “why, who, what, when, where, how” and then CERs can be established; consequently, cost estimates can be generated according to settled algorithm and the designer can be optimized.

There are also many cost estimating models for components, parts or even material (Tan et al, 2008) that are in the lower levels in a project compared with the objectives of this research. For instance, Ben-Arieh (2000) presents a model for machine parts using experience and features of both parts and processes. Farag and El-Magd (1992) introduce an integrated approach that provides a combination of product design, materials selection and cost estimation by listing all related information and then computer the benefit ratio of each material options pair for the most optimum choice.

Many commercial cost models are available for general usage, such as True H and Price H of PRICE® Systems, SEER-H, ForeCostXXI, and etc. A particular cost model for a specific enterprise can be set up with customized inputs, such as historical data, similar cases, and special requirements of this company.

2.4 Selection of Methodology

As Pugh (2004) stated, the choice between "top-down" and "bottom-up" cost estimating approaches depends on the background and purpose of estimating. Fielding (1999) believes that the former is for conceptual or preliminary design while the latter for detail design and production.

Selecting cost estimating methods is normally dependent on amount and quality of available information (Duverlie et al, 1999; Koonce, 2003; NASA, 2004; RTO, 2007; Young, 2008). As Kwak (2005) mentioned, data availability will drive the method of cost estimating. Christensen (2005) presents 5 levels of cost estimating in practice classified by data availability of each stage in engineering process as shown in table 2.1. It is obvious that the accuracy will be improved as the definition progressing to provide more detail information for cost estimating.

Table 2.1 – Classification of Cost Estimating (Christensen, 2005)

Cost Estimate Class	Level of Definition (% of complete definition)	End Usage Typical purpose of estimate	Methodology Typical estimating method	Expected Accuracy Range Typical variation in low and high ranges
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study of Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 70%	Control or Bid/Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%

Rush and Roy (2000) suggest following matrix for cost estimating method selection.

Table 2.2 – Estimating Process Matrix (Rush and Roy, 2000)

Tools and Processes used when	Parametric Estimating	Neural Networks	Case Based Reasoning	Activity Based Costing	Detailed Cost Estimating
Concept design phase (innovation)	√	×	√	×	×
Concept design phase (similar products)	√	√	√	×	×
Feasibility Studies	√	√	√	×	×
Project definition	√	√	√	×	×
Full scale development	×	×	×	√	√
Production	×	×	×	√	√

However, Evans (2006) believes that this matrix can not fit the complex practice very well so that presents a DESCEM (DEcision support for the Selection of Cost Estimation Methods) system to select cost estimating method(s) by matching user's requirements and available knowledge to various alternative methods.

Despite the amount of related data, using one method can not fit the practice (Duverlie et al, 1999). Other methods are necessary to calibrate or validate the estimates and then improve the accuracy and reliability. Newnes et al. (2008) offer a comprehensive overview on predicting life cycle cost of a product at conceptual design phase that reviews many literatures and will be useful to have understandings of cost estimating quickly.

2.5 Accuracy

Kundu (2002&2003) illustrates the accuracy of cost estimations as below:

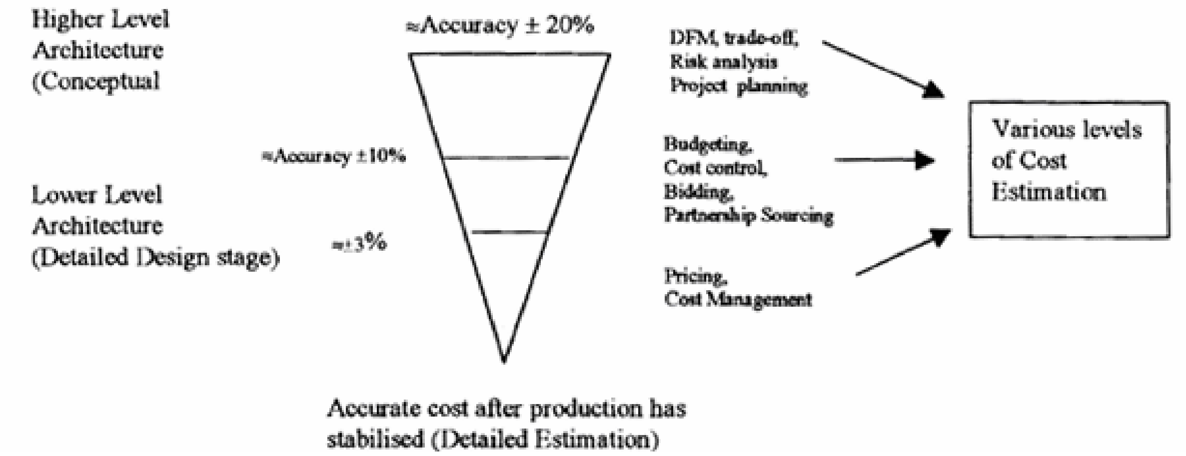


Figure 2.10 – Requirements for Cost Estimations (Kundu, 2002&2003)

The accuracy of cost estimates will increase gradually as design progress. According to the information cited by Asiedu (1998), the accuracy of design phases are listed below.

Table 2.3 – Estimating Accuracy (Asiedu, 1998)

Phase	Accuracy Range	Cost Estimating Approach
Conceptual Design	-30% to +50%	Parametric Approach
Preliminary Design	-15% to +30%	Analogous and detailed estimating methods
Detail design	-5% to +15%	Detailed estimating

That also is illustrated by Crosby et al (2003):

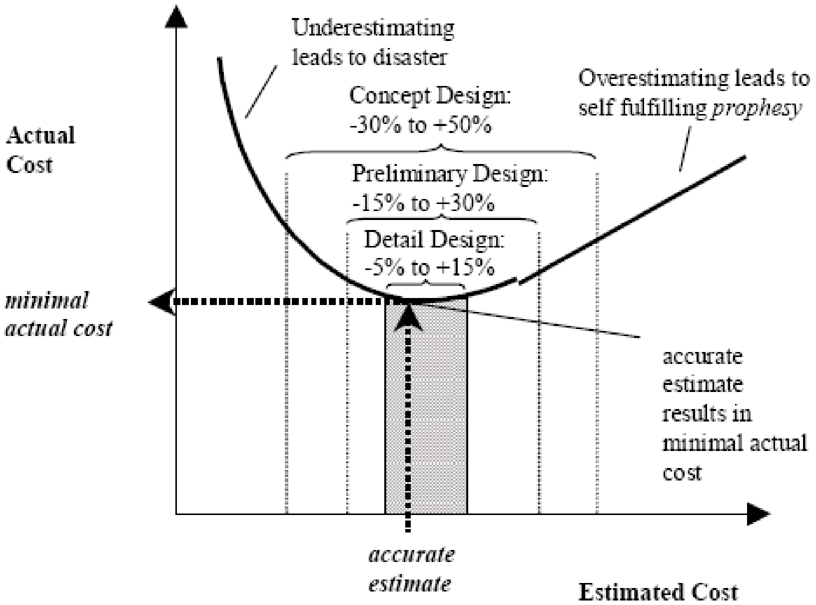


Figure 2.11 - Achieving minimal cost with accurate estimating (Crosby et al, 2003)

Asiedu (1998) mentions that LCC analysis including uncertainty and dependencies studies could result in ineffective cost estimates; and the inaccurate estimates can greatly increase the cost of a product because underestimates will cause reorganization, replanning and reworks while overestimates can not save the redundant investments.

2.6 Quality of Cost Estimating

The quality of cost estimates is essential for making correct decisions. Even the proper approaches and data were input to generate cost estimate, there still be risks which may jeopardize the whole project.

Uncertainty of cost estimates will gradually go to a low level as the design matures. However, there will still be uncertainty even after the design was frozen because the uncertainty in manufacturing and operating stages (Scanlan, 2002).

Cumulating data and developing techniques can continuously improve the quality of cost estimation, including process and accuracy. The storage of all cost estimating models will allow real-time updates and refinement of the overall model. (Young, 2008)

In addition, sensitivity study is another approach to qualify the estimates. As Hamilton (1968) depicted, there are two primary reasons for sensitivity studying: first is that it offers an indication of the cost estimating models' accuracy since it shows the impact on the total cost of an assumed error in any specific field; and the second reason is that it shows which parts of the cost model(s) have the greatest impact on the cost estimates and therefore requires the greatest emphasis during the whole process.

2.7 Impact of New Technologies

Acquisition cost of aircraft is increasing as new technologies are applied; on the other hand, it will be lowered by learning effects and aging of these new technologies (Lee, 2000). New technologies also result into underestimates (Young, 2008) due to the uncertainty during the developing process.

The cost estimating models should not be used mechanistically because the advances in technology must be taken into account and the circumstances surely will be different compared with existing cases, and all these particular conditions will weaken the capability of estimating models (Proffitt, 1994).

According to Kennedy (2008), programmes that began with immature technologies, which account for 84 per cent of all weapon systems, experienced a 32.3 percent cost increase, whereas others 16 per cent that began with mature technologies increased just 2.6 per cent. Therefore, the technology level must be taken into account from the early phase of design just as mentioned by Nelson and Timson (1974) that significant improvement of cost estimates can be achieved by measuring technology advance during the programme.

With assistance of computer, digital manufacturing can optimize the manufacturing process within a virtual environment; and can be integrated with other design or business systems seamlessly to validate costing and generate as well as use optimized data in early design enabling better decision making from manufacturing perspective (Butterfield, 2005). In Butterfield's sample, 19 per cent improvement in the cost efficiency was achieved, and tooling costs decrease because optimized processes do not need more work station to meet the production rate.

2.8 Summary

The importance of cost estimating is emphasized with review of literatures. For conceptual design, cost estimating is more vital as majority of the life cycle cost will be determined in this phase.

Some cost estimating approaches are introduced, especially the analogy and parametric considering following research for aircraft conceptual design. Due to limited information in this phase, the estimates are rough and with uncertainty. However, it will help both managers and engineers to make proper decisions.

Other issues related to cost estimating are presented to describe current situations, which will be useful for the development in the research.

To sum up, the review of existing achievements of cost estimating will facilitate the deployment of this research largely and provide a consistent foundation.

3 Objectives and Methodologies

This chapter is to present detail description of the objectives of this research. The research methodologies are introduced in this chapter as well.

3.1 Research Objectives

Cost estimating normally uses existing cost estimating model(s) with consideration of particular situations in reality. However, cost models developed by academia for exploration or by consultants for generic usage rarely fit industry practises (Kundu, 2003).

Thus, the objective of this research is:

To identify a suitable cost estimating methodology for aircraft conceptual design.

In order to improve the analysis of economic performances for a new aircraft project on which making decision and resources allocation are based, aircraft cost estimating methodology is to be researched in the thesis. The research objective is concentrated on aircraft acquisition cost which covers development and production from the manufacturer's perspective.

The impacts of cost drivers in design are to be identified through developing a cost estimating methodology, which will help to design for cost in following stages. Also, a systemic framework of cost estimating is able to be highlighted based on the understanding produced by this research.

3.2 Methodologies

3.2.1 Cost Breakdown

For unit aircraft, the component cost structure is to be used for the research.

One aircraft can be divided into 3 major function components: airframe, propulsion, and avionics. Thus, the unit acquisition cost is:

$$\text{Acquisition Cost} = \text{Airframe Cost} + \text{Engines Cost} + \text{Avionics Cost} + \text{Profit}$$

Further, the airframe cost can be subdivided into structure (skins, frames, stringers, stiffeners, beams, bulkheads, and etc.) and miscellaneous subsystems (landing gear, wheels, power suppliers, air-condition system, fuel system, and etc.). Then the airframe cost is:

Airframe Cost = Structure Cost + Miscellaneous Cost

And structure cost can be divided as following:

Structure Cost = Material + Labour + Overhead + Investment

In manufacturers' perspective, structure is the focus of cost estimating while other components are purchased and less controllable.

All following studies are based on equations for unit aircraft.

3.2.2 Investigation

A checklist for internal evaluation of parametric cost estimating system in a company is suggested by Apgar (2004), which can "evaluate its adequacy of the current system and identify areas for improvement before such a system is put into use and before DCAA (Defense Contract Audit Agency) conducts a more formal external review".

Likewise, a questionnaire was developed for this research to investigate current situation, learn the facts in manufacturing and engineering.

3.2.3 Estimating Approaches

As reviewed in chapter 2, the most suitable approaches for conceptual design are analogy and parametric. In this research, both of them will be used to develop the cost models for an aircraft in conceptual design.

3.2.3.1 Analogy Approach

Analogy approach is performed to produce relatively reliable and accurate estimates according to actual data of similar projects within a short time, especially when making decision before starting a new project. See corresponding section in the literature review for more details.

3.2.3.2 Parametric Approach

Parametric approach is a statistical method as reviewed in chapter 2. The statistical techniques will relate the cost to some parameters based on data of historical aircraft. Knowing the impacts of identified cost drivers, the decision can be made as well as design can be optimized. See corresponding section in literature review for more details.

3.2.4 Mathematical Approaches and Computer Applications

For the parametric approach, some statistical techniques are required to derive the CERs from historic data. Least-squares regression is a powerful tool to relate independent characteristics to dependent variables and then reveal the correlations.

Two kinds of regression techniques are used to derive the CERs: one is OLS (Ordinary least square), which is the basic technique in statistics; and the other is PLSR (Partial Least Square Regression), which is to cope with small-size database with missing information.

To make mathematics simple and fast, Microsoft Excel was used to do some basic calculations, e.g. processing data, multiple least-regressions, and generating charts. Another software, XLSTAT (Version 2008.7.01), was used to do partial least-squares regression (PLSR) mainly because it is an add-on integrated with Microsoft Excel and easy to operate in a Excel-like environment. A free 30-day evaluation version of XLSTAT can be downloaded from the official website (http://www.xlstat.com/).

4 Industrial Situation in Asia

This chapter is to present the results of investigation about the current situation of cost estimating in Asia's aerospace industry. These findings will guide the research.

4.1 Introduction

In the light of developing aircraft acquisition cost estimating methodology for conceptual design, the current situations in industry, for instance, the methods being used currently, the availability of historic data, people's understanding about cost estimating, and the implementation in real environment, need to be learned first in order to focus the research on the demands of industry and make the research down-to-earth; and then the cost models can be expected to solve existing problems effectively.

An investigation was carried out in form of questionnaire answered by selected professionals at various positions in engineering and manufacturing.

All questionnaire-related information are presented in appendix C.

4.2 Current Industrial Situation in Common

According to Apgar (2004), there are 3 primary findings in parametric cost estimating systems of most companies:

- Company cost estimating procedures and manuals do not appropriately describe the existing parametric estimating process; the process may be obsolete or inadequate.
- Company estimators or pricers are not familiar with, or not following prescriptive parametric estimating procedures
- Company is not adequately utilizing relevant historic data to build parametric estimating models or to recalibrate CERs. And the database is not collected and maintained in a correct way, consequently can no longer represent the design technology or manufacturing process.

Souchoroukov et al (2002) identified the problems in current industries that the manufacturers did not fully utilize their in-hand costing expertise due to lack of communication, costing interaction, common terminology, and knowledge with regards to each others' role. Hence, a research is performed by Souchoroukov in 2004 to improve cost estimating internal practice between CE-C (Cost Estimating Commercial) and CE-E (Cost Estimating Engineering) in enterprises. Also, a FUCE (FUnction-based Cost Estimating) framework, aiming to "translate the un-quantified terminology and the requests associated with the product specifications used by CE-C into a medium that CE-E can process using their resources, and creates estimates that are based on a standardized approach", has been established to link the commercial and engineering communities at the conceptual design stage (Roy et al, 2007).

Normally, an IPT (Integrated Product Team) is able to convene experts from all functions involved in the project and then provides an effective platform for communication between members by scheduled meetings, team working, periodical reports or releases, and etc. However, the FUCE model may be not suitable for the whole aircraft due to thousands of functions of an aircraft but smaller assemblies and large components (Roy et al., 2007), which is the fact in most companies in Asia.

4.3 Commercial Aerospace Industry in Asia

As major manufacturers of commercial aircraft are mainly based in Europe and America, Asia's aerospace companies are involved in commercial aircraft primarily by supplying components, including machine parts, sheet metals, assemblies, installations, and even whole fuselages, to major manufacturers like Boeing and Airbus.

In the light of bidding for orders and pursuing higher profit, cost becomes critical and as a result, cost estimating is essential, especially when developing a costly, time consuming, and high-risk aircraft programme.

Due to the lack of historic products in past decades, all aerospace companies in Asia have little experience about developing a commercial aircraft from the very beginning. However, China and Japan are planning to change the situation with their new regional jets: ARJ-21 and MRJ respectively. A larger aircraft in 150-seat class is potentially the next target of them in not-far future, to compete with Boeing and Airbus.

It can be seen from table 4.1 that some in-developing models are closer to 150-seat class.

Table 4.1 – Schedule of new comers in 100-seat class

Manufacturer	Bombardier			Sukhoi		ACAC		Mitsubishi
Model	CRJ1000	C series		SSJ100		ARJ21		MRJ
		-110	-130	-95i	-110i	-700	-900	
Seats	100	110	130	98	110	78-85	105	70-90
Entry into Service	2009	2013	2013	2008	2012	2009	2011	2012

Data Source: Airfinance, November, 2007

4.4 Investigation

4.4.1 Interviewees

All persons questioned are from either engineering or manufacturing in aviation industry of Asia. To derive comprehensive learning from various viewpoints, the interviewees were chosen taking account of their roles and positions in the flow process of a programme. The involvement of management level will facilitate learning the cost facts in their companies as their understanding and attitudes will determine the cost policies.

A total of 26 interviewees (15 from manufacturing and 11 from engineering) gave their responses about cost and cost estimating in their companies. See appendix C for details.

4.4.2 Results of Questionnaire

Some results are summarized in this section. See appendix C.3 for all results.

At first, there are still 15.4 per cent of questioned people will not consider the impacts their works' putting on cost because there is no cost procedures in their companies. The answers about the first priority in work are much more disappointed: only 11.5 per cent select cost as the first in their lists, lower than that of "performance" (27%), "feasibility" (23%). These numbers show that cost has not been emphasized deservingly.

The answers to question "Which phase is the most important one in that LCC estimating should be conducted" show that there are 42.3 per cent think cost estimating should be conducted in production or operation phases rather than RDT&E. It indicates that the aerospace industry in Asia did not put appropriate emphasis on engineering yet.

Table 4.2 – Phase to Conduct CE

Phase	Percentage
RDT&E	57.7%
Production	23.1%
Operation	19.2%
Total	100%

About independent specialized cost estimating department, 26.9 per cent of the experts believe that there is a dedicated work team in their companies while 57.7 per cent think that there is no such a department but the cost estimating function is being performed by the financial department. The others, 15.4 per cent of total, have no ideas about such a department. The results show that the cost estimating function of companies is not well known yet and emphasized enough.

As to implementation of cost estimating, there are only 9 persons (34.6%) have been involved for new projects, of them 6 are from manufacturing (40% of manufacturing people and 23% of total) while 3 from engineering (27.3% of engineering people and 11.5% of total). Although this can not indicate that engineering lacks of cost estimating, there still is a gap between engineering and manufacturing.

About the reason why the cost estimates can not satisfy people who concern, the results are as following:

Table 4.3 – Reasons of Unsatisfied Cost Estimates

Reason	Percentage
No systematic implementation	53.80%
No specialists	42.30%
No enough emphasizing	34.60%
No sufficient data	26.90%
No suitable approaches	23.10%
No experience	23.10%

It highlights the lack of cost estimating system and personnel. Data and emphasis are important reasons also. And approaches and experience of cost estimating are not the main reasons for weak cost estimating.

However, although majority of interviewees do not think approach will be problem when making cost estimates, three subjective methods (empirical, expert judgement, and analogy) take the first three places in the list of possible approaches. Only 3.8 per cent of people choose parametric or computer aided approaches, which are the form of many commercial cost models, for example, SEER, PRICE, and ACE IT. It can be observed that most of people did not realize the problems of cost estimating approaches and in-depth combination of several approaches in a system has not been achieved.

Table 4.4 – Approaches used in Practice

SN	Approach	Percentage
A.	Empirical	69.20%
B.	Expert Judgement	42.30%
C.	Analogy	42.30%
D.	Standard	19.20%
E.	Parametric	3.80%
F.	Computer Aid	3.80%

With respect to the difficulties in cost estimating, the results are as follows:

Table 4.5 – Difficulties in Cost Estimating

Difficulty	Percentage
Managements' Emphasis	46.15%
System	38.46%
Uncertainty Analysis	34.62%
Historic Data	26.92%
Professionals	26.92%
Approach	15.38%
Accuracy Improvement	3.85%

It can be noticed that management's emphasis takes the first place, followed by system. This conclusion highlights that the main problem in Asia's aerospace industry is the cost system without enough attention from the high level. Further, approaches are not the focus of cost estimating due to widely using of subjective methods.

4.4.3 Summary

It can be learned that the main problem in Asia's aerospace industry is primarily about the cost system, which is normally the result of cost policies in a company. Based on this understanding, this research is trying to help establishing a cost system for aircraft, particularly the cost estimating approaches for conceptual design.

5 Preparation for Methodology Development

In this chapter, the preparation work for methodology development, including establishing the ground rules, assumptions, and database for cost estimating research, are presented.

All ground rules and assumptions are global rules for both analogy and parametric approaches used in the research, as determined in chapter 3.

5.1 Ground Rules

Prior to starting cost estimating, ground rules and assumptions need to be established as required by the objectives and the interests of the research. They are only for this research and must be updated or adjusted when possibly applying to other aircraft programmes.

5.1.1 Ground Rules

Ground rules are the basic regulations to conduct the estimating. Any confusion should be explained by following facts.

Currency	U.S. Dollar
Constant year of currency	2008
Units	MKS except specified.
Aircraft Type	Jet Transport
Engine Type	Gas Turbine Engine
Project volume	1000 (4 for development)
Profit Ratio	10%

And two validation aircraft are defined as CRJ 900 and B737-700 (one is from 150-seat class while another from 90-seat class).

5.2 Assumptions

Assumptions are parts of the global ground rules. Unless specific data are available, these assumptions are to be used throughout the research.

5.2.1 Cost Distribution

As described in chapter 3, the costs of purchased and in-house components are treated separately.

Kroo (2006) presents a table of aircraft manufacturing cost distribution for a modern transport.

Table 5.1 – Distribution of Airplane Manufacturing Costs (Kroo, 2006)

Component	Proportion
Airframe	
Basic Structure (Wing, Fuselage, Tail)	41.50%
AC Power System	2.40%
Hydraulic and Auxiliary Power Systems	2.10%
Air Conditioning and Pressurization	1.90%
Landing Gear, Wheels, Tires, Brakes	1.70%
Furnishings including Lighting	14.50%
Miscellaneous Systems and Components	0.80%
Propulsion	
Propulsion System including Engines	17.10%
Avionics	
Avionics (Communication and Navigation)	12.70%
Flight Control and Guidance Systems	5.30%
Total	100.00%

B737-700, one of the validation aircraft is used as sample for cost distribution. The typical engine used on it is one model of CFM 56 series and the unit list price is $6.75 million regardless of model. On B737-700, two engines will account for 21.67 per cent in the total cost ($M13.5 to $M62.3), which is higher than that in Kroo’s list. So the proportion of engines in total aircraft cost is assumed as 20 per cent, a middle number between 17.1% and 21.67%.

With respect to avionics, the proportion is assumed as 20 per cent of the cost of aircraft without avionics, which is in the range both Roskam (1990) and Raymer (2006) mentioned in their books, unless specific actual data are available. Thus, the avionics accounts for 17 per cent of the total cost of aircraft

Airframe includes structure and miscellaneous as defined in chapter 3. Based on Kroo's distribution, the proportion of structure is adjusted to 40 per cent and miscellaneous accounts for 13 per cent.

Profit will take the remaining 10 per cent as determined in ground rules.

Thus, following assumptions are developed to be used in research when specific information is unavailable.

Table 5.2 – Cost Distribution Assumptions

Cost Element	Proportion
Engine Cost C_{eng}	20%
Avionics Cost C_{avi}	17%
Structure Cost C_{stru}	40%
Miscellaneous Cost C_{mis}	13%
Profit	10%
Total	100%

5.2.2 Labour Rate

The labour rates will affect aircraft cost largely because aerospace is still a labour intensive industry although more automated machines are used at present. It can be classified into 4 occupations: engineering, tooling, manufacturing, and quality control, which can be found in the works of Roskam (1990), Raymer (2006) and Burns (1994).

Table 5.3 – Estimated Labour Rates in Regions

Occupation	Labour Rate ($/hour)		
	USA, Canada & Europe	Brazil	China
Engineering	79	60	40
Manufacturing	52.5	36	20
Tooling	62	46	30
Quality Control	52.5	36	20

The labour rates listed in table 5.3 are assumed for the research. They are validated and proven to be reasonable (refer to appendix D for more details) and should be updated when actual data are available.

5.3 Database

5.3.1 Aircraft Database

There are a total of 37 active aircraft in the database, ranging from 40-seat class to 550-seat class. Their list prices (acquisition costs) and major characteristics are collected for the research, which are shown in table 5.3.

Table 5.4 – Aircraft in Database

Aircraft	List Price ($M)				Typical Seats
	Official Website (average)	Airline Fleet & Network Management (Issue 58, Nov.-Dec. 2008)	Airfinance (No. 315, Nov. 2008)	Jane's All the World's Aircraft 2006-2007	
				Price(year)	
A318-100	59.1	59.1	49	41.7(2001)	100
A319-100	70.3	70.3	59	48.7(2001)	124
A320-200	76.9	76.9	63	53.7(2001)	150
A321-200	90.3	90.3	75	65.6	185
B737-600	53.5	53.5	49.5	45-53.5(2005)	103
B737-700	62.25	62.3	56.5	52-61(2005)	134
B737-800	74.75	74.5	67.75	63.5-72(2005)	154
B737-900	79.5	77.285	71.75	66.5-77(2005)	172
A330-200	180.9	180.9			293
A330-300	200.8	200.8			335
A340-300	215.5	215.5		161.1(2002)	295
A340-500	237.1	237.1		177.8(2002)	318
A340-600	249.4	249.4		186.4(2002)	380
A350-800	208.7	169.3		153.5(2004)	312
A350-900	240.6	188.15		170.5(2004)	366
A350-1000	269.6	210.83			412
A380-800	327.4	327.4		265(2002)	555
B747-400	244	238		205-236.5(2005)	524
B767-200ER	130	121.7		112.5-124(2005)	224
B767-300ER	149.25	149.25		128-141.5(2005)	269
B777-200		191.54		171-189(2005)	400
B777-200ER	212.5	212.5		179.5-203(2005)	400
B777-200LR	243.75	243.8		209-232	313
B777-300		228		198.5-225.5	451
B777-300ER	264.5	264.5		226-253	350
B787-3	148.75	156.88		125-135	290
B787-8	162	162		125-135	210
B787-9	194.5	188.2		125-135	250

(Continued)

CRJ-100/200		24.85		20	50
CRJ-700/705		29.5		18.11	70
CRJ-900		33.9		19.11	86
ERJ-135 ER		17.67		11.8	37
ERJ-145 ER		25.04			50
E170 LR		29.47		24.8	70
E175 LR		31.71			82
E190 LR		35.12		29.6	100
E195 LR		37.09			108

Data Source: as described in the table

Refer to appendix B.1 for detail information of all aircraft in the database.

5.3.2 Engine Database

There are totally 44 engines in the engine database, mainly including models used on aircraft in the database.

Table 5.5 – Engines in Database

SN	ENGINE TYPE	MANUFACTURER	AIRCRAFT
1	CFM56-3B1	CFMI	B737-300
2	CFM56-3B2	CFMI	B737-400
3	CFM56-3C1	CFMI	B737-500
4	CFM56-5A1	CFMI	A320
5	CFM56-5B3/P	CFMI	A321-200
6	CFM56-5B4/P	CFMI	A320
7	CFM56-5B5/P	CFMI	A319-100
8	CFM56-5C4/P	CFMI	A340-300
9	CFM56-7B22	CFMI	B737-600
10	CFM56-7B24	CFMI	B737-700
11	CFM56-7B26	CFMI	B737-800
12	CFM56-7B27	CFMI	B737-900ER
13	CF34-3B1	GE	CRJ-200
14	CF34-8C1	GE	CRJ-700
15	CF34-8E5	GE	E170
16	CF6-80A2	GE	B767-200ER
17	CF6-80C2A5	GE	A300-600R
18	CF6-80C2B1F	GE	B747-400
19	CF6-80C2D1F	GE	MD-11
20	CF6-80E1A3	GE	A330-200
21	GE90-115B	GE	B777-300ER
22	GE90-94B	GE	B777-200ER/300
23	V2527-A5	IAE	A320-200

(Continued)

24	JT8D-217C	Pratt & Whitney	MD-82
25	JT8D-219	Pratt & Whitney	MD-82
26	PW2037	Pratt & Whitney	B757-200
27	PW4056	Pratt & Whitney	B747-400
28	PW4060	Pratt & Whitney	B767-300ER
29	PW4090	Pratt & Whitney	B777-200/300
30	PW4098	Pratt & Whitney	B777-200/300
31	PW4152	Pratt & Whitney	A310-300
32	PW4158	Pratt & Whitney	A300-600
33	PW4168A	Pratt & Whitney	A330
34	AE3007A1P	ROLLS-ROYCE	ERJ-145 ER
35	BR715(-58)	ROLLS-ROYCE	B717-200
36	BR715A1-30	ROLLS-ROYCE	(B717)
37	RB211-524H-T	ROLLS-ROYCE	B747-400/B767-300
38	RB211-535E4	ROLLS-ROYCE	B757-200
39	TAY 650	ROLLS-ROYCE	FOKKER 100
40	TAY 650-15	ROLLS-ROYCE	F100
41	TRENT 556	ROLLS-ROYCE	A340-600
42	TRENT 772B-60	ROLLS-ROYCE	A330-300
43	TRENT 892B-17	ROLLS-ROYCE	B777
44	TRENT 895	ROLLS-ROYCE	B777-200ER

Data Source: Airline Fleet & Network Management, issue 57, Sep.-Oct. 2008,

Refer to appendix B.2 for detail information of all jet engines collected for this research.

5.3.3 Avionics Database

It is difficult to find a constant configuration for avionics even on the same models of aircraft because of various requirements from airlines. Costs of some major components are collected, as shown in appendix B.3, to be chosen as reference when estimating avionics cost.

5.4 Data Normalization

All collected data, both aircraft and engines, need to be normalized first to be placed at the same ground level for utilizing.

5.4.1 Inflation

One basic issue is that all prices or costs are to be transferred into a constant year dollar so that the prices are comparable to each other. Thus, producer price indices (PPI) are selected for escalation because the PPI of aircraft and engine manufacturing are able to reflect the inflation trends in aerospace industry felicitously.

See appendix B for details.

5.4.2 Data Diversity

There are many sources used to collect the required data, mainly including magazines, annual books, books, and websites.

To solve the problem of dissimilar data for the same aircraft or engine, several well-known authoritative publications are chosen as the basic data sources, for example, Jane’s annual books and manufacturers’ official websites; and others are supplements for reference only. All data in the database are normalized based on basic sources except they are not given in them.

Some list prices from magazines are checked with deal prices. It proved that all list prices in the database are reliable since they are close to the actual acquisition costs in trades.

5.4.3 Data Estimating

There are missing parameters in some variants of engines or aircraft even in the authorized sources. In these cases, the missing parameters are estimated according to other variants in the same series or class if possible. An example is presented in appendix B.4. And any bracketed parameters in the detail datasheet are estimated with this approach.

5.4.4 Database Maintenance

After building up the database for cost estimating, the maintenance of database is required to keep all existing data up to date as well as add new data when more information become available as project moving forward.

Comparing with database establishment, maintenance is a much more time-consumable and costly task due to the long life of cost system in a company. Otherwise, as the actual data accumulating, the particular cost pattern of the company can be recognized and the cost system will consequently be improved gradually. Hence, maintenance is somewhat more important than establishing the database.

5.5 Expert Judgement

With the limited information at the early stage of a programme, subjective options are essential to make estimates or decisions. In fact, these judgements are important even when actual data are available.

The involved experts and the form of synthesizing all judgements are both important because one expert is not enough as well as many experts' options may conflict. Moreover, the levels of knowledge and understanding, the coverage of involved fields, the quality of communication, and so on should be considered when seeking expert judgements.

Normally, a meeting or a temporary team is appropriate for cost estimating. The former one is sometimes called "round table", and the latter one often is an integrated product team (IPT) in which the members will be changed as programme proceeding and objectives changing.

6 Analogy Estimating

This chapter is to develop an analogy method for aircraft acquisition cost estimating using actual data of similar aircraft. Some adjustment factors are determined based on specific situation of programme.

6.1 Analogy Samples

Analogy samples are chosen according to the proposed product. On the one hand, the similarities are important for producing reliable predictions based on actual data of samples; on the other hand, the differences should be measurable to be adjusted quantitatively.

6.1.1 Similarities

Once samples are selected, it is easy to find out similarities between samples and proposed product because those are the reasons of choosing them as samples, not others. Basically, the samples and new product should be the same kind as it is illogical to estimate cost of ship using data of airplane.

With respect to commercial aircraft, they might be performances or parameters such as size, seat-class, weight/mass, range, propulsion, speed, material, and etc. The more similar characteristics samples have, the more accurate predictions are.

Otherwise, the samples can be partly similar to proposed product, e.g. one or some components of certain sample are similar to that in new product though others are completely different. The similar parts can be treated separately to involve as many actual data as possible.

6.1.2 Differences

As described in literature review, adjustment factors are applied to actual data of historic projects to quantify the differences between target and samples, e.g. inflation, technology, and labour. Any differences that can affect cost must be covered by the proposed estimating model. In general, they may be particular time, location, developer, facility, policy and etc.

As to aircraft, the most possible differences normally will be the regional differentiae as global procurement is the trend for aerospace industry, especially for engine and avionics system which account for great proportion in the total aircraft cost.

Generally, following aspects can be identified to be adjusted in cost estimating for a new aircraft project developed by particular manufacturer located in certain region:

- Overhead – Or say particular pattern or policy in a company, which will affect the overhead cost of a programme significantly.
- Labour Rate – It is mainly about the region where the manufacturer is located.
- Investment – Costs of facilities will increase when developing a product never experienced before or with advanced technology.
- Then-year – The most regular issue to reflect the inflation.
- Technology – It includes technology, facility, technique, process, material, and etc. Many technologies or techniques were advanced but are mature or well developed at present; consequently, their costs decrease to a low level.
- Material – It can be regarded as one part of technology. However, it is liable to consider material solely at present for its significant impact on weight reduction.
- Difficulty – There is a judgement factor "F_{diff}" to account for difficulty in Roskam's cost models. However, here it is to introduce impacts of experience, skill, purchase, airworthiness, and other non-technology issues in this research, which will cause cost increases due to lack of experience.

There may be other factors to be concerned during the analogy estimating process, depending on the actual situation of new project; and to be determined with comprehensive analysis.

Some of these factors are global adjustment for the whole aircraft, e.g. technology and difficulty factors; while others will only impact one area, e.g. labour rate and overhead factors.

6.2 Cost Model

6.2.1 Aircraft

As defined in chapter 3, the acquisition cost of one aircraft is divided into 4 cost components plus profit:

$$C_{ac} = C_{stru} + C_{avi} + C_{eng} + C_{mis} + P_u$$

where C_{ac} stands for unit acquisition cost, C_{stru} cost of unit airframe structure, C_{avi} cost of unit avionics system, C_{eng} engine cost of unit aircraft, C_{mis} cost of unit miscellaneous systems, and P_u profit of each aircraft. Proportion of each element is assumed in table 5.2.

Therefore, the similar facts are to be remained and the differences are to be adjusted mainly with expertises since few data are available at the time.

The global and local adjustment factors, which are introduced in section 6.1.2, are allocated to corresponding cost elements of proposed aircraft.

$$C_{ac}=f_{tech}*f_{diff}*[(f_{mat}*C_{mat}+f_{lab}*C_{lab}+f_{oh}*C_{oh}+f_{inv}*C_{inv})+C_{avi}+C_{eng}+C_{mis}]*CEF+Pro.$$

where f_{tech}, f_{diff}, f_{mat}, f_{lab}, and f_{oh} stand for adjustment factors for technology, difficulty, material, labour rate, and overhead respectively. CEF stands for cost escalation factor which is the ratio of PPI_{2008} to $PPI_{then\text{-}year}$.

Other adjustment factors should be added as necessary or required, as to be determined with expert judgement according to the circumstance.

6.2.2 Engine

Similarly, the costs of engine samples are adjusted for new engine type.

$$C_{eng} = f_{tech}*f_{diff}*C_{eng\text{-}sample}*CEF$$

where $C_{eng\text{-}sample}$ stands for acquisition cost of sample engine, and others are as that in previous section.

The adjustment factors will affect the estimate greatly and must be applied carefully.

6.3 Validation

6.3.1 Aircraft

To deploy validation, a new 150-seat civil aircraft, which uses similar technologies as current active aircraft, is assumed to be developed by a new comer based in western country. Thus, B737-700 and A319 are selected as analogy samples for cost estimating and the analogy estimating results are as following:

Table 6.1 – Aircraft Analogy Estimating Validation Results

Analogy Estimate($M)			Based on A319-200 ($70.3M)	Based on B737-700 ($62.3M)
			62.92	55.76
Assumption	Structure Proportion		40%	40%
	Engine Proportion		20%	20%
	Avionics Proportion		17%	17%
	Miscellaneous Proportion		13%	13%
	Profit Ratio		10%	10%
	Labour Cost Proportion		30.77%	30.77%
	Overhead Cost Proportion		30.77%	30.77%
	Investment Cost Proportion		7.69%	7.69%
	Material Cost Proportion		30.77%	30.77%
Adjustment Factor	Structure	Labour Rate	1	1
		Overhead	1.1	1.1
		Investment	1.1	1.1
		Material	1	1
	Global	Technology	0.8	0.8
		Difficulty	1.1	1.1
		PPI Ratio	1	1

All adjustment factors are determined with consideration of the situation encountered by the new comer without experience to this class. Difficulty, investment, and overhead will consequently cost more; on the contrary, technology adjustment factor is less than 1 because both samples were developed in 1990s and their technologies are well developed now and then cost less.

The estimates are 10 per cent lower than the actual costs of analogy aircraft. The reduction is primarily contributed by mature technology but offset by difficulty and the impacts of local adjustments in structure cost at the same time.

6.3.2 Engine

A greener turbine engine is expected by the new 150-seat aircraft. Thus higher BPR and lower SFC require advanced technologies. The engines of A319 and B737-700, CFM56-5B5/P and CFM56-7B24, are used to make estimates. The results are as below:

Table 6.2 – Engine Analogy Estimating Validation Results

Engine Type		CFM56-5B5/P	CFM56-7B24
Actual Cost($M) - 2008		6.35	7.50
Adjustment	Technology	1.10	1.10
	Difficulty	1.10	1.10
	CEF	1.00	1.00
Estimated Cost($M)		7.68	9.08

Improving fuel efficiency will cause 20% increase of engine acquisition cost. However, the significant increase can be offset by the saving of fuel in operation.

6.4 Framework of Analogy Approach

According to the rationale of analogy approach, a framework can be illustrated as below:

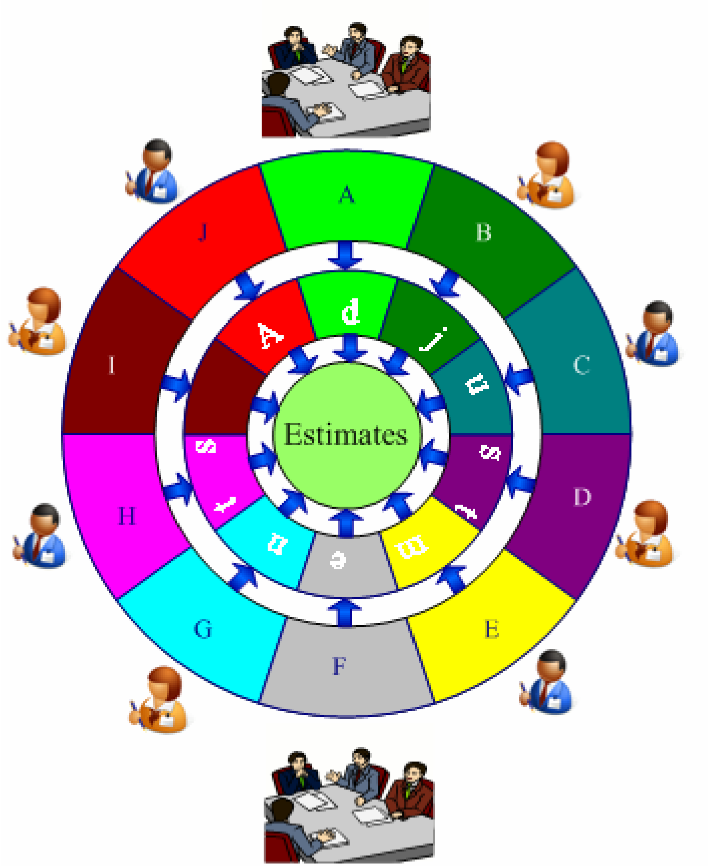


Figure 6.1 – Analogy Cost Estimating Framework

It looks like a round table where A to J represent factors which possibly affect the cost, e.g. labour rates, part fabrication, assembly, and tooling. Then judgements are generated to adjust actual data of existing products. As illustrated in figure, involved experts may be individuals or several persons in the same area.

If necessary, the rough estimates need to be calibrated and improved with actual data, or checked with predictions of other approaches.

7 Parametric Estimating

This chapter is to develop an acquisition cost estimating methodology for commercial aircraft at conceptual design phase using parametric approach, mainly with regression techniques of statistics.

7.1 Aircraft Acquisition Cost

Acquisition cost can be regarded as price as the customer will pay to acquire the aircraft. Therefore, list prices collected from publications are used in the research.

7.1.1 Explanatory Variables

As reviewed in literatures, weight and speed are the most commonly used explanatory variables for aircraft CERs. Otherwise, the independent explanatory variables are expected to be identified and included in derived CER by researching. Thus, Principal Component Analysis (PCA), one function module of XLSTAT, is used to address the correlations between variables first, and then the number of variables can be reduced to facilitate following research.

However, the result shows that only age, delivery number, power loading and labour rate base are independent from others, as shown in figure 7.1.

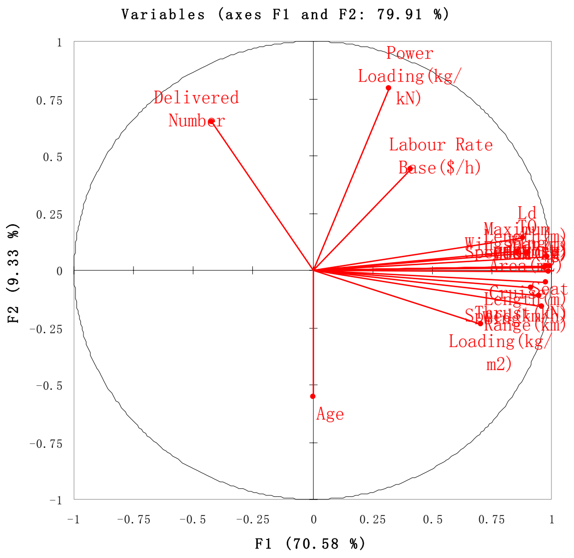


Figure 7.1 – Aircraft Parameters' Correlation Circle in PCA

All other variables are correlated to each other, including not only mass and speed but also wing area, length, seat, range, thrust, and etc. So it can be concluded that any variation of one of them will cause changes to others to some extent.

However, these mathematic results can not be accepted by aircraft designers technically because most parameters will affect or be affected by others since aircraft is a complex system and many are relatively independent to others, e.g. wing area to range.

To identify the significant variables, stepwise regression techniques, including stepwise, forward, and backward, are used. The results are as following:

Table 7.1 – Explanatory Variables

Technique	Linear			Exponential		
	Stepwise	Forward	Backward	Stepwise	Forward	Backward
Explanatory Variables	Wingspan, Length, MTOM	Wingspan, Length, OEM, MTOM	Length, OEM, Delivery Number, Range	Seat, Wingspan, Cruise Speed	Seat, Wingspan, Cruise Speed	Seat, Delivery Number, Wing Area, Cruise Speed
R^2	0.997	0.997	0.997	0.995	0.995	0.996
Adjusted R^2	0.996	0.996	0.997	0.994	0.994	0.994
Objection	No	No	Yes	Yes	Yes	Yes

According to these results, some explanatory variables can be identified since they appear in most models, i.e. length, seat, wingspan, OEM or MTOM. However, two of these variables are not with correct trends in corresponding models: delivery number with positive coefficient and cruise speed with negative coefficient. So four models are objected as shown in table above.

Considering results of PCA, length, seat, wingspan, and mass are all related to each other, not independent variables. In fact, it is difficult to find completely independent variables in aircraft design because aircraft design is a complex system engineering in which any small change of one factor will put impacts on others to different extent.

Therefore, the independency of variables is ignored in the research. All variables are to be put into regression and related to the cost, and then the contribution of each variable to cost is measured with either standardized coefficient in ordinary least-squares regression (OLSR), or importance of variable in projection (VIP) in partial least-squares regression (PLSR).

7.1.2 CER

With collected list prices and parameters of various aircraft, regression approach is applied to derive the CERs statistically.

The detail information of applying ordinary least-squares regression (OLSR) and partial lest-squares regression (PLSR) can be found in appendix E.

After comparison, the equation in exponential form derived by applying PLSR is chosen as the CER for acquisition cost of aircraft for conceptual design phase.

$$\text{Cost}=0.0181*\text{Seat}^{0.290}*\text{Wingspan}^{0.518}*\text{OEM}^{0.232}*\text{MTOM}^{0.222}$$

where OEM is operational empty mass and MTOM is maximum take-off mass, which are defined in conceptual design phase with passenger capacity and wingspan together.

The features of the model are as follows:

Quality of Model

Q^2 cumulated index	0.982
R^2Y cumulated index	0.982
R^2X cumulated index	0.994

Table 7.2 – VIP of Explanatory Variables in Aircraft CER

Variable	VIP	Standardized coefficient
MTOM(kg)	1.010	0.253
Wingspan(m)	1.006	0.252
OEM(kg)	0.986	0.247
Seat	0.997	0.250

Both the VIPs and standardized coefficients of these four variables are similar and the goodness of cost model is quite satisfied.

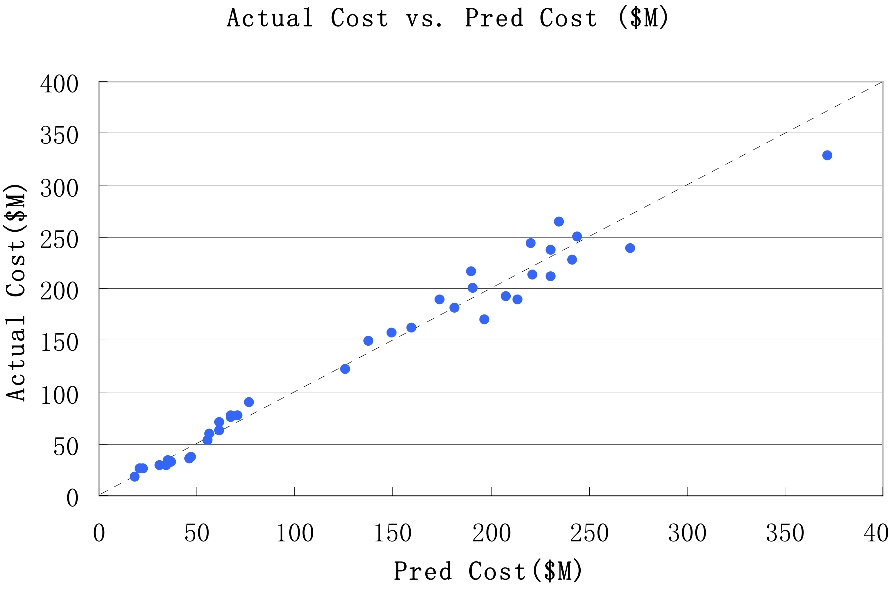


Figure 7.2 – Predicted Cost vs. Actual Cost of Aircraft

It can be seen from figure 7.2 that most cost estimates are close to actual costs, especially those under $170 million. And the errors of estimates are presented in percentage of actual cost as following:

Table 7.3 – Estimating Errors of CER

Aircraft	Actual Cost($M)	Predicted Cost($M)	Error	Error Percentage
A318-100	59.1	57.10095	-1.99905	-3.38%
A319-100	70.3	62.286	-8.014	-11.40%
A320-200	76.9	68.59909	-8.30091	-10.79%
A321-200	90.3	77.2725	-13.0275	-14.43%
B737-600	53.5	56.41227	2.912266	5.44%
B737-800	74.5	68.27708	-6.22292	-8.35%
B737-900	77.285	71.97093	-5.31407	-6.88%
A330-200	180.9	183.8092	2.90915	1.61%
A330-300	200.8	192.5435	-8.25652	-4.11%
A380-800	327.4	375.2932	47.89316	14.63%
B747-400	238	273.6459	35.6459	14.98%
B767-200ER	121.7	127.3101	5.6101	4.61%
B767-300ER	149.25	139.2986	-9.95138	-6.67%
B777-200	191.54	209.5663	18.02631	9.41%
B777-200ER	212.5	223.4959	10.99594	5.17%
B777-300	228	244.1245	16.12454	7.07%
CRJ-100/200	24.85	22.87557	-1.97443	-7.95%
CRJ-700/705	29.5	31.62635	2.126351	7.21%
ERJ-135 ER	17.67	18.95994	1.289937	7.30%
ERJ-145 ER	25.04	21.29641	-3.74359	-14.95%

(Continued)

A350-800	169.3	196.8524	27.55238	16.27%
A350-900	188.15	214.145	25.99498	13.82%
A350-1000	210.83	231.2458	20.41579	9.68%
A340-300	215.5	191.5355	-23.9645	-11.12%
A340-500	237.1	232.625	-4.47499	-1.89%
A340-600	249.4	246.7356	-2.66435	-1.07%
B777-300ER	264.5	237.3743	-27.1257	-10.26%
B787-3	156.88	150.9728	-5.90723	-3.77%
B787-8	162	161.3845	-0.61555	-0.38%
B787-9	188.2	175.8945	-12.3055	-6.54%
E170 LR	29.47	34.9012	5.431197	18.43%
E175 LR	31.71	37.231	5.520999	17.41%
E190 LR	35.12	46.64384	11.52384	32.81%
E195 LR	37.09	48.14662	11.05662	29.81%
B777-200LR	243.8	222.5894	-21.2106	-8.70%
B737-700	62.3	62.23922	-0.06078	-0.10%
CRJ-900	33.9	36.22799	2.327986	6.87%
Average Error(Absolute Value)				9.60%

The accuracy of cost model is quite satisfied since the average error percentage is under 10 per cent. Considering limited information at aircraft conceptual design phase, this CER is easy and quick to be used for decision making.

7.1.3 Analysis

To be used at conceptual design, the CER is expected to include certain number of parameters, aiming to involve more significant impacts from various quantitative design parameters, or say cost drivers, for optimization; for instance, weight, speed, thrust (which will affect cost of engines significantly), range (which will have impacts on both fuel weight and consumption), and labour rate (which somewhat will determine the complexity of design). However, more parameters mean that the CER is complex and more uncertainties are introduced.

The derived CER indicates four explanatory variables: seat, wingspan, operational empty mass, and maximum take-off mass. The former two represent the size of aircraft while the latter two are giving weight. It is different from existing cost models. The main reason is that all data used to develop the CER are of civil jet transports as well as actual engineering or production data from industry are not available. For instance, speed is eliminated because all sample aircraft have similar subsonic velocity.

Size is the basic parameter of aircraft and can explain cost well, as shown below:

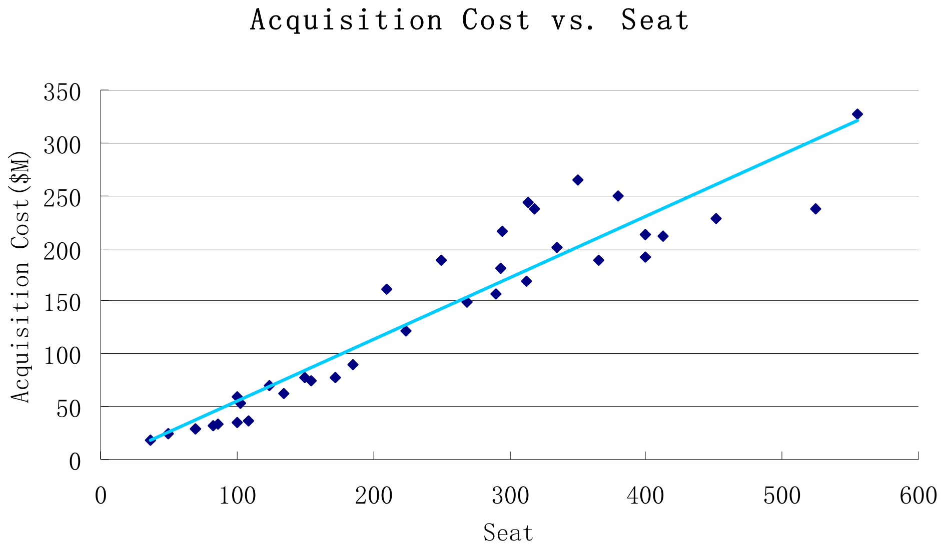


Figure 7.3 – Acquisition Cost vs. Seat

Knowing that explanatory variables should be independent, one confused finding in the CER is that both OEM and MTOM appear and contribute to the cost estimate. In reality, MTOM is the sum of OEM, payload, and fuel mass; consequently, OEM can be independent if the other two vary greatly, and vice versa. Otherwise, the quality will impair significantly if either OEM or MTOM is eliminated from the equation. Therefore, both of them are remained considering possible varying payload and fuel mass.

7.2 Component Cost

The total acquisition cost can be divided as mentioned in chapter 3, i.e., development cost, flyaway cost, and profit of the whole project, as shown in following equation:

$$C_P = C_{RDT\&E} + C_{MAN} + P$$

where C_P stands for the programme's acquisition cost, $C_{RDT\&E}$ the development cost (nonrecurring cost), C_{MAN} manufacturing cost of entire programme (recurring cost), and P the total profit of the programme.

Then the acquisition cost of unit aircraft is

$$C_U = \frac{C_P}{N} = \frac{C_{RDT\&E} + C_{MAN} + P}{N} = \frac{C_{RDT\&E}}{N} + C_{FLY} + P_U$$

where C_U stands for acquisition cost of unit aircraft, N the total production number, C_{FLY} flyaway cost of each aircraft, and P_U the profit of one aircraft.

The RDT&E and manufacturing cost is estimated using existing cost models of Roskam in the research due to lack of engineering and industrial data. And the profit can be set as certain proportion of total, i.e. 10 per cent as defined in ground rules.

Flyaway cost comprises three major components physically: airframe, engines, and avionics, which should be considered separately because of their different importance for manufacturers. In addition, there is still engineering work even for aircraft in production, which is predicted with Roskam's CER also.

7.2.1 Airframe

Airframe is manufactured mainly by the manufacturers although many components are supplied by other contractors. Since acquisition costs of engines and avionics are relatively fixed, the cost of airframes is much concerned by manufacturers.

As mentioned in chapter 3, airframe cost is:

$$C_{af} = C_{stru} + C_{mis}$$

7.2.1.1 Structure Cost

There is few airframe information or data in publications. In this case, the estimating approach is based on following equation:

$$C_{stru} = C_{mat} + C_{lab} + C_{oh} + C_{inv}$$

$$C_{mis}=F_{mis}*C_{stru}$$

- *Material*

Material cost includes not only costs of raw materials but also certain costs of processing; and it can be estimated with the weight and material price.

Utilization factor are introduced to consider the material removed in processing. With respect to materials, it will be more accurate if all materials are divided by the kind and type, i.e. aluminium, steel, titanium, composite, bolts, rivets, paint, sealant, and etc. However it is difficult to obtain such detail information at conceptual design phase. Thus a base material price is adjusted and then used to represent all materials. Obviously, the base material is aluminium alloy.

Without actual data, the weight of structure, i.e. AMPR weight, can be estimated using Roskam's equations (Roskam, 1990):

$$W_{AMPR} = \text{invlog}\,(0.1936+0.8645*\log(MTOW))$$

where MTOW stands for maximum take-off weight in lbs.

Then, a rough estimate for material cost at conceptual design stage is given by:

$$C_{mat} = W_{AMPR} * Price_{al} * F_u * F_m$$

where F_u stands for normalized material utilization factor considering the great disparity between different processes, for instance, machining and sheet metal. Without actual data, its value is suggested to be

$F_u =$ 4 for regional aircraft
5 for mid-range transport aircraft
6 for long-range transport aircraft

F_m is the judgement factor of price and the value are recommended to be:

$F_m =$ 5 for regional and mid-range transport aircraft
5.5-6 for long-range transport aircraft

$Price_{al}$ is the average price of aluminium alloy covering plate, bar, and sheet. It is \$6.35 per lb at present market, tax is not included; however, it will be lower than \$5 in the material procurement system for major manufacturers.

- *Labour*

The labour cost of aircraft structure includes design, manufacturing, and quality control. It needs to be adjusted for advanced technologies and materials as well.

Lacking industrial data, the labour hour per unit aircraft can be predicted by modified equations of Roskam:

$$MHR_{eng} = 0.0396*W_{AMPR}^{0.791}*V_{MAX}^{1.526}*N^{-0.817}*F_{tech}*F_{CAD}$$

$$MHR_{manu} = 29.984*W_{AMPR}^{0.740}*V_{MAX}^{0.543}*N^{-0.476}*F_{tech}$$

where MHR_{eng} stands for engineering man-hour for each aircraft while MHR_{manu} manufacturing man-hour per unit aircraft. N is the total production number of the project. F_{tech} is the judgement factor for difficulty of the new programme, ranging from 1.0 for conventional jet transport like B737 and A320, to 1.5 for advanced aircraft such as A380 and B787; while F_{CAD} is the “computer aided design” factor, and the value is 0.7 since CAD techniques are widely applied in aerospace industry.

It is widely accepted that quality control cost is 13 per cent of production cost (Roskam, 1990, Raymer, 2006, Burns, 1994).

Therefore, the labour cost is:

$$C_{lab} = MHR_{eng}*R_{eng} + MHR_{manu}* R_{man} + C_{qc}$$

R_{eng} and R_{man} are labour rate for engineering and manufacturing respectively. Lacking industrial data, the labour rates mentioned in chapter 5 can be used for estimating.

- *Overhead*

The overhead cost will vary with particular policies in different companies and is hard to predict by parameters unless the unique cost estimating pattern of a company has been figured out according to historic data. Thus, it is directly related to the labour cost on which the overhead actions are based:

$$C_{oh}=F_{oh}*C_{lab}$$

where F_{oh} is the overhead factor. Normally its value ranges from 0.5 to 1.2, depending on manufacturers and their management framework.

- *Investment*

The investment for a new project includes equipments, facilities, buildings, toolings, or even interests of loan. It will be affected largely by the technologies used on new product.

$$C_{inv}=F_{tech}*F_{inv}*C_{lab}$$

where F_{tech} is as in labour cost section; F_{inv} is the judgement factor of investment and suggested to be:

$F_{inv} = 0.2$	for regional aircraft
$F_{inv} = 0.25$	for mid-range transport aircraft
$F_{inv} = 0.35$	for long-range transport aircraft

7.2.1.2 Miscellaneous

Miscellaneous include functional systems except engines and avionics, for instance, landing gear, APU, air conditioning, power supply system, and interiors. Certainly, the costs of these systems vary with the size of aircraft, namely, the structure of aircraft.

Lacking actual data of these systems, the total cost of miscellaneous systems can be predicted based on structure cost:

$$C_{mis}=F_{mis}*C_{stru}$$

where F_{mis} stands for the judgement factor of miscellaneous systems per unit aircraft. The suggested values of Fmis are as following:

$F_{mis}=0.2$ for regional transport aircraft
$F_{mis}=0.3$ for mid-range transport aircraft
$F_{mis}=0.4$ for long-range transport aircraft

7.2.2 Engines

Cost of engines takes a significant proportion in the total cost of aircraft. There are several main providers of jet engines in the world, for instance, Rolls-Royce, CFM, GE, and Pratt & Whitney.

As the integrator, aircraft manufacturers provide engine manufacturers the proposal of engines for the prototype aircraft. The proposal should be produced by aircraft designers considering the performances determined at aircraft conceptual design phase, including thrust, weight, SFC, diameter as well as the life cycle cost. Then the conceptual design process of engine will be performed to decide whether to redesign an existing model or start a new design.

7.2.2.1 Explanatory Variables

Historic achievements have revealed that the most relational parameters are: maximum thrust, maximum Mach number, turbine inlet temperature, dry weight, and specific fuel consumption, which can be found in the engine cost models of Rand (Hess et al, 1987) and NASA (at *http://cost.jsc.nasa.gov/ATECM.html*).

For this research, 11 parameters are collected. Likewise, all parameters are analysed with PCA for independency. The results are illustrated in figure below.

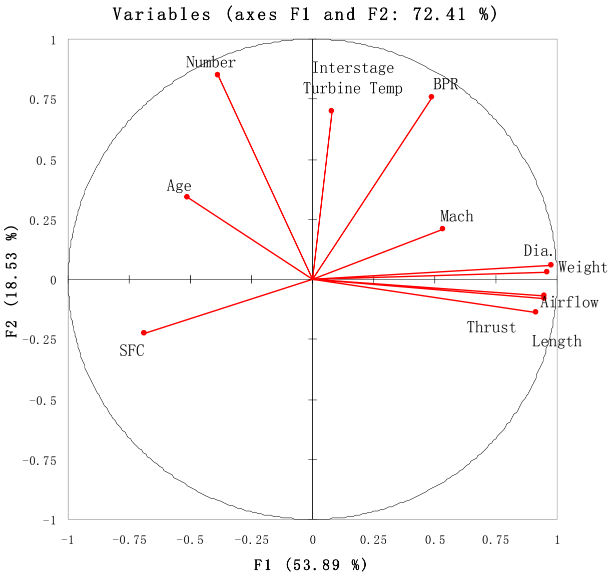


Figure 7.4 – Jet Engine Parameters' Correlation Circle in PCA

It can be seen that thrust can be highly related to dry weight, fan diameter, airflow, and length. So 7 independent variables are identified for turbine engine CER development.

7.2.2.2 Engine CER

The engine cost model for this research is derived by applying partial least-squares regression to independent variables. See appendix E.2 for details.

$$C_{ENG}=-18.144+0.0191*\text{Thrust(kN)}+0.193*\text{BPR}+0.011*\text{Temp.(°C)}$$
$$-12.187*\text{SFC(lb/lb·hour)}+20.174*\text{Mach}$$

All identified explanatory variables are common with historical turbine engine CERs. The average accuracy is around 26 per cent, somewhat satisfied for conceptual design to learn the impacts of engine parameters on cost. Otherwise, engine manufacturers can be involved to provide accurate estimates for engines.

7.2.3 Avionics

Avionics comprises many electrical functional systems, such as communication, navigation, flight control, flight management, and etc. These systems were dedicated units, or say subsystems, not long time ago; but now are highly integrated to reduce the costs as software complexity and support costs grew (Newport, 1994).

It is difficult to estimate the cost of avionics due to the limited information comparing with open aircraft database. Otherwise, the configuration of avionics varies with customers so that the cost is affected greatly by the specific selection made by airlines.

Following list presents some avionics solutions for aircraft in different seat class. Many subsystems are same regardless of size.

Table 7.4 – Applications of Rockwell Collins' Avionics Solutions

MODEL	PART NAME	A320 Family	A330 A340	B737-NG	B747-400	B767-400	B777
ADF-900	Automatic Direction Finder	√	√	√	√	√	√
AFDS-770	Autopilot Flight Director System						√
AOC-900	Data Link Communications	√	√				
CMCS-7000	Central Maintenance Computer System				√		
CMU-900	Data Link Communications			√	√	√	
DDI-713	Digital Indicator						
DME-900	Distance Measuring Equipment	√	√	√		√	√
FCS-700A	Autopilot Flight Director System				√	√	
GLU-920	Multi Mode Receiver-Global Landing System	√	√	√	√	√	√
HFS-900D/ CPL-920D	Data Link Communications			√	√	√	
HGA-2100B	SATCOM High Gain Antenna	√		√	√	√	√
IDS-7000	Integrated Display System				√		
IGA-2100B	SATCOM Intermediate Gain Antenna	√		√	√	√	√
LFDS	Large Format Display System					√	
LMAT-2000	Laptop Maintenance Access Terminal						√
LRA-900	Low-range Radio Altimeter	√	√	√	√	√	√
MAT-2000	Maintenance Access Terminal						√
TPR-901	Mode S Transponder	√	√	√	√	√	√
VHF-900B	Very High Frequency Transceiver	√	√	√	√	√	√
VOR-900	VHF Ommidirectional Range/Marker Beacon Receiver	√	√	√	√	√	√
WXR-2100	Weather Radar System	√	√	√	√	√	√

Source: http://www.rockwellcollins.com/ecat/at/xxplatformList.html?expand=1&path=Platform

Therefore, the weights or powers of avionics devices in different aircraft will be similar or even same; consequently the cost can not be related to weight of avionics or aircraft simply.

To develop a cost estimating approach, the total cost of avionics is divided as following:

$$C_{avi}= F_{avi\text{-}diff} * (C_{avi\text{-}hd}+C_{avi\text{-}sw}+C_{avi\text{-}d}+C_{avi\text{-}i})$$

where $F_{avi\text{-}diff}$ stands for difficulty judgement factor and its value is suggested to be:

$F_{avi\text{-}diff}$ =	1.0	for conventional avionics system
	1.2-1.5	for advanced avionics system

$C_{avi\text{-}hd}$ stands for hardware cost, $C_{avi\text{-}sw}$ software cost, $C_{avi\text{-}d}$ system design cost, and $C_{avi\text{-}i}$ installation cost.

The hardware prices of some typical devices are collected to generate a cost base for the whole avionics system. See appendix B.3 for detail information of devices.

Thus, a proportion factor "$F_{avi\text{-}pro}$" is required to define the cost proportion of base kit mentioned above in the whole avionics system.

$$C_{avi\text{-}hd} = F_{avi\text{-}pro} * C_{avi\text{-}hb}$$

where $C_{avi\text{-}hb}$ is the cost of base avionics kit; and $F_{avi\text{-}pro}$ is suggested to be:

$F_{avi\text{-}pro}$ =	1.0-1.2	for regional aircraft
	0.6-0.8	for mid-range transport aircraft
	0.4-0.6	for long-range transport aircraft

Other cost elements of avionics are predicted based on hardware cost:

$$C_{avi\text{-}sw} = C_{avi\text{-}hd} * F_{avi\text{-}sw}$$

$$C_{avi\text{-}d} = C_{avi\text{-}hd} * F_{avi\text{-}d}$$

$$C_{avi\text{-}i} = C_{avi\text{-}hd} * F_{avi\text{-}i}$$

$F_{avi\text{-}sw}$, $F_{avi\text{-}d}$, and $F_{avi\text{-}i}$ are the judgement factor for software, design, and installation respectively. And their values are recommended as following if no actual data are available:

$F_{avi\text{-}sw}$ =	0.8-1.2	for regional aircraft
	1.5-2.0	for mid-range transport aircraft
	2.5-4.0	for long-range transport aircraft
$F_{avi\text{-}d}$ =	0.4-0.5	for regional aircraft
	0.6-0.8	for mid-range transport aircraft
	0.8-1.2	for long-range transport aircraft
$F_{avi\text{-}i}$ =	0.5	for regional aircraft
	1.0	for mid-range transport aircraft
	1.5-2	for long-range transport aircraft

Thus, the total avionics cost is:

$$C_{avi}=F_{avi\text{-}diff}*(C_{avi\text{-}hd}+C_{avi\text{-}sw}+C_{avi\text{-}d}+C_{avi\text{-}i})=F_{avi\text{-}diff}*C_{avi\text{-}hd}*(1+F_{avi\text{-}sw}+F_{avi\text{-}d}+F_{avi\text{-}i})$$

In addition, to predict avionics cost, the configuration needs to be pre-defined based on the basic devices presented in appendices. And the judgement factors should be determined according to the specific mission of aircraft and updated once actual data are available.

7.3 Validation

As defined in ground rules, two aircraft are used to make validation for developed cost estimating approaches.

7.3.1 Aircraft Cost

Both B737-700 and CRJ 900 are validated during the PLSR process. The results are shown in figure and table below.

The estimates errors for both aircraft are provided in table 7.5.

Table 7.5 – Estimates Error of Validation Aircraft

Aircraft	Actual Cost($M)	Estimated Cost($M)	Error	Accuracy
B737-700	62.3	62.23922	-0.10%	0.10%
CRJ-900	33.9	36.22799	6.87%	6.87%

The validation results show that the cost estimating model can provide accurate estimates for decision making at aircraft conceptual design stage.

The predicted costs are illustrated against actual costs in figure 7.4 below.

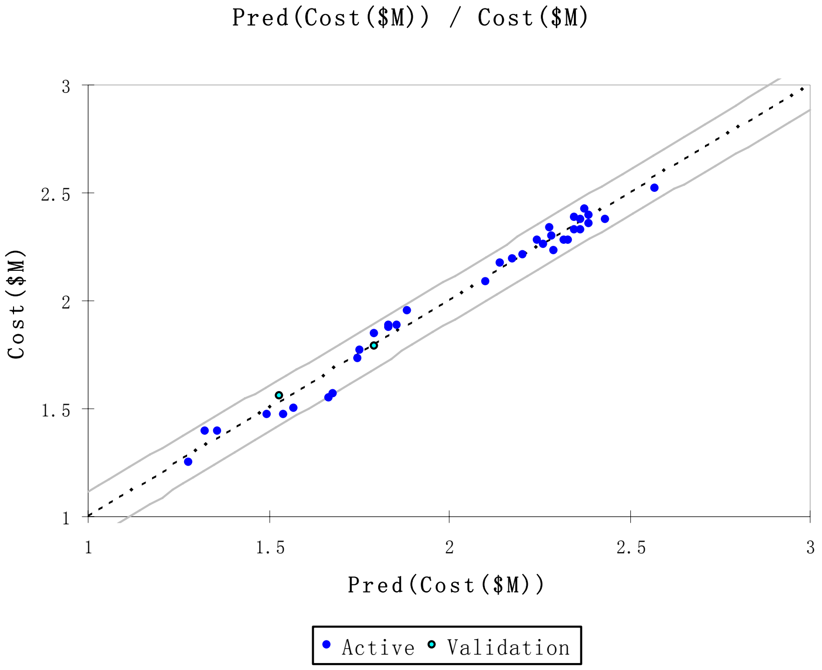


Figure 7.5 – Aircraft Cost Model Validation

It is clear that both estimates are close to the actual costs, the estimate cost of B737-700 is even on the line of cost model.

See appendix E for detail information about validations of other CERs during the process of research to compare.

7.3.2 Components Cost

7.3.2.1 Airframe Cost

With the model presented in section 7.2.1, validation aircraft are estimated using following facts.

First, the price of $10 per pound for aluminium alloy is used to include taxes and expenditures of raw material processing, which is necessary for parts fabrication and normally not covered by machining labours because the processing is to provide stock material per drawing requirement.

To crosscheck the airframe cost estimates, airframe estimates from CERs of Burns and Roskam are used to validate.

All factors and parameters used in acquisition cost estimating are presented as below.

Table 7.6 – Airframe Cost Validation

Aircraft	B737-700	CRJ 900
MTOW(lb)	*133002.65*	*80498.24*
Production Number	*1000*	*1000*
Maximum speed(knot)	*473.00*	*475.70*
Structure Cost($)	25,772,961	16,291,967
Material Cost($)	10,498,257	5,441,045
AMPR Weight(lb)	41,993	27,205
Price($/lb)	10.00	10.00
Utilization Factor	5.00	4.00
Price Factor	5.00	5.00
Labour Cost($)	6,788,757	4,932,237
Engineering		
Engineering Hour	6,990	5,002
Engineering Rate	79.00	79.00
Engineering Cost($)	552,253	395,173
Manufacturing		
Manufacturing Hour	105,124	76,478
Manufacturing Rate	52.50	52.50
Manufacturing Cost($)	5,519,030	4,015,102
Quality Cost($)	717,474	521,963
Quality Factor	0.13	0.13
Overhead Cost($)	6,788,757	4,932,237
Overhead Factor	1	1
Investment Cost($)	1,697,189	986,447
Investment Factor	0.25	0.20
Miscellanies Cost($)	7,731,888	3,258,393
Factor	0.30	0.20
Airframe Cost($)	33,504,850	19,550,361
Burns' Estimate($)/Error	30,234,630/ 10.82%	19,465,711/ 0.43%
Roskam's Estimate($)/Error	23,907,533/ 40.14%	17,454,197/ 12.01%

It can be seen that both validation aircraft are a little overestimated compared with Burns' estimates, but much higher than that of Roskam. The results can be accepted considering Burns's CERs are newly developed.

7.3.2.2 Engine Cost

Likewise, the engines on both validation aircraft are used as validation samples, and the cost estimates from engine CER mentioned in section 7.2.2 are compared with actual costs as shown in table 7.7.

Table 7.7 – Engine Cost Validation

Aircraft	B737-700	CRJ 900
Engine Model	CFM56-7B24	CF34-8C1
Thrust(kN)	107.69	63.40
BPR	5.30	5.10
Interstage turbine Temp.(°C)	950	960
SFC(lb/lb hour)	0.54	0.68
Airflow(kg/s)	341.00	200.00
Mach Number	0.82	0.78
Number of Engines	2	2
Engine Cost Estimate($M)	4.94	1.98
Engine Actual Cost($M)	5.7	2.3
Error in percentage	-13.26%	-13.81%
Engines Cost($)	9,887,998	3,964,682

Both estimates are with around 13 per cent error, which is reasonably accepted for conceptual design.

7.3.2.3 Avionics Cost

Because of lack of actual cost of avionics, the estimates are validated by the proportion of avionics cost in aircraft cost.

Table 7.8 – Avionics Cost Validation

Aircraft	B737-700	CRJ 900
Base Kit Cost($)	1,739,861	1,739,861
Percentage	75%	100%
Factor		
Hardware	1.00	1.00
Software	2.00	1.00
Design	0.60	0.40
Installation	1.00	0.50
Difficulty	1.00	1.00
Avionics Cost($)	10,671,147	5,045,597
Proportion	18.31%	15.91%

The results are reasonable according to the cost distribution developed by Kroo (2006).

7.3.2.4 Total Cost

The total acquisition cost comprises of costs of these three components plus profit for manufacturers. With profit ratio of 10 per cent, the final acquisition costs for both validation aircraft are:

Table 7.9 – Aircraft Cost Validation

Aircraft	B737-700	CRJ 900
Airframe Cost($)	33,504,850	19,550,361
Engines Cost($)	8,284,519	3,946,988
Avionics Cost($)	10,671,147	5,045,597
Profit($)	5,828,946	3,171,438
Estimated Acquisition Cost($)	58,289,463	31,714,384
Actual Cost($)	62,300,000	33,900,000
Error	-6.44%	-6.45%

It can be seen that both estimates are under the actual costs and the accuracy are around 6 per cent. Knowing that the accuracy ranges from -30% to +50% at conceptual design phase, the CERs derived in this research are validated with high accuracy.

7.3.3 Summary

All CERs are calibrated with B737-700 and CRJ-900, and the estimates are proved to be valid for aircraft conceptual design.

The component estimates show that the airframe is overestimated while engine underestimated. Both total cost estimates are close to the actual costs with around 6% error.

8 Case Study

In this chapter, the acquisition cost of baseline aircraft defined in group design project (GDP), Flying Crane, is estimated using developed CERs to present a case study. Based on the case, the sensitivity studies are conducted for in-depth understanding.

8.1 Facts of Flying Crane

A baseline aircraft, Flying Crane, has been defined in the group design project focusing on aircraft conceptual design. Its main parameters and performances are determined with trading-off between several alternative concepts. See appendix A for an abridged report of the GDP.

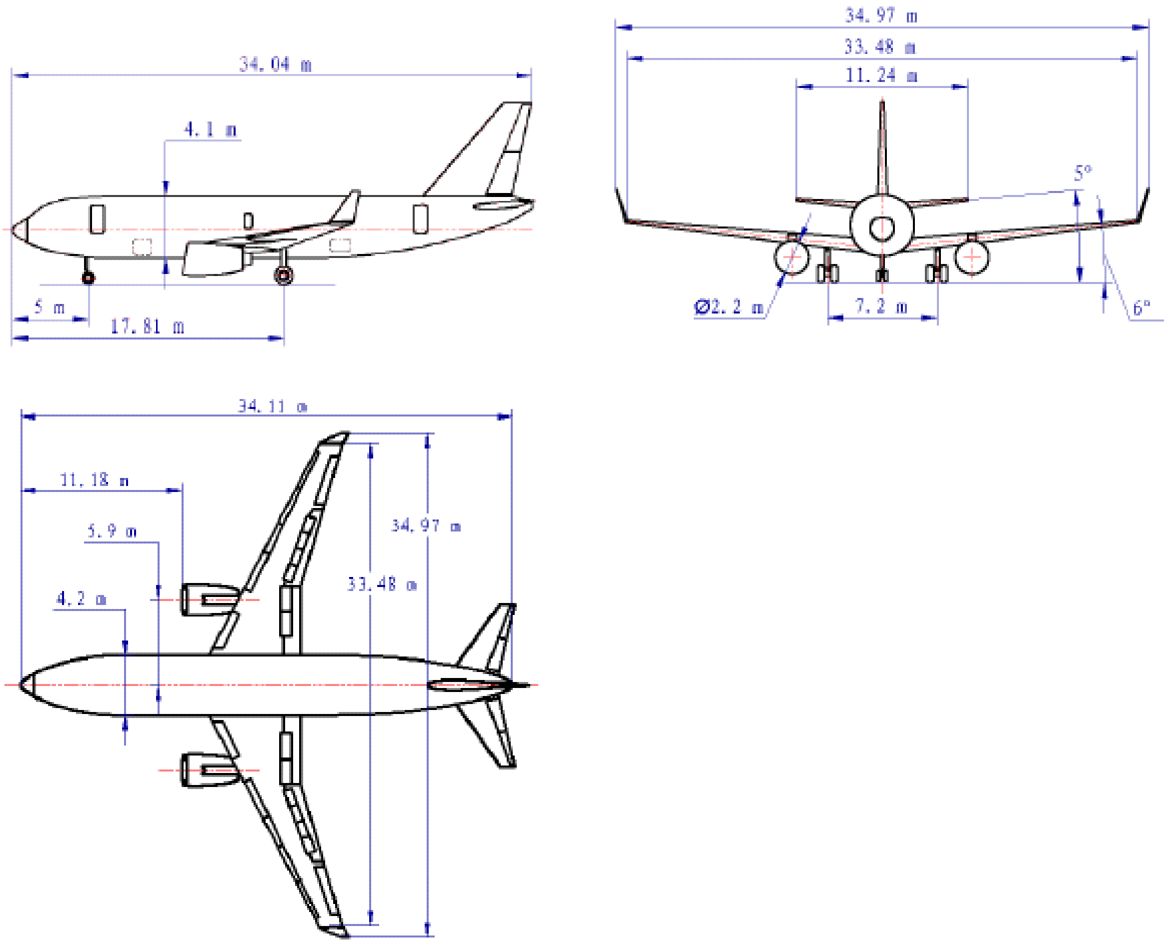


Figure 8.1 – Three-View of Flying Crane

Cost related parameters are listed below:

Table 8.1 – Parameters of Flying Crane

Aircraft Parameters	
Maximum Passenger capacity	128 (two-class)
Maximum take-off mass	64,582 kg
Operational empty mass	37,844 kg
Range	2,000 miles + Reserves
Max. Speed	447.38 knot (828.54 km/h)
Wing span (winglet not included)	33.48 m
Propulsion Parameters	
Maximum Thrust	100.74 kN
BPR	8
SFC	0.53 lb/lb*hour
Inter Turbine Temperature	900°C
Maximum Mach Number	0.8

8.2 Analogy

It is easy to find similar aircraft for analogy estimating. Here A319 and B737-700 are selected.

Table 8.2 – Analogy Aircraft for Flying Crane

Aircraft	A319	B737-700
Seat (typical 2-class)	124	134
OEM(kg)	40,160	38,147
MTOM(kg)	64,400	60,330
Actual Cost($M)	70.3	62.3

Since Flying Crane is to be manufactured in China, all adjustment factors are determined based on the particular conditions of aerospace industry in China. See Table 8.3 for values of adjustment factors and the estimates:

Table 8.3 – Analogy Estimates for Flying Crane

Proposed Aircraft			Flying Crane	
Analogy Estimate($M)			Based on A319($70.3M)	Based on B737($62.3M)
			58.69	52.01
Adjustment Factor	Structure	Labour Rate	0.5	0.5
		Overhead	1.1	1.1
		Investment	1.1	1.1
		Material	1	1
	Global	Technology	0.8	0.8
		Difficulty	1.1	1.1
		PPI Ratio	1	1

With lower labour in China, the acquisition cost of new 150-seat civil aircraft is 16.5 per cent lower than that of A319 or B737-700.

Taking costs from other source ($59M for A319 and $56.5M for B737-700) into account, the lower estimate is chosen as the final result because the cost of B737 is more reasonable for deals.

8.3 Parametric

8.3.1 Aircraft

The cost explanatory parameters: seat, wingspan, OEM, and MTOM are input and the result is $ 61.47 million.

The estimate is very close to both the actual cost ($ 62.3M) and estimated cost ($ 62.24M) of B737-700. And it is easy to understand, especially cost-related parameters of both aircraft are compared as below:

Table 8.4 – Flying Crane vs. B737-700

Aircraft	Flying Crane	B737-700
Seat (two-class)	128	134
Wingspan(m)	33.48	34.31
OEM(kg)	37,884	38,147
MTOM(kg)	64,582	60,330
Actual Cost($M)	NA	62.3
Estimated Cost($M)	61.47	62.24

In fact, B737-700 is one of two sample aircraft for comparison and trading-off in group design project (the other one is A319), which are selected once the size of proposed aircraft is decided.

8.3.2 Components

Knowing that Flying Crane is to be designed and manufactured in China, some parameters and factors are adjusted according to the actual situation in China's aerospace industry, mainly the labour rates, the difficulty factor, and investment factor considering lack of developing such a large aircraft.

With parameters given in table 8.1, the costs of major components are:

Table 8.5 – Components Cost of Flying Crane

Aircraft	Flying Crane
Airframe Cost($)	22,735K
Structure Cost($)	17,488K
Material Cost($)	11,134K
AMPR Weight(lb)	44,539.73
Price($/lb)	10.00
Utilization Factor F_u	5.00
Price Factor F_m	5.00
Labour Cost($)	2,762K
Engineering	
Hour	8,870.78
F diff	1.50
F CAD	0.80
Rate($/h)	40.00
Cost($)	354K
Manufacturing	
Hour	106,534.44
Rate($/h)	20.00
Cost($)	2,130K
Quality Cost($)	277K
QC Factor	0.13
Overhead Cost($)	2,762K
OH Factor	1.00
Investment Cost($)	828K
Investment Factor	0.30
Miscellaneous Cost($)	5,246K
Mis. Factor	0.30
Engine Cost ($)	9,808K
Unit Cost($)	4,904K
Number of Engines	2
Avionics Cost ($)	9,786K
Base Kit Cost($)	1,740K
Proportion	0.80
Avionics Hardware($)	2,175K
F_{avi-sw}	2.00
F_{avi-d}	0.50
F_{avi-i}	1.00
$F_{avi-diff}$	1.00
Profit($)	4,832K
Profit ratio	0.10
Aircraft Cost($)	47,033K

The final acquisition cost of Flying Crane is $ 47.03M, 25 per cent lower than that of B737-700 mainly because of lower labour rates.

8.4 Sensitivity Study

8.4.1 Labour Rate Sensitivity

There is great disparity of 23 per cent between the acquisition costs derived from aircraft model and components model respectively. The main reason is obvious: the aircraft cost model is based on sample aircraft manufactured in western countries, using the western labour rates.

On the other hand, the estimate of component model is 10% lower than that of analogy model ($47.03M to $52.01M) though low labour rates are introduced into analogy model; and presents more cost details to managers and designers.

If using western labour rates (which can be found in chapter 5) in components cost model, the estimated acquisition cost of Flying Crane is $ 59.36M, very close to that of aircraft cost model ($61.47M). It addresses that both aircraft and component CERs are reasonable and can be accepted for early study.

As to analogy CER, the sensitivity of labour rate ratio is presented as below. The base is the labour rate in western countries as the analogy sample is B737-700 of Boeing Company.

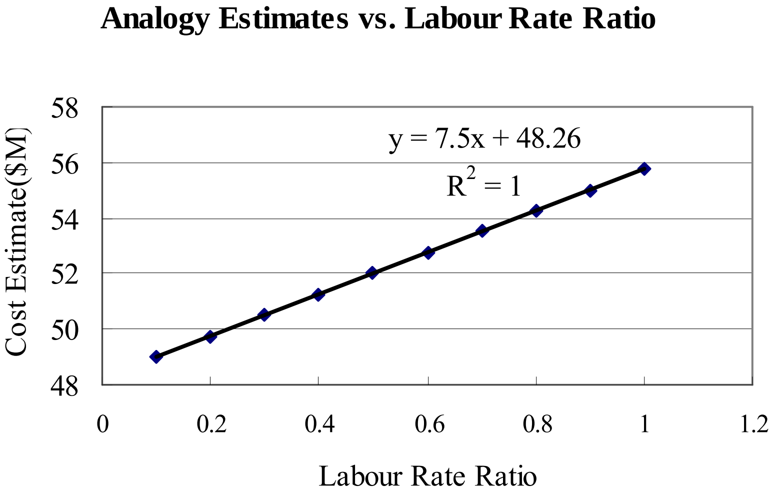


Figure 8.2 – Labour Sensitivity of Analogy Cost Model

With assumption of engineering labour rate is two times of manufacturing labour rate, the labour sensitivity of components cost model can be illustrated as figure 8.3 shown:

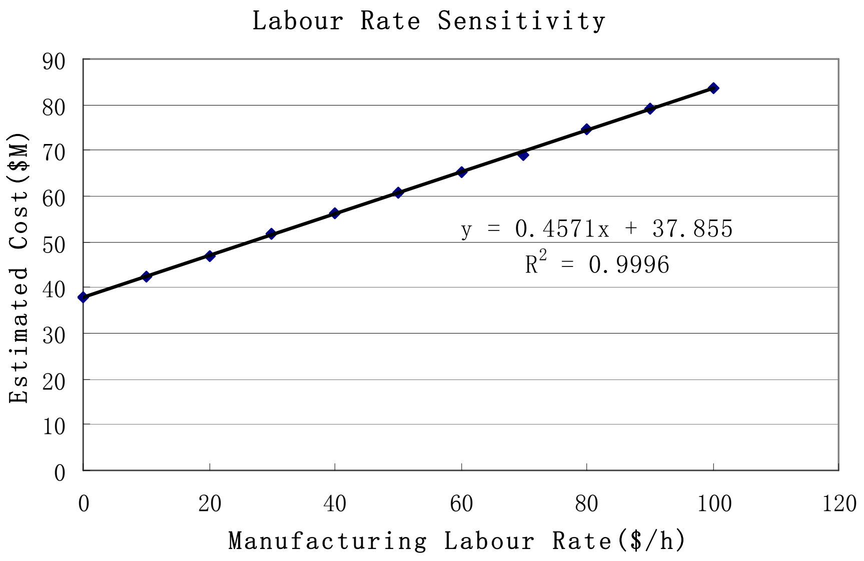


Figure 8.3 – Labour Sensitivity of Components Cost Model

The regressed equation means that every one dollar increase of labour rate will cause 457,100 dollars increase of acquisition cost.

8.4.2 Production Volume

Production volume, i.e. total number of production during the life cycle, will impact the unit acquisition cost significantly because the development cost are to be partook by all sold aircraft and consequently will decrease as number increases.

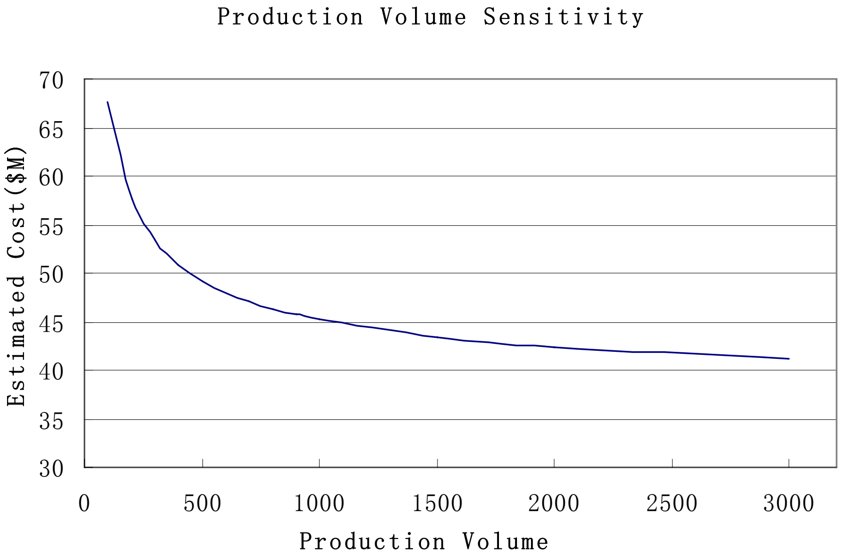


Figure 8.4 – Production Volume Sensitivity of Components Cost Model

As shown in the figure 8.4, the unit acquisition cost drops down dramatically when production number climbs to 500; and then the impact of volume starts getting weak while the cost is closing to the bottom line.

Therefore, the market needs to be analysed to predict programme volume based on market forecasting and possible share.

8.4.3 Others

Otherwise, some other factors will influence the acquisition cost as well but are not reflected within the model. They should be considered when possible.

8.5 Summary

Three estimated costs are derived using developed methodologies. Although they are not the same and some are even 20 per cent higher than others, the connection can be identified considering the principle of each method.

For analogy estimate, adjustment factors are introduced to reflect the different conditions of manufacturer in China. However, those subjective factors represent differences roughly just according to experiences or knowledge, which heavily depend on judgements. Any small change will be scaled-up in the final estimate.

As to the aircraft cost model, all explanatory variables in equation are related only to aircraft itself, can not reflect the different environment so that a B737-like cost estimate is derived. It is not satisfy when manufacturer is changed.

The last one, cost model for aircraft component, is a combination methodology of both analogy and parametric approaches. It can provide detail information about cost elements and distributions. Some are based on quantitative parameters of actual aircraft while other are determined qualitatively. The negative impacts of each approach are offset by the other. Consequently, the estimate is more reliable. Meanwhile, many cost reducing measures can be conducted purposively.

9 Discussion and Recommendation

This chapter is to discuss acquisition cost estimating methodologies developed above and highlight key points concluded from research. Then the conclusion is given as well as the future works are addressed.

9.1 Discussion

9.1.1 Investigation

The results of questionnaire indicate that the main problem in Asian aerospace industry is lack of an appropriate cost estimating system, especially a cost system covering both engineering and manufacturing. With respect to manufacturing, bottom-up approach can be used to predict costs as detail information are available. However, it is too late for the whole programme. Cost estimates should be produced at the early stage for DFC. But without own historic actual cost database, analogy associated with expert judgement became the most widely-used approach for most companies considering only one large transport aircraft (Y-10) was developed in 1970s throughout the Asian aircraft history.

Although some existing CERs can be applied, e.g. the CERs of Roskam and Burns, the cost estimates can not fit the particular practice as mentioned in previous chapters, especially within a totally different environment such as China.

Most interviewees have limited knowledge about cost estimation. Besides work experiences, it is somewhat because of absence of system and procedures in a company.

9.1.2 Explanatory Variables

9.1.2.1 Aircraft Model

The weight is the most regular explanatory variable in historical aircraft CERs. However, the new CERs are about not only weight but also size, which is new to aircraft CERs; while speed, another regular variable, is eliminated.

As shown in table 7.2, the VIP of wingspan takes the second place among four variables, which shows that size of aircraft is highly related to the acquisition cost mathematically although weight can represent the size largely as found in section 7.1.1.

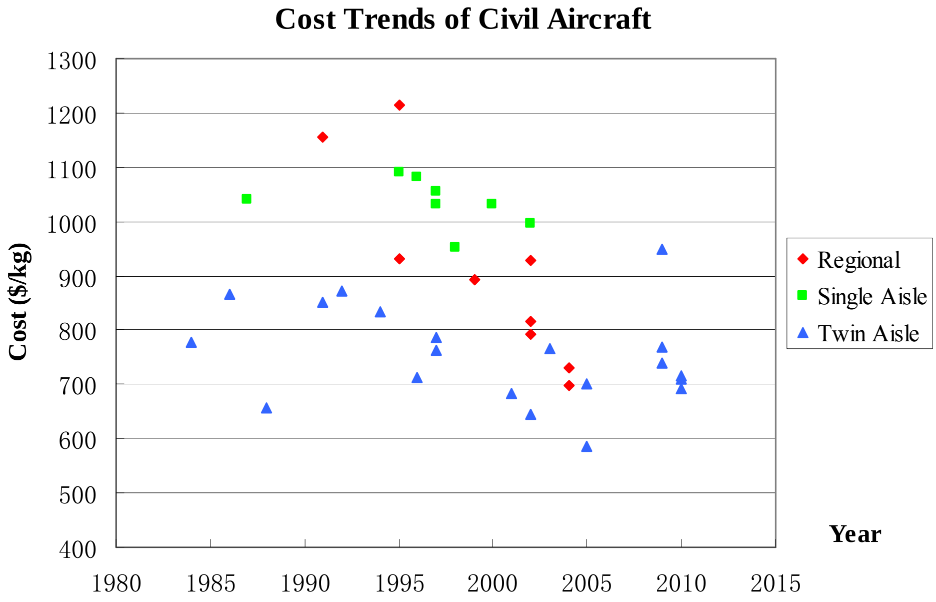


Figure 9.1 – Cost Trends of Civil Aircraft

It can be seen from figure above that the trends of acquisition cost per unit weight are decreasing, which somewhat weaken the impacts of weight on cost as new technologies are introduced mainly to reduce weight and consequent fuel consumption. Therefore, size is becoming an important parameter for cost estimating especially at an early stage.

Speed is eliminated during the statistical analysis mainly because all samples are with the same mission and similar speed while existing CERs are primarily based on a large number of aircraft including both military and civil aircraft. Hence, their speed varies with their missions and can represent the cost.

Production volume is another important variable in existing CERs. However, it is not found related to cost statistically in the research and only appears in component model using existing CERs for development cost due to lack of industrial data. Nowadays, the price largely depends on market prices of competitors rather than own actual cost and profit. Therefore, the possible market share must be predicted to see whether it is profitable or not. That is also one part of decision making at early stage.

Normally, passenger capacity is decided at the very beginning based on market forecasting and possible share. Once the baseline is determined, the acquisition cost is consequently restricted in a narrow range: regional, single aisle, or twin aisle; and variants' cost vary based on the baseline cost. However, it will not help designers optimizing the design as expected because both width and length of cabin will be defined once baseline configuration is determined and are hard to be changed.

Wingspan is a better explanatory parameter than seat because it can be related to many other design parameters, e.g. wing area, wing loading, aspect ratio, and lift. So it is possible to utilize this parameter for DFC (Design For Cost). With trading-off between various alternatives, there are lots of works to do for selecting proper wingspan associated with other performances.

9.1.2.2 Component Model

For airframes, no new variables are identified in material and labour cost model because existing CERs are used due to lack of actual data,. Overhead and investment costs are estimated based on labour cost for the same reason.

Overhead cost normally varies with policies of manufacturers and consequently is hard to predict. Since all administration actions are for real production, it is reasonable to generate estimate from labour cost; and it is also the regular method in industrial accounting. Production volume and rate will impact investment cost largely. However, the former one was eliminated during the regression while the latter one not treated as variable for cost estimating. They should be studied as programme processing and production data becoming available.

As to engine cost model, five independent parameters are identified and all of them were already revealed by existing researches. The research emphasizes these parameters again with turbine engines for commercial aircraft.

Avionics is predicted with judgement because of lack of actual data. Although it is validated, the estimating should be conducted carefully for the uncertainty.

In fact, the best solution for engines and avionics is getting cost estimates from suppliers.

9.1.3 Database

To a great extent, the similarity of samples will determine the accuracy and reliability of estimates. A jet's cost certainly can not be estimated based on turboprops though their airframes are similar; and cost of a light aircraft with 2 seats is not comparable to that of large aircraft with more than 100 seats. Thus, choosing appropriate sample products is the key of building up a suitable database and generating reliable models.

In this research, cost CERs are developed based on 37 active commercial aircraft ranging from regional aircraft to large transports, which are different from historic researches and then produce different explanatory variables. In fact, many samples are variants developed from the baseline, which is the most common solution to reduce cost and meet different capacity requirements; and consequently are not representative independently. But if only baselines are considered, the size of database is much small that will go against cost estimating. Thus, improvement can only be achieved by collecting more actual data from industry throughout the database maintenance, especially after the particular cost pattern is recognized.

That is the reason why cost models provided by consultants or academies can not fit the industrial practice and one own cost system is required for a specific producer.

9.1.4 Cost System

With adequate historical data of past like products, it is convenient to derive the cost estimating relationships by suitable approaches such as regression method used in the research. However, existing products may not be appropriate for other developers due to the limited public data and particular manners of manufacturers. A cost estimating system is essential to overcome these difficulties.

It can be learned that a universal cost model is not achievable. Particular database and proper approaches are the basis of a specific cost system in unique environment. Any existing CERs can provide only guidance and reference for a specific manufacturer.

The results of this research can be used as start point of building up such a cost estimating system. In following stages, estimates should be validated using actual costs; databases must be updated with real data; and approaches are to be improved with the learning. Then the particular pattern can be recognized and both the database and approaches can be integrated for a satisfied cost estimating system.

In fact, cost estimating is not a simple process of applying certain methods but a complex system comprising of approaches, data, validation, analysis, and endless updating. Then, a simple cycle of cost estimating system can illustrated as shown in figure 9.2.

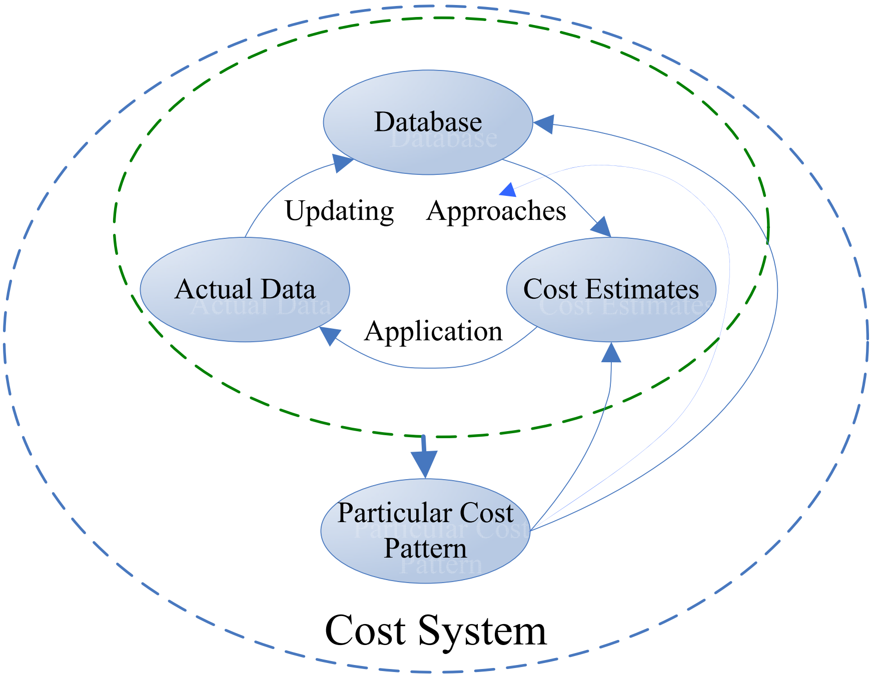


Figure 9.2 – Cost System Cycle

9.1.5 Uncertainties

As judgements are used in both analogy and parametric approaches, uncertainties are introduced to CERs and estimates. It is difficult to avoid uncertainties as many facts are unknown or unsecured at beginning of programme. But uncertainties can be gradually reduced by updating database once actual data become available.

9.1.6 Other Impacts

9.1.6.1 Labour Rate

It can be identified from table 7.3 that the most significantly overestimated aircraft are ERJs from Embraer based in Brazil. The reason can be discussed to be the lower labour rates in Brazil though there are no evidences to prove. It is reasonable because labour rate is not represented in the final CER which mainly is based on aircraft manufactured by western countries.

The validation can somewhat prove the significance of labour rate. In analogy method, the acquisition cost of aircraft will decrease by nearly 20 per cent when half labour rates are applied. As to parametric method, the reduction is the same, which also validated the analogy method. Therefore, a simple relationship can be found:

$$\text{Acquisition Cost} = \text{Base Value} + \text{Slope} * \text{Labour rate}$$

where the Base Value and Slope vary with aircraft's size.

In addition, labour will also affect the trade-off for design complexity because easier designs will reduce the total labour cost of both design and manufacturing by being performed by less-skill persons.

9.1.6.2 New Technology

Technology is qualitative feature and hard to be represented quantitatively in mathematical equations. Using subjective judgement is the normal way to account for the impact of it. As the result, the risk and uncertainty are both high just as mentioned in literature, 32.3 percent cost increase will be caused by immature technologies (Kennedy, 2008).

Thus, the technology level must be determined and then quantitated at beginning of programme for not only cost estimating but also risk analysis.

9.1.6.3 Others

Impacts of qualitative variables, e.g. production efficiency, can be reflected through judgement or after particular pattern and clear correlations are identified. Sometimes, quantitative variables are difficult to be predicted as well; for instance, learning effect will not remain the same trend if workers are being changed.

9.1.7 Design For Cost (DFC)

At aircraft conceptual design phase, the objective is to select a satisfied concept for proposed aircraft. With derived cost models and identified cost-related features, managers and designers can employ effective measures for DFC. And it will help to make decision when trading-off between alternatives.

9.2 Recommendation

9.2.1 Database

It can be learned that the database will determine the approaches and the estimates' accuracy and reliability. Without own historic projects, available data of other manufacturers' aircraft can be used as a start point for establishing an own database. However, the database must be updated once actual data becomes available.

After establishment, maintenance of the database becomes the main regular work for database. All actual data should be added or updated as programmes moving forward. And it is recommended to be carried out under the control of procedures which are parts of a system.

9.2.2 Cost Estimating Methodology

It is chosen according to the availability of data as reviewed in literatures. The research revealed that a combination of several approaches is more practical and consequently reliable for early stages with limited information.

The cost models developed in the research can be applied to aircraft conceptual design if there is no other choice. Also, they can be modified to match particular conditions in specific companies. The idea and process presented in the thesis can help to develop CERs with different data though the models are restricted by limited data.

Likewise, the methodology may be particular as well since each manufacturer has its own pattern on programmes. So it should not be limited in the range of existing approaches and to be developed based on specific situation in certain companies.

9.2.3 Cost Personnel

Cost estimator is another important factor in a cost estimating system besides database and methodology. Cost estimators should be familiar with both cost estimating and technical things including engineering and manufacturing. That is also the reason why experts are needed. Experience sometimes is more important than figures in database, e.g. when no appropriate data can be derived from past products. Even the artificial intelligence can not take the place of human brain.

Training programmes are also required by estimators to learn cost-related techniques and engineering knowledge. Cost estimator with experience on engineering or manufacturing can produce more practical estimates as they are the experts.

9.2.4 Cost Estimating System

The achievements of this research can be used to be reference for establishing a cost estimating system for a specific aircraft manufacturer. However, it is only the start point of a complex cost system and should be improved gradually as cost database is updated and methodology is developed at the same time.

Procedures and regulations are required to keep the system running for a long time because both database maintenance and methodology development are time-consuming. In addition, records of cost estimating are also important to track estimates and methods.

A dedicated cost estimating department is recommended to cope with cost-related issues including database, methodology, consultation, organization, and coordination for new projects.

9.2.5 Future Research

Although several aircraft acquisition cost estimating methods are developed through the research, these CERs need to be improved with actual data as more details become available in following stages. An industrial cost system is required to maintain the database and then identify particular patterns of a specific company. Otherwise, more approaches are to be developed for not only conceptual design phase but also other phases throughout the lifespan.

Therefore, the future work will be centred on the cost estimating system accompanied with cost estimating methodologies for all stages during the life cycle of civil aircraft, especially design and production stages from a manufacturer's perspective.

10 Conclusion

Due to limited information at early stage, analogy and parametric approaches are selected to develop CERs for aircraft acquisition cost.

Then, a cost estimating process is presented by the research. As the achievements, some cost models are developed to predict acquisition cost with limited information at aircraft conceptual design phase.

Analogy method can provide cost estimates just after aircraft class is defined and data of similar products are collected. All differences are adjusted with judgement factors considering changes of time, technology, region, and etc. However, for a manufacturer without own products, it is impossible to grasp the pattern from other manufacturers' products and then produce sound estimates. The analogy estimates help to make programme forecasting according to existing aircraft and present market; but few further works can be deployed for following design stage because it can not reflect the impacts of quantitative variables, which are essential to designers for DFC. Therefore, analogy method is suitable for managers who need to decide what kind of aircraft to be developed, know how much it will likely cost, and predict the financial performance of programme, especially when quick forecasting is required.

As to parametric method, several explanatory variables are figured out for commercial aircraft and jet engines separately. Some of them have been addressed by existing achievements, e.g. weight, thrust, and BPR; while others are new to CERs, e.g. seat and wingspan. Meanwhile, speed, as a common explanatory variable in most CERs, is eliminated during the process of regression because all aircraft sample have similar speed so that it is not meaningful statistically. With two validation aircraft from different classes, these CERs are valid with relatively high accuracy; and then can be used at aircraft conceptual design phase. In case study, cost estimates are presented for a potential new aircraft that will be manufactured in China, which also calibrate the cost models.

Also, it is beneficial to learn the impacts of explanatory parameters on cost for design trading-off as they have significant impacts on cost and cost has became a vital design driver. All identified parameters and their impacts can guide the design as well as help engineers to trade-off in conceptual design. With these parameters, in-depth study can be conducted to optimize design and make balance between performance and cost.

Although the analogy and parametric approaches are developed separately, it is inevitable to use analogy in parametric to judge unknown data. It is common in practice because it is difficult to make accurate estimates using only one method. Also, the estimates need to be crosschecked by other approaches. Therefore, the combination of analogy and parametric approaches is a suitable and reliable method to fulfil the objectives of this research. With several design parameters of concepts and existing samples, the variety trend of cost can be revealed by the cost models.

The achievements can be used as a start point of a cost estimating system in a company who is new to the area of proposed aircraft. The system will be improved as programme processing and more information become available. Of course, more methodologies are to be developed to make detail cost estimates for components or activities.

In addition, the importance of database can be recognized from the research. As discussed above, the developed cost models vary with the database largely, e.g. speed is eliminated because all samples are civil subsonic aircraft with similar speed, so that speed does not make sense in the equations; and likewise, weight will not explain the cost as well if aircraft in the same class are used as samples.

References

Andrade, M. C., Pessanha Filho, R. C., Espozel, A. M., Maia, L. O. A., Qassim, R. Y., (1999), “Activity-Based Costing for Production Learning”, International Journal of Production Economics, 62 (1999), pp. 175-180

Apgar, Henry, (2001), “Cost as An Independent Variable (CAIV): A Process and Methodology to Acquire and Operate an Affordable System by Setting Aggressive Life Cycle Cost Targets and Trading off Performance, Cost, and Schedule”, AIAA 2001-4674

Apgar, Henry, (2004), “Gaining Approval for Your Parametric Estimating System”, AIAA 2004-6014

Asiedu, Y. and Gu, P. (1998), "Product life cycle cost analysis: state of the art review", International Journal of Production Research, Vol. 36 No.4, pp.883-908.

Beltramo, Michael N., (1988), “Beyond Parametrics: The Role of Subjectivity in Cost Models”, Elsevier: Engineering Costs and Production Economics: An International Journal for Industry, 14 (1988), 131-136.

Ben-Arieh, D., “Cost Estimation System for Machined Parts”, International Journal of Production Research, 2000, VOL.38, No. 17, pp. 4481-4494

Birkler, J. L., Garfinkle, J. B. & Marks, K.E., (1982), “Development and Production Cost Estimating Relationships for Aircraft Turbine Engines”, N-1882-AF, Rand Corporation, Oct 1982

Burns, J. Wayne, (1994), “Aircraft Cost Estimation Methodology and Value of a Pound Derivation for Preliminary Design Development Applications”, 53rd Annual Conference of Society of Allied Weight Engineers, Inc., Long Beach, CA, 23-25 May 1994, SAWE Paper No. 2228, Category No. 29

Butterfield, J., Mawhinney, P., (2005), “An Integrated Approach to the Conceptual Development of Aircraft Structures Focusing on Manufacturing Simulation and Cost”, AIAA 2005-7355

Castagne, S. and Curran, R., (2004), “A generic tool for cost estimating in aircraft design”, AIAA 2004-6235

Cavalieri, S., Maccarrone, P., and Pinto, R., (2004), “Parametric vs. Neural Network Models for the Estimation of Production Costs: A Case Study in the Automotive Industry,” Int. J. Prod. Econ., 91(2), pp.165–177

Choi, Jin-Woo, Kelly, Don, Raju, John, (2007), “A knowledge-based engineering tool to estimate cost and weight of composite aerospace structures at the conceptual stage of the design process”, Aircraft Engineering and Aerospace Technology: An International Journal, 79/5 (2007), pp. 459–468

Christensen, Peter, Dysert, Larry R., (2005), “Cost Estimate Classification System – as Applied in Engineering, Procurement, and Construction for the Process Industries”, TCM Framework: 7.3 – Cost Estimating and Budgeting, AACE International Recommended Practice No. 18R-97, Feb 2nd, 2005

Cotter, Jarrod and Blackah, Paul, (2008), “Lancaster – Owners’ Workshop Manual”, Haynes Publishing, ISBN 978 1 84425 463 7, April 2008

Crosby, S., Kundu, A.K., Curran, R., Raghunathan, S., (2003), “Fabrication and Assembly Cost Drivers for Aircraft Manufacturing”, AIAA 2003-6827

Curran, R., Raghunathan, S., Kundu, A.K., Crosby, S., Shields, P., Eakin, D., (2002), “Competitive Aircraft Design and Manufacture”, AIAA 2002-5852

Curran, R., Raghunathan, S., (2004), “A Methodology for Integrated Cost Engineered Systems within Aerospace”, AIAA 2004-6207

Curran, R., Castagne, S., (2005), “Integrating Manufacturing Cost and Structural Requirements in a Systems Engineering Approach to Aircraft Design”, AIAA 2005-2068

Cyr, Kelley, (1994), “Cost Estimating Methods for Advanced Space Systems”, N95-20741,Readings in Program Control, p 15-24, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950014324_1995114324.pdf, accessed on September 19, 2008

Dalkey, Norman C., (1969), “The Delphi Method: An Experimental Study of Group Opinion”, RM-6115, Rand Corporation

Dean, Edwin B., (1995), “Parametric Cost Deployment”, Technical Report: NASA-qfd-95-p27

De Cos, Javier, Sanchez, Fernando, Ortega, Francisco, Montequin, Vicente “Rapid Cost Estimation of Metallic Components for the Aerospace Industry”, International Journal of Production Economics, 112(2008), pp. 470–482

Ditto, William Joel, (1985), “Cost Estimating Relationships for Fixed Wing Aircraft: List Price Vs Empty Weight”, AD-A164 196, Technical Memorandum TM 85-F-7, September 1985

DoD (Department of Defense), (1992), “Cost Analysis Guidance and Procedures”, DoD 5000.4M, December 1992, pp.31.

Duverlie, P., Castelain, J. M., (1999), "Cost Estimation during Design Step: Parametric Method versus Case Based Reasoning Method", Journal of Advanced Manufacturing Technology 15, pp. 895-906

Evans, D.K., Lanham, J.D., Marsh, R., (2006), "Cost Estimation Method Selection: Matching User Requirements and Knowledge Availability to Methods", University of the West of England, Bristol, 2006

Farag, M. M., EI-Magd, E., (1992), "An Integrated Approach to Product Design, Materials Selection and Cost Estimation", MATERIALS & DESIGN, Vol. 13, No. 6, 1992

Fielding, J.P., (1999), "Introduction to Aircraft Design", Cambridge Aerospace Series (No. 11), Cambridge University Press, October 1999

Forsberg, S.L. and Kelvesjö, S. M. Plantin, (1999), "CER Development for Aircraft Engineering", Cranfield Research Report: CRAN-EI/2000/RR/1, Cranfield University, 1999

Fox, Bernard, Boito, Michael, Graser, John C., Younossi, Obaid, (2004), "Test and Evaluation Trends and Costs for Aircraft and Guided Weapons", Rand MG-109, Rand Corporation, 2004

Gates, Jim, Greenberg, Marc, (2006),"Cost Estimating Methodologies (teaching note of Defense Acquisition University)", https://acc.dau.mil/GetAttachment.aspx?id=30373&pname =file&aid=5379&lang=en-US, accessed on June 14, 2008

Gayretli, A. and Abdalla, H.S., (1999), "A Featured Based Prototype System for the Evaluation and Optimization of Manufacturing Processes", Comput. Ind. Eng., 37, pp.481-484

Gunston, Bill, (2006), "Jane's Aero-Engines", Issue 20, Jane's Information Group, September 2006

Hamaker, Joe, (2006), "NASA Cost Estimating with Emphasis on the Exploration Systems Architecture Study", NIA/SACD Distinguished Lecture Series in Systems Analysis, National Institute of Aerospace, February 10, 2006

Hamilton, John L., (1968), "Life Cycle Cost Modelling", AD TECH REPORT 68-8, Systems and Cost Analysis Division, Comptroller and Director of Programs, US Army Materiel Command, Washington, D.C. 20315, DEC 1968

Hatry, Harry P., (1966), "Statistical Cost Estimating Relationships-some basic issues (Aircraft Examples)", TP66-3, Office of the Assistant Sectary of Defense (Systems Analysis)

Hess, R. W., Romanoff, H. P., (1987), "Aircraft Airframe Cost Estimating Relationships - Study Approach and Conclusions", R-3255-AF, Rand Corporation, Dec 1987

Hicks, B. J., Culley, S. J., Mullineux, G., (2002), "Cost Estimation for Standard Components and Systems in the Early Phases of the Design Process", Journal of Engineering Design, 2002, Vol. 13, No.4, pp. 271-292

Jackson, Paul, (2006), "Jane's All the World's Aircraft (2006-2007)", Jane's Information Group, 2006

Jenkinson, Lloyd R., Simpkin, Paul and Rhodes, Darren, (1999), "Civil Jet Aircraft Design", AIAA Education Series, 1999, ISBN-10: 1-56347-350-X, ISBN-13: 978-1-56347-350-0

Kankey, Roland D., (2007), "Cost Estimating", www.dau.mil/regions/Midwest/docs/2007%20 STL%20Acq%20Ins%20Day%20--%20Cost%20Estimating.ppt, accessed on Aug 9th, 2008

Kaplan, Robert S., (1988), "One Cost System isn't Enough", Harvard Business Review, January-February 1988, pp. 61-66

Kaufmann, Markus, (2008), "Cost/Weight Optimization of Aircraft Structures", Licentiate Thesis, 2008,http://www.diva-portal.org/diva/getDocument?urn_nbn_se_kth_diva-4645-3__fulltext.pdf, accessed on June 1st, 2008

Kennedy, Ken and Golden, Kristy, (2008), "Acquisition Cost Estimating Update", http://www.ndiagulfcoast.com/events/archive/event_05182008/AcquisitionCostEstimatingUpdatebyMsGoldenandMrKennedy.ppt, accessed on June 24th, 2008

Koelle, D.E., (1994), "Space Launch Systems Cost Estimation as Design Tool", Acta Astronautica Vet. 34, pp. 175-181, 1994

Koonce, David, Judd, Robert, Sormaz, Dusan, Masel, Dale T., (2003), "A Hierarchical Cost Estimation Tool", Computers in Industry, 50(2003), 293–302

Kroo, Ilan, (2006), "Aircraft Design: Synthesis and Analysis", Version 1.2(September 2006), Copyright 1997-2006 by Desktop Aeronautics, Inc., http://adg.stanford.edu/aa241/AircraftDesign.html, accessed on 14th June, 2008

Kundu, A. K., Curran, R., Crosby, S., Raghunathan, S., (2002), "Rapid Cost Modelling at the Conceptual Stage of Aircraft Design", AIAA 2002-5853

Kundu, A. K., Raghunathan, S. et al., (2003), "Cost Modelling as a Holistic Tool in the Multi-Disciplinary Systems Architecture of Aircraft Design - The Next Step 'Design for Customer' ", AIAA 2003-1333

Kwak, Young Hoon, Watson, Rudy J., (2005), “Conceptual Estimating Tool for Technology-driven Projects: Exploring Parametric Estimating Technique”, Technovation 25 (2005), pp. 1430-1436

Large, Joseph P., (1976), “Parametric Equations for Aircraft Airframe Costs”, R-1693-1-PA&E, Feb. 1976

Lee, Joosung Joseph, (2000) “Historical and Future Trends in Aircraft Performance, Cost, and Emissions”, MSc. Thesis, B.S. Mechanical Engineering, University of Illinois at Urbana-Champaign, 2000

Lere, John. C., (2000), “Activity-Based Costing: a Powerful Tool for Pricing”, Journal of Business & Industrial Marketing, Vol. 15, No. 1, 2000, pp. 23-33

Levenson, G. S., (1966), “Cost-Estimating Relationships for Aircraft Airframes”, Reports Rand/RM-4845, 1966, Rand Corporation

Levenson, G. S., (1972), “Cost-Estimating Relationships for Aircraft Airframes”, R761-PR, Rand Corporation, Feb. 1972

Li, Shou'an, Song, Bifeng & Zhang, Hengxi, (2007), “Method for Multivariate Analysis with Small Sample in Aircraft Cost Estimation”, Journal of Aircraft, Vol. 44, No. 3, May-June 2007

Marx, William J., Mavris, Dimitri N., Schrage, Daniel P., (1995), “A Hierarchical Aircraft life Cycle Cost Analysis Model”, AIAA 1995-3861

Mauchand, M., Siadat, A., Bernard, A. and Perry, N., (2008), “Proposal for Tool-based Method of Product Cost Estimation during Conceptual Design”, Journal of Engineering Design, 19:2, pp. 159-172

Murman, Earll M., Hansman, R. John, Clarke, John-Paul, (2001), “Aircraft System and Product Development: Teaching the Conceptual Phase”, AIAA 2001-0866

NASA, (2004), “NASA Cost Estimating Handbook 2004”, http://www.ceh.nasa.gov/webhelpfiles/Cost_Estimating_Handbook_NASA_2004.htm

Nelson, J. R., Timson, F. S., (1974), “Relating Technology to Acquisition Costs: Aircraft Turbine Engines”, R-1288-PR, March 1974, Rand Corporation

Newnes, L. B., Mileham, A. R., Cheung, W. M., Marsh, R., Lanham, J. D., Saravi, M. E. and Bradbery, R.W., (2008), “Predicting the whole-life cost of a product at the conceptual design stage”, Journal of Engineering Design, 19:2, pp. 99-112

Newport, John R., (1994), "Avionics Systems Design", ISBN 0-8493-2465-3, CRC Press, Inc., Boca Raton, Florida 33431

Niazi, Adnan, Dai, Jian S., Balabani, Stavroula, Seneviratne, Lakmal, (2006), "Product Cost Estimation: Technique Classification and Methodology Review", Journal of Manufacturing Science and Engineering, MAY 2006, Vol.128, pp. 563-575

Ou-Yang, C. and Lin, T.S., (1997), "Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation," International Journal of Advanced Manufacturing Technology, 13(9), pp.618-629.

Pahl, G., and Beitz, W., (1996), "Engineering Design: A Systematic Approach", 2nd ed., Springer-Verlag, Berlin

Palmer, Adele R., Larson, Eric V., (1992), "Cost Factors in the Army, Volume 2 - Factors, Models and Methods", Rand R4078.2, Rand Corporation

Peffley, A.F., Hagen, J.E., and Bock, R.R., (1996), "A User's Manual for Developing Cost Estimating Relationships", NASA Contractor Report 194428, D658-10343-1, Aug. 1996

Price, Mark, Curran, R., Murphy, A., Raghunathan, S., Early, J., Castagne, S., Benard, E., Crawford, B., (2006), "Integrating Design, Manufacturing and Cost for Trade-offs on Aircraft Configurations", AIAA 2006-7739

Proffitt, J.T., (1994), "Life Cycle Costs of Aircraft Systems", Life Cycle Costing and the Business Plan, IEE Colloquium on Volume, Issue, 1 Feb 1994, Page(s):1/1 - 1/3

Pugh, P. G., (2004), "Concept Costing for Defence projects: the Problem and its Solution", Defence and Peace Economics, 2004, Vol. 15 (1), February, pp. 39-57

Raju J., (2003), "A Conceptual Design and Cost Optimization Methodology", AIAA-2003-1505, American Institute of Aeronautics & Astronautics, 44th AIAA/ASME/AHS Structures, Structural Dynamics and Materials Conference, Norfolk, Virginia, April, 2003

Raymer, Daniel P., (2006), "Aircraft Design: a Conceptual Approach", AIAA Education Series, Published by AIAA, © 2006, 4th Edition, New York, NY, 2006, ISBN 1-56347-829-3

Rehman, S. and Guenov, M. D., (1998), "A Methodology for Modelling Manufacturing Costs at Conceptual Design," Comput. Ind. Eng., 35(3–4), pp. 623-626.

Richey, Karen, Echard, Jennifer, Panwar, Madhav, (2003), "Training on Cost Estimation & Analysis", http://www.intosaiitaudit.org/COSTESTIMATION.ppt, accessed on July 31st, 2008

Roskam, Jan, (1990), “Airplane Design VIII: Airplane Cost Estimation: Design, Development, Manufacturing and Operating”, Roskam Aviation and Engineering, Ottawa, Kansas, 1990

Roy, Rajkumar, Christopher Seamus Rush, Tuer, Geoff, (2002), “Cost Estimating Rationale Capture”, 2002 AACE International Transactions. Morgantown, WV.

Roy, Rajkumar, Rush, Christopher Seamus and Gorroño, Valentin, (2003), “Cost Estimating Rationale Capture: Beyond the Aerospace Industry”, 2003 AACE International Transactions

Roy, Rajkumar, (2003), “Cost Engineering: Why, What And How?”, Decision Engineering Report Series, ISBN 1-861940-96-3, Cranfield University, July 2003

Roy, R., Souchoroukov, P. and Griggs, T., (2007), “Function-based Cost Estimating”, International Journal of Production Research, 46:10, pp. 2621 - 2650

RTO, (2007), “Methods and Models for Life Cycle Costing”, TR-SAS-054, Final Report of Task Group SAS-054, Research and Technology Organization, NATO, June 2007

Rush, Christopher, Roy, Rajkumar, (2000), “Analysis of Cost Estimating Processes used within a Concurrent Engineering Environment throughout a Product Life Cycle”, Proceedings of CE 2000 Conference, pp. 58-67

Rush, Christopher, Roy, Rajkumar, (2001), “Expert Judgement in Cost Estimating: Modelling the reasoning process”, Concurrent Engineering. 2001; Volume 9, No. 4, pp. 271-284

Sandberg, Marcus, Boart, Patrik, Larsson, Tobias, (2005), “Functional Product Life-cycle Simulation Model for Cost Estimation in Conceptual Design of Jet Engine Components”, Concurrent Engineering, Volume 13, Number 4, pp. 331-342, December 2005

Scanlan, Jim, Hill, Terry; Marsh, Rob, Bru, Christophe, Dunkley, Martin, Cleevely, Paul, (2002), “Cost Modelling for Aircraft Design Optimization”, Journal of Engineering Design, 2002, Vol. 13, No.3, pp. 261-269

Shishko, Robert, (2004), “Developing Analogy Cost Estimates for Space Missions”, AIAA 2004-6012, Space 2004 Conference and Exhibit, 28-30 September 2004, San Diego, California, USA

Shtub, Avraham and Zimerman, Yoav, “A Neural-Network-based Approach for Estimating the Cost of Assembly Systems”, International Journal of Production Economics, 32 (1993), pp. 189-207

Smith, Alice E. and Mason, Anthony K., (1997), “Cost Estimation Predictive Modelling: Regression versus Neural Network”, The Engineering Economist, 42:2, pp. 137-161

Souchoroukov, Petros, Roy, Rajkumar, Mishra, Keren, “Data & Information in Cost Estimating”, Presentation on SCEA 2002, Phoenix (Scottsdale), Arizona, USA, June 11th-14th, 2002

Stewart, Rodney D., Wyskida, Richard M., (1995), “Cost Estimator's Reference Manual”, 2nd edition, 1995, New York: Wiley Interscience, ISBN: 978-0-471-30510-1

Tammineni, S.V. and Scanlan, J.P., (2007), “Knowledge Based System for Cost Modelling”, AIAA 2007-7798, 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)
 2nd Centre of E, 18 - 20 September 2007, Belfast, Northern Ireland

Tan, Xincai, Xu, Yuchun, Early, Juliana, Wang, Jian, Curran, Richard, Raghunathan, Srinivasan, “A Framework for Systematically Estimating Life Cycle Cost for an Integrated Wing”, AIAA 2007-7809, 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)18 - 20 September 2007, Belfast, Northern Ireland

Tan, X, Xu, Y, Raghunathan, S., Gore, D., Doherty, J., (2008), “Cost of Aluminium for Life Cycle”, AIAA 2008-1123

Watson, P., Curran, R., Murphy, A., Cowan, S., Hawthorne, P., Watson, N., (2004), “A Cost Estimating Model for Aerospace Procurement: Pro-COST EST”, AIAA 2004-6237

Willcox, Karen, “Cost Analysis”, Course 16.885 - Aircraft Systems Engineering, MIT, 2004, http://ocw.mit.edu/NR/rdonlyres/Aeronautics-and-Astronautics/16-885JFall-2004/9DFE0985-C9C2-486B-BD37-42060E082AB2/0/pres_willcox.pdf, accessed on August 3rd, 2008

Young, Mike and Markley, Ted, (2008), “A Better Cost-Estimating Tool: The Key to Not Going Over Budget”, Defense AT&L, July-August 2008, pp. 24-27

Zack, James G., (2007), “Cost Estimating - A Dying Art?”, Cost Engineering Vol. 49/No. 1, January 2007

APPENDICES

A - GDP Report

Conceptual Design of a 130-Seat Civil Airliner Flying Crane

(Individual Report by Tienan Zhao)

Key words: Aircraft, Conceptual Design, Market, Design Drivers, Cost Estimating

Abstract

A civil aircraft named “Flying Crane” is produced conceptually by Group Design Project deployed by AVIC delegates. This report is to present the individual work accomplished in each phase of GDP.

1. Introduction

The Group Design Project is to go through the entire process of aircraft conceptual design, and then develop a conceptual design of an 80-150 seat commercial aircraft.

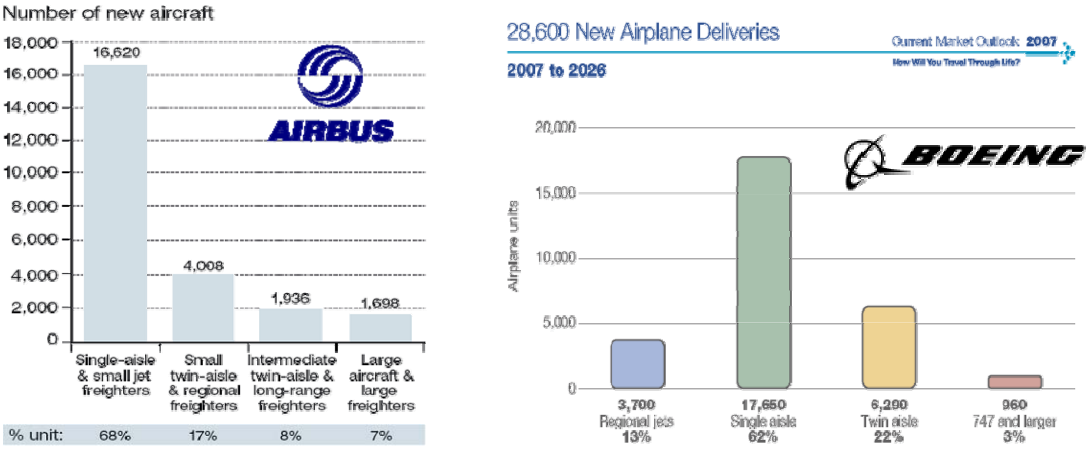
The whole conceptual design consists 4 phases as following:

- Derivation of Requirements
- Conceptual Design – Parametric Study
- Conceptual Design – Analysis
- Consolidation, Marketing and Final Review

2. Phase I – Level 1: Derivation of Requirements

The phase I is aiming to research manufacturer, operators, and potential customer in current air transport environment and not far future for launching a new aircraft programme. The individual objective is financial issue about aircraft acquisition, operation and global market.

The market forecasting of Boeing and Airbus indicate that single aisle aircraft will take the largest share of civil aircraft demanded in coming 20 years.



Source: Manufacturers

Figure 1 - Market Forecasting from Boeing and Airbus (2007)

With in-depth investment about current fleet, airlines, and financing methods, the situation of present airline industry has been learned for generating a proposal of a new transport aircraft.

3. Phase I – Level 2: Design Drivers

Many technical and non-technical factors will impact the design to different extent. These factors drive the new aircraft design move towards a certain direction. That is where the term "Design Drivers" comes from.

3.1 Market Location

Besides the seat class determined according to market forecasting, the target region, potential customers, and competitors are to be considered as well to define a market location for the new aircraft.

3.2 Direct Operating Cost

DOC is the most important and sensitive factor for airlines. It comprises of following elements:

- Standing charges (overhead of flight)
    - Depreciation of capital investment
    - Interest charges of capital
    - Aircraft insurance
- Flight costs
    - flight crew cost
    - fuel & oil cost, and
    - airport charges.
- Maintenance costs
    - Airframe (Labour & material)
    - Engine (Labour & material)

3.3 Environment issues

It requires reducing emissions mainly with weight reduction. Therefore designers are using more and more advanced materials in aircraft.

3.4 Acquisition Cost

Acquisition cost will impact the standing charges largely because operators need to finance the acquisition by loan or leasing, and is to be depreciated in serving years.

3.5 Developing Technology

Advanced technologies will increase the development cost and delay the schedule largely.

3.6 Available Facilities

It can be related to technology and cost because the decision of whether to update or replace existing facilities depends on the technologies used and costs of new facilities.

3.7 Time into Service

It is hard to say that the earlier one can take more market share; however, being earlier means having more time than competitors to deal with the market, improve design & production, and develop variants.

3.8 Labour

As a labour-intensive industry, labour cost accounts for a significant proportion in the acquisition cost.

3.9 Material Selection

Another issue about technology and cost. Using advanced material will reduce the weight, meanwhile, make manufacturing more costly.

4 Phase II - Conceptual Design: Parametric Study

In this phase, 24 delegates are divided into 4 groups to develop 4 specific aircraft separately. Each group is named by a kind of colour, namely Gold, Blue, Yellow, and Red.

The individual work in Blue team is to make cost estimation focusing on project's financial performances, i.e. the cost of development & production, price, DOC, and breakeven point using parametric approaches developed by Roskam (1990) and Burns (1994).

The final results with production volume of 1,000 are presented as below.

Table 1 - Cost Estimates

	Roskam	Burns
AMPR Weight (lb)	40,530	54,917.5
Speed	449.6kts	
RDT&E Cost($M)	1,424.01	1,527.63
Production Cost($)	49,287.94	47,191.04
Unit Price($)	50.71	52.65
Breakeven Number	252	290
DOC ($/mile)	12.38	N/A
DOC (¢/seat mile)	8.25	N/A

5 Phase III - Conceptual Design: Analysis

This phase is to select two designs from four options developed in phase II and then more detail calculation, developing and analysis will be conducted for in-depth research. In addition to parameters produced in prior phase, 3-view drawing, computer models, and other related more detailed works are necessary in order to facilitate final decision-making.

The Blue and Red team's designs are selected by scoring in various aspects, which were researched in Phase I, Level 2, and named as Jade and Amber respectively. Some primary performances of both designs are described as below. The difference between two aircraft is: Red aircraft has two aisles with wider fuselage while Blue aircraft has a traditional configuration.

Range	2000nm

Capacity	150 seats in single class
Cruise Speed	0.78 Mach

And the individual task is to generate the computer model for Blue aircraft using CATIA V5R17.

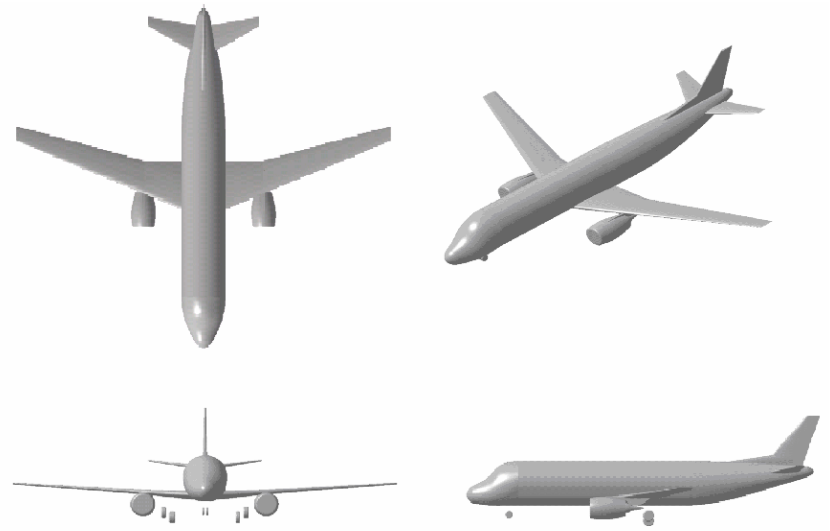


Figure 2 - CATIA Model of “Blue” Aircraft

6 Phase IV - Consolidation, Marketing and Final Review

This is the final phase of this-year group design project. Only one aircraft is selected for final consolidation and presentation.

The twin-aisle aircraft is chosen as the final decision. Then the cost estimates are recalculated with following parameters:

Maximum Take-Off Weight	64,582kg
Operating Empty Weight	36,949kg
Maximum Speed	447.38 knot (828.54 km/h)

Table 2 - Final Cost Estimates

AMPR weight	Estimated Unit Price($M)/Breakeven Number	
	Burns	Roskam
Burns	55.08/321	56.76/314
Roskam	49.32/259	51.71/264
Average	52.74/292	54.30/290
Final Estimate	53.52/291	

Also, the market is analysed with consideration of the innovation of twin-aisle configuration.

The width of fuselage is expanded to 4.2m while A319 is 3.95m wide and B737 NG is less. The greater width brings more space associated with disappeared mid-seat and more aisle-side seats, thus no passenger will be obliged to sit in the mid-seat with inconvenience.

Another advantage is the larger space makes various configurations possible.

- The baseline configuration has a little bit narrower seat due to the second aisle. However, it is hard to say that passengers would not like aisle-side seat rather than normal size mid-seat.
- The twin-aisle configuration can be changed into single-aisle configuration easily associated with much wider seat (especially for the mid-seat), which will make passengers more comfortable during their flight travelling.
- For freighter configuration, wider fuselage is able to accommodate two LD3 containers abreast with minor change to the floor and cabin wall.

The drawbacks are easy to be figured out as well. Wider fuselage means greater drag force and heavier weight of aircraft, which will increase the fuel consumption.

Considering existing competitors, a wider 150 seat aircraft provides much more possible configurations for various usages at a lower acquisition cost and operating cost. It can be expected to take some market shares in forthcoming huge volume of single-aisle aircraft demands.

7 Conclusion

Through this aircraft conceptual design project, all delegates experienced the integrated process that presents the contents, methods and ideas of aircraft conceptual design. And a concept design is produced with the efforts of all involved delegates finally.

Individually, the market survey and cost estimating, which are the main work author did in this project, give a comprehensive understanding of current air transport market and economical analysis for survival in such a competitive market, especially with Boeing and Airbus in the same sector. Though both Boeing and Airbus have developed their most popular 150-seat aircraft and dominated the market for a long period, there is still preponderance in China aviation industry for developing a new aircraft larger than current ARJ21.

This project is very helpful to all involved people who have worked on aircraft for several years and acquired certain experiences and knowledge, especially when they are possibly to develop a new 130 or 150 seat aircraft.

References

Roskam, Jan, ‘Airplane Design Volume VIII – Airplane Cost Estimation: Design, Development, Manufacturing and Operating’, 1990

Burns, J. Wayne et al, ‘Aircraft Cost Estimation Methodology and Value of A Pound Derivation for Preliminary Design Development Applications’, 53rd Annual Conference of Society if Allied Weight Engineers, Inc, Long Beach, CA, 23-25 May 1994

B - Database

B.1 Aircraft Database

Aircraft	Cost ($M)	Seat	Wingspan (m)	Length (m)	Wing Area (m2)	OEM (kg)	MTOM (kg)	Wing Loading (kg/m2)	Max. Speed (km/h)
A318-100	59.1	100	34.1	31.45	122.6	39035	59400	481.2	900
A319-100	70.3	124	34.1	33.83	122.6	40160	64400	522.9	900
A320-200	76.9	150	34.09	37.57	122.4	42100	73900	599.5	903
A321-200	90.3	185	34.09	44.51	122.6	48200	83400	727.1	903
B737-600	53.5	103	34.31	31.24	125	37104	56245	450	876
B737-800	74.5	154	34.31	39.47	125	41145	70535	327	876
B737-900	77.285	172	34.31	42.11	125	42493	74840	318	876
A330-200	180.9	293	60.3	59	361.6	120500	230000	633.4	913
A330-300	200.8	335	60.3	63.58	361.6	124500	230000	633.4	913
A380-800	327.4	555	79.6	72.725	845	270000	560000	662.7	955
B747-400	238	524	64.44	70.67	541.16	180485	362880	670.5	939
B767-200ER	121.7	224	47.57	48.51	283.3	84960	156490	552.3	914
B767-300ER	149.25	269	47.57	54.94	283.3	90810	172370	608.3	900
B777-200	191.54	400	60.93	63.73	427.8	140660	229580	536.5	945
B777-200ER	212.5	400	60.93	63.73	427.8	144830	297555	614.9	945
B777-300	228	451	64.8	73.86	427.8	158030	299370	699.8	945
CRJ-100/200	24.85	50	21.21	26.77	54.54	13730	21523	394.6	860
CRJ-700/705	29.5	70	23.24	32.51	68.63	19731	32999	480.8	875
ERJ-135 ER	17.67	37	20.04	26.33	51.18	11390	19000	371.2	834
ERJ-145 ER	25.04	50	20.04	29.87	51.18	11940	20600	402.5	834
A350-800	169.3	312	64	60.6	443		245000	676.8	945
A350-900	188.15	366	64	66.9	443		265000	732	945
A350-1000	210.83	412	64	73.9	443		295000	801.1	945
A340-300	215.5	295	60.3	63.68	361.6	130000	253500	760.5	914
A340-500	237.1	318	63.45	67.51	437	170900	368000	835.2	930
A340-600	249.4	380	63.45	74.96	437	177700	365000	835.2	930
B777-300ER	264.5	350	64.8	73.86	427.8	167830	345050		945
B787-3	156.88	290	51.71	56.72		101151	165100		945
B787-8	162	210	60.12	56.72		109769	219540		945
B787-9	188.2	250	60.12	62.81		115213	244940		945
E170 LR	29.47	70	26	29.9		20940	37200		890
E175 LR	31.71	82	26	31.68		21810	38790		890
E190 LR	35.12	100	28.72	36.24		28080	50300		890
E195 LR	37.09	108	28.72	38.65		28970	50790		890
B777-200LR	243.8	313	64.8	73.86	427.8	145150	347820		945
B737-700	62.3	134	34.31	33.63	125	38147	60330	482.6	876
CRJ-900	33.9	86	24.84	36.37	68.63	21432	36514	532.1	881

(Continued)

Aircraft	TO Length (m)	Ld Length (m)	Range (km)	Thrust (kN)	Power Loading (kg/kN)	Age (Year)	Delivered Number	Labour Rate Base ($/h)
A318-100	1670	1355	1462	212	307	5	6253	52.5
A319-100	1720	1430	1813	240	327	12	6253	52.5
A320-200	1960	1490	2592	240	312	20	6253	52.5
A321-200	2220	1540	2138	266	313	11	6253	52.5
B737-600	1616	1342	1340	202	463	10	5024	52.5
B737-800	2100	1646	1990	234	463	10	5024	52.5
B737-900	2591	1662	2060	243	463	7	5024	52.5
A330-200	2530	1722	6650	605.2		10	1852	52.5
A330-300	2515	1753	5600	605.2		15	1852	52.5
A380-800	2987	2103	8200	1246	463	2	200	52.5
B747-400	2820	1905	6185	1105.38	352	19	720	52.5
B767-200ER	2301	1524	4830	552.69	348	24	803	52.5
B767-300ER	2530	1677	4890	552.69	343	20	803	52.5
B777-200	2073	1570	5235	685.3	335	13	1096	52.5
B777-200ER	2515	1616	7700	801	349	11	1096	52.5
B777-300	2667	1844	6015	836.6	328	10	1096	52.5
CRJ-100/200	1527	1423	965	345.587	263	16	1036	52.5
CRJ-700/705	1564	1551	1649	519.76	293	7	322	52.5
ERJ-135 ER	1700	1360	1700	66.0914	285	9	915	36
ERJ-145 ER	1970	1390	1620	66.0914	305	12	915	36
A350-800			8300	667.5			500	52.5
A350-900			8100	774.3			500	52.5
A350-1000			8000	845.5			500	52.5
A340-300	3125		7200	277.68		15	1852	52.5
A340-500	3125		8650	471.7		5	1852	52.5
A340-600	3140		7500	498.4		6	1852	52.5
B777-300ER	3200	1860	7930	1023.5		4	1096	52.5
B787-3			2725	471.7		0	895	52.5
B787-8			7875	569.6		0	895	52.5
B787-9			8250	623		0	895	52.5
E170 LR	1689	1316	2000	124.6	294	4	865	36
E175 LR	1910	1352	1800	124.6	307	4	865	36
E190 LR	1983	1379	2200	164.65	282	4	865	36
E195 LR	2179	1428	1800	164.65	285	4	865	36
B777-200LR	2530	1829	9420	979		2	1096	52.5
B737-700	1744	1418	1540	234		11	5024	52.5
CRJ-900	1779	1596	1596	519.76		5	289	52.5

B.2 Jet Engines Database

Manu	Engine Type	Cost ($M)	Thrust (kN)	BPR	Number	Interstage Turbine Temp.(°C)	SFC (lb/lb h)	Mach	Airflow (kg/s)	Length (m)	Dia. (m)	Dry Weight (kg)	Age	AIRCRAFT
RR	AE3007A1P	1.85	38.27	4.8	2700	950	0.630	0.8	670	2.71	1.10	717.77	9	ERJ-145 ER
RR	BR715(-58)	2.39	97.90	4.8		900	0.630	0.76	284	3.61	1.58	2115.64	10	B717-200
RR	BR715A1-30	2.39	97.90	4.8		900	0.630	0.76	289	3.61	1.58	2115.64	10	(B717)
GE	CF34-3B1	1.5	41.03	6.2	5600	(918)	0.689			2.62	1.24	758.18	16	CRJ-200
GE	CF34-8C1	2.3	61.37	4.9	5600	960	0.680		200	3.26	1.32	1066.90	7	CRJ-700
GE	CF34-8E5	2.8	64.53	4.9	5600	(990)	0.680			3.26	1.32	1121.38	4	E170
GE	CF6-80A2	2.4	222.50	4.59	5676	940	0.576	0.8	749	4.24	2.19	3977.04	4	B767-200ER
GE	CF6-80C2A5	5	272.79	5.05	5676	960	0.680	0.8		4.27	2.36	4303.92	4	A300-600R
GE	CF6-80C2B1F	5.7	258.10	5.19	5676	960	0.605	0.8	803	4.27	2.36	4444.66	4	B747-400
GE	CF6-80C2D1F	5.5	228.06	5.03	5676	960	0.680	0.85	803	4.27	2.36	4444.66	4	MD-11
GE	CF6-80E1A3	9.2	310.61	5.1	5676	1000	0.680		874	4.41	2.44	4824.66	4	A330-200
CFMI	CFM56-3B1	2	89.00	5	19722	(930)	0.680		294	2.36	1.52	1941.30	4	B737-300
CFMI	CFM56-3B2	2.2	97.90	5.9	19722	(930)	0.657	0.85	310	2.36	1.52	1952.65	24	B737-400
CFMI	CFM56-3C1	3	104.58	6	19722	(930)	0.648	0.8	306	2.36	1.52	1952.65	24	B737-500
CFMI	CFM56-5A1	4.325	111.25	6	19722	890	0.596			2.42	1.73	2267.73	20	A320
CFMI	CFM56-5B3/P	6.1	146.85	5.4	19722	940	0.596		439	2.60	1.73	2383.50	9	A321-200
CFMI	CFM56-5B4/P	5.3	120.15	5.7	19722	940	0.596			2.60	1.73	2383.50	9	A320
CFMI	CFM56-5B5/P	4.5	97.90	6	19722	940	0.596		371	2.60	1.73	2383.50	9	A319-100
CFMI	CFM56-5C4/P	6.2	151.30	6.4	19722	975	0.545	0.8	466	2.62	1.84	3967.96	9	A340-300
CFMI	CFM56-7B22	5.2	101.02	5.3	19722	950			331	2.63	1.55	2386.68	9	B737-600
CFMI	CFM56-7B24	5.7	107.69	5.3	19722	950			341	2.63	1.55	2386.68	9	B737-700
CFMI	CFM56-7B26	6.1	117.04	5.1	19722	950		0.8	354	2.63	1.55	2386.68	9	B737-800
CFMI	CFM56-7B27	6.6	121.49	5.1	19722	950			355	2.63	1.55	2386.68	9	B737-900ER
GE	GE90-115B	18.75	513.09	7.2	1030	1090	0.53		1,653	7.29	3.26	8290.04	9	B777-300ER
GE	GE90-94B	13.3	416.97	8.7	1030	1030				7.29	3.26	7556.38	9	B777-200ER/300

(Continued)

Manu	Engine Type	Cost ($M)	Thrust (kN)	BPR	Number	Interstage Turbine Temp.(°C)	SFC (lb/lb h)	Mach	Airflow (kg/s)	Length (m)	Dia. (m)	Dry Weight (kg)	Age	AIRCRAFT
PW	JT8D-217C	1	92.78	1.81	14000	875	0.737			3.92	1.25	2049.81	28	MD-82
PW	JT8D-219	1.5	96.57	1.77	14000	875	0.737		222	3.92	1.25	2049.81	13	MD-82
PW	PW2037	5.09	170.21	6	852	895	0.563			3.59	1.99	3314.20	24	B757-200
PW	PW4056	5.1	252.54	5.03	2000	904		0.8		3.37	2.39	4182.70	23	B747-400
PW	PW4060	5.5	267.00	5.03	2000	904			817	3.37	2.39	4236.73	23	B767-300ER
PW	PW4090	9.8	408.47	6.4		925			1,158	4.87	2.84	7146.41	13	B777-200/300
PW	PW4098	9.8	408.47	6.4		925	0.56			4.87	2.84	7146.41	23	B777-200/300
PW	PW4152	3.6	231.40	5	2000	894				3.37	2.39	4236.73	21	A310-300
PW	PW4158	6.09	258.10	4.8	2000	904				3.37	2.39	4236.73	21	A300-600
PW	PW4168A	7.92	302.60	5.1		870		0.8	903	4.14	2.54	5311.80	9	A330
RR	RB211-524H-T	6.5	269.67	4.1	1100	785	0.57	0.85	728	3.18	2.19	4299.38	10	B747-400 B767-300
RR	RB211-535E4	4.2	178.45	4.3	1100	877	0.598			2.99	1.88	3297.86	24	B757-200
RR	TAY 650	1.6	67.20	3.06	1600	850	0.690	0.78	193	2.41	1.14	1516.36	9	FOKKER 100
RR	TAY 650-15	1.09	67.20	3.1	1600	850	0.690	0.78	193	2.41	1.14	1516.36	19	F100
RR	TRENT 556	7.65	249.20	7.6	596	900	0.568	0.82	859	3.91	2.47	4721.60	6	A340-600
RR	TRENT 772B-60	8.2	316.40	5		850	0.584	0.82	898	3.91	2.47	4767.00	13	A330-300
RR	TRENT 892B-17	13.3	407.62	5.8	442	900	0.560	0.83	1,201	4.37	2.79	5947.40	13	B777
RR	TRENT 895	12.2	422.75	5.8	442	900	0.560	0.83	1,219	4.37	2.79	5947.40	13	B777-200ER
IAE	V2527-A5	5.4	118.37	4.8	6252	932	0.574	0.8	385	3.20	1.61	2365.34	15	A320-200

Note: All data in brackets are estimated as explained in B.4.

B.3 Avionics Database

(Data Source: http://www.avionix.com/, accessed on 10th Jan. 2009)

SN	Manufacturer and Model	Cost	In Base Kit
ADF			
1	Bendix/King KR-87 Digital ADF System	$5,139.00	
2	Bendix/King KR-87 ADF System (Recon.)	$2,689.00	
3	Bendix/King KR-86 ADF (Recon.)	$1,449.00	
4	Collins ADF-650 ADF System (Recon.)	$1,189.00	
5	Collins ADF-650A ADF System (Recon.)	$1,389.00	
6	Narco ADF-841 (Recon.)	$1,989.00	
7	Terra TDF-100D	$1,789.00	
8	Bendix/King KDA-692 ADF Adapter with Super Flag	$3,489.00	Y
9	Bendix/King KDF-806 Digital Superflag/EFIS ADF System	$10,589.00	Y
10	Bendix/King KFS-586A Digital ADF Control Display Unit	$6,389.00	Y
11	Bendix/King KFS-579A TAC/NAV Control Head	$8,433.00	Y
Radar System			
1	Bendix/King RDS-81 Radar System (Recon.)	$13,989.00	
2	Bendix/King RDS-82 Radar System (Recon.)	$14,989.00	
3	Bendix/King RDS-82 VP Radar System	$16,989.00	Y
4	Bendix RDR-150 Radar System (Recon.)	$5,989.00	
5	Bendix IN-152A Radar indicator (Recon.)	$1,589.00	
6	Bendix IN-2026A Color Radar indicator (Recon.)	$4,989.00	
7	Bendix/King KTA 870 TAS with Traffic Module for KMD 550/850	$29,081.00	
8	Bendix/King KAC 510 Weather Radar Module for KMD 550	$6,433.00	
9	Bendix/King RDR-2000 ART-2000 Digital Weather Radar	$29,712.00	
10	Bendix/King RDR-2100 ART-2100 Digital Weather Radar	$40,176.00	Y
11	Garmin GWX-68 Radar 12" Antenna	$21,995.00	
12	Sperry/Honeywell PRIMUS 300SL Slim-Line Series Color Radar System. DI-2007, RT-3002, AP-3001 (Reconditioned System)	$8,989.00	
13	Sperry/Honeywell PRIMUS 400 Series Color Radar System. DI-4001, RT-4001 and AP-4001 (Reconditioned System)	$9,989.00	
14	Sperry/Honeywell PRIMUS 400SL SlimLine Color Weather Radar Systems	$10,989.00	
15	Bendix/King Narco KWX-56 Color Radar (Recon.)	$8,989.00	
Altimeter			
1	Bendix/King KRA-10A Radar Altimeter (Recon.)	$8,489.00	
2	FreeFlight TRA 3000 Radar Alitimeter & Indicator	$4,389.00	
3	FreeFlight TRA 3500 Radar Altimeter & Indicator	$6,646.00	
4	Bendix/King KRA-405B Radar Altimeter with KNI 416 Indicator	$20,689.00	Y
HSI			
1	Collins PN 101 Slaved HSI (Recon)	$6,889.00	
2	Century Flight Systems NSD-360A-15 Non-Slaved HSI	$6,589.00	
3	Century Flight Systems NSD-360A Slaved HSI	$8,389.00	
4	Century Flight Systems NSD-360A Slaved HSI w/ Bootstrap	$9,489.00	
5	Century Flight Systems NSD-1000 Slaved HSI	$8,789.00	

(Continued)

6	Century Flight Systems NSD-1000 Slaved HSI w/ Bootstrap	$9,989.00	
7	Bendix/King KCS-55A HSI System	$11,389.00	Y
8	Bendix/King KCS-55A HSI System (Recon.)	$8,495.00	
9	Bendix/King KI-825 Electronic HSI	$11,995.00	Y
10	Sandel SN-3500 MFD/EHSI/EFIS	$8,989.00	
11	Sandel SN-4500 MFD/EHSI/EFIS	$19,989.00	
12	Mid-Continent LIFESAVER 4300 Electric Horizon with Internal Battery Option	$3,989.00	
13	Bendix/King KCS-55A-01 HSI System (Recon)	$8,995.00	
DME			
1	Bendix/King KN-62A DME	$5,789.00	
2	Bendix/King KN-63 DME/KDI-572	$9,489.00	
3	Bendix/King KN-64 DME	$4,589.00	
4	Narco Dme 890 (Recon)	$1,689.00	
	Collins TCR-451 DME (Recon.)	$1,189.00	
6	Bendix/King KDM-706A DME with/KDI 572 Indicator 28V	$18,430.00	Y
7	Bendix/King KA-120 Converter for DME/Glideslope w/Rack	$1,971.00	Y
8	Bendix/King KDA-689 Arinc Serial Adapter for KDM 706	$3,870.00	Y
HF			
1	Bendix/King KHF-950 HF System 28 Volt. (Recon.)	$28,500.00	
2	Bendix/King KAC 992 HF COUPLER 28V	$30,810.00	Y
3	Bendix/King KHF-1050 HF System Dual Vertical Install	$47,979.00	Y
4	Bendix/King KHF 1050 POWER AMPLIFIER	$10,968.00	Y
5	Bendix/King KHF 1050 ANTENNA COUPLER	$25,263.00	Y
6	Bendix/King KRX 1053 REC/EXCITER	$13,180.00	Y
Transceiver			
1	Bendix/King KTR-909 UHF Transceiver with KFS 599A Control Head	$22,589.00	Y
2	Bendix/King KY-196B COM 28V VHF Transceiver	$5,289.00	Y
3	Bendix/King KTR 908 VHF XCVR 25KHZ 152MHZ W/SELCAL	$24,968.00	Y
Transponder			
1	Bendix/King KT-70 Mode S Transponder	$4,989.00	
2	Bendix/King KT-70 Mode S Transponder (Recon.)	$3,689.00	
3	Bendix/King KT-70 Mode S Transponder with MEM	$5,560.00	
4	Bendix/King KT-71 Transponder	$5,189.00	
5	Bendix/King KT-71 Transponder (Recon.)	$1,595.00	
6	Bendix/King KT-73 Mode S Transponder (Recon.)	$3,689.00	Y
7	Bendix/King KT-73 Mode S Transponder (Exchange for KT-76A)	$4,549.00	
8	Bendix/King KT-76A Transponder Exchange	$1,389.00	
9	Bendix/King KT-76A Crown Transponder 28V	$1,729.00	
10	Bendix/King KT-76C Digital Transponder	$2,189.00	
11	Bendix/King KT-79 Transponder (Recon.)	$1,989.00	
12	Garmin GTX-320A Transponder	$1,550.00	
13	Garmin GTX-320A Transponder AK-350 Encoder KwikMount Package	$1,949.00	
14	Garmin GTX-327 Transponder	$2,289.00	

(Continued)

15	MICROAIR T2000SFL Transponder	$1,989.00	
16	Narco AT-155 Transponder (Recon.)	$1,099.00	
17	Narco AT-165 Transponder; System with Mounting Rack and Installation Kit	$1,620.00	
18	Narco AT-165C New for Direct Replacement of the All Cessna/ARC/Sperry/300/400/RT359A/459A Transponders	$1,692.00	
19	Terra TRT-250D Transponder (Recon.)	$1,495.00	
20	Bendix/King KFS-578A Transponder Control Head	$7,989.00	Y
NAV			
1	Bendix/King KN-53 G/S NAV/GS Receiver (Recon.)	$1,389.00	
2	Bendix/King KNS-80 NAV/DME/RNAV/GS (Recon.)	$1,489.00	
3	Narco NAV-122 (Recon.)	$2,289.00	
4	Narco NAV-122D	$3,830.00	
5	Narco NAV-825	$2,100.00	
6	Narco NAV-825 (Recon.)	$1,389.00	
7	Bendix/King KFS-564A Digital NAV Control Head	$5,989.00	Y
8	Bendix/King KA-138 NAV Switching Kit	$5,562.00	Y
NAV/COM			
1	Bendix/King KX-125 NAV/COM	$2,689.00	
2	Bendix/King KX-155 NAV/COM 14V	$3,189.00	
3	Bendix/King KX-155A NAV/COM 28V (Recon.)	$2,289.00	
4	Bendix/King KX-165 GS NAV/COM (Recon.)	$3,189.00	
5	Bendix/King KX-165A NAV/COM 28V (Recon.)	$2,689.00	
6	Bendix/King KX-165A NAV/COM 8.33 KHZ/28V	$4,389.00	Y
7	Garmin SL-30 NAV/COM	$4,589.00	
8	Narco MK-12D+w GS ID-825 Pack NAV/COM & Indicator	$3,953.00	
9	Narco MK-12D Cessna Replacements NAV/COM	$2,126.00	
10	Narco MK12D/R NAV/COM	$2,275.00	
11	TKM Michel MX-12 NAV/COM	$1,749.00	
12	TKM Michel MX-170C NAV/COM	$1,749.00	
13	TKM Michel MX-300 NAV/COM	$1,749.00	
14	TKM Michel MX-385 NAV/COM	$1,749.00	
15	Garmin GNS-430W GPS/COM/NAV/ILS	$11,389.00	
GPS/COM			
1	Garmin GNC-250XL GPS/COM	$3,450.00	
2	Garmin GNC-300XL GPS/COM	$3,189.00	
3	Garmin GNC-420W GPS/COM	$10,589.00	
4	Garmin GNC-420AW GPS/COM	$14,829.00	
5	Garmin GNS-430AW GPS/COM/NAV/ILS	$14,740.00	
6	Garmin GNS-530 WGPS/COM/NAV/ILS	$15,729.00	
7	Garmin GNS-530W TAWS GPS/COM/NAV/ILS	$22,479.00	
8	Garmin GNS-530AW GPS/COM/NAV/ILS	$25,989.00	Y
GPS			
1	Garmin GPS-150 XL GPS	$2,495.00	
2	Garmin GPS-155XL TSO GPS	$5,995.00	
3	Garmin GPS-400 GPS/MAP	$7,895.00	

(Continued)

4	Garmin GPS-500 GPS/MAP	$11,895.00	
5	Garmin A-33 GPS Active Antenna	$389.00	
6	Bendix/King KLN-900 BRNAV/Oceanic GPS	$17,689.00	Y
Moving Map System			
1	Bendix/King KMD-150 MFD	$3,889.00	
2	Bendix/King KMD-250 MFD with GPS	$5,694.00	
3	Bendix/King KMD-250 MFD	$5,454.00	
4	Bendix/King KMD-550 Color MFD	$9,181.00	
5	Bendix/King KMD-850 Color MFD with Radar Interface	$15,614.00	Y
6	Bendix/King SM-IIIC V 3.0 Color Skymap	$2,589.00	Y
7	Bendix/King SkyMap SM-IIIC	$2,389.00	
8	Garmin/UPSAT MX-20 I/O Traffic + Radar MFD	$14,995.00	
9	Garmin/UPSAT MX-20 I/O Traffic MFD	$8,495.00	
10	Garmin G600 Glass Cockpit for Production Aircraft	$29,772.00	
11	Garmin GMX 200 Multifunction Display Standard	$8,489.00	
12	Garmin GMX 200 Multifunction Display Radar	$11,389.00	
13	Garmin GMX 200 Multifunction Display Radar/Traffic	$13,489.00	
Instrument			
1	J.P. Instruments EDM-700-F Analyzer/Fuel Computer w/Transducer (4 EGT / 4 CHT)	$1,915.00	
2	J.P. Instruments EDM-700-F Analyzer/Fuel Computer w/Transducer (6 EGT / 6 CHT)	$2,525.00	
3	J.P. Instruments EDM-711 (Single Eng) (4 EGT / 4 CHT)	$1,593.75	
4	J.P. Instruments EDM-711 (Single Eng) (6 EGT / 6 CHT)	$2,205.75	
5	J.P. Instruments EDM-760 Analyzer (4 EGT / 4 CHT)	$2,970.75	
6	J.P. Instruments EDM-760 Analyzer (6 EGT / 6 CHT)	$3,820.75	
7	J.P. Instruments EDM-760-F Analyzer/Fuel Computer w/Transducer (4 EGT /4 CHT)	$5,189.00	Y
8	J.P. Instruments EDM-760-F Analyzer/Fuel Computer w/Transducer (6 EGT / 6 CHT)	$5,690.00	
9	J.P. Instruments EDM-800 Analyzer (4 EGT / 4 CHT)	$2,779.50	
10	J.P. Instruments EDM-800 Analyzer (6 EGT / 6 CHT)	$3,991.50	
11	J.P. Instruments EDM-800/711 Analyzer (4 EGT / 4 CHT)	$3,310.75	
12	J.P. Instruments EDM-800/711 Analyzer (6 EGT / 6 CHT)	$3,735.75	
13	J.P. Instruments EDM-900-4C All-In-One Engine Display & Monitoring	$2,889.00	
14	J.P. Instruments EDM-900-6C All-In-One Engine Display & Monitoring	$3,149.00	
15	J.P. Instruments EDM-930-4C All-In-One Engine Display & Monitoring	$3,789.00	
16	J.P. Instruments EDM-930-6C All-In-One Engine Display & Monitoring	$3,989.00	
17	Shadin Digidata	$3,369.00	
18	Shadin Digiflo (-L) (3.25 in. Mount) Fuel Flow	$2,160.00	
19	Shadin Digiflo (-L) + GPS Interface Fuel Flow	$2,160.00	
20	Shadin Digiflo (-L) Twin Engine Fuel Flow	$2,549.00	
21	Shadin Microflo (-L) (2 1/4 in. Mount) Fuel Flow	$1,795.00	
22	Shadin Miniflo (-L) (1/2 in. high ATI Mount) Fuel Flow	$1,795.00	

(Continued)

23	Vision Microsystems VM 1000 4 Cylinder Engine Management System TSO'd	$4,142.00	
24	Vision Microsystems VM1000C 4 Cylinder Engine Management System (Non-TSO'd Experimental Aircraft Only)	$1,895.00	
25	Electronics Intl. MVP-50 Glass Panel Engine Monitor & In-Flight InfoSys (4 Cyl/Single)	$4,489.00	
26	Electronics Intl. MVP-50 Glass Panel Engine Monitor & In-Flight InfoSys (6 Cyl/Single)	$4,989.00	
27	Electronics Intl. UBG-16 Ultimate Bar Graph Engine Analyzer (4 Cyl/Single)	$1,419.00	
28	Electronics Intl. US-8A Ultimate Engine Analyzer (16 ch/twin)	$2,049.00	
29	Electronics Intl. US-8A Ultimate Engine Analyzer (12 ch/twin)	$1,989.00	
30	Insight Gemini 1200-42; 4CTwins EGT/CHT	$2,889.00	
31	Insight Gemini 602-6 (6EGT 6CHT)	$1,489.00	
32	Insight Gemini 1200-43; 4C Turbo Twin	$3,489.00	
33	Insight Gemini 1200-62; 6C Twins	$2,989.00	
34	Insight Gemini 1200-63; 6C Turbo Twin	$3,689.00	
35	Bendix/King KI-202 Indicator	$1,869.00	
36	Bendix/King KI-202 Indicator (Recon.)	$1,089.00	
37	Bendix/King KI-203 Indicator	$2,189.00	Y
38	Bendix/King KI-203 Indicator (Recon.)	$789.00	
39	Bendix/King KI-204 Indicator	$1,989.00	
40	Bendix/King KI-204 Indicator (Recon.)	$1,489.00	
41	Bendix/King KI-206 Indicator	$1,989.00	
42	Bendix/King KI-206 Indicator (Recon.)	$1,489.00	
43	Bendix/King KI-208A Indicator	$1,329.00	
44	Bendix/King KI-208 Indicator (Recon.)	$689.00	
45	Bendix/King KI-208A Indicator (Recon.)	$1,089.00	
46	Bendix/King KI-209 Indicator (Recon.)	$989.00	
47	Bendix/King KI-209A Indicator	$1,489.00	
48	Bendix/King KI-209A Indicator (Recon.)	$1,289.00	
49	Bendix/King KI-214 Indicator (Recon.)	$1,095.00	
50	Collins IND-350 (Recon.)	$789.00	
51	Collins IND-350A (Recon.)	$889.00	
52	Collins IND-351 (Recon.)	$889.00	
53	Collins IND-351A (Recon.)	$1,089.00	
54	Mid-Continent MD200-306 CDI (Garmin)	$1,939.00	
Data			
1	Garmin GDL-69 Satellite Weather Data Link Receiver	$5,449.00	
2	Garmin GDL-69A Satellite Weather Data Link Receiver with XM Radio Entertainment Capability	$6,449.00	
3	Bendix/King KDR-610 XM Radio Satellite Data Link Weather Receiver	$6,559.00	Y
4	Bendix/King KDR-610 XM Radio Satellite Receiver w Interface for KMD-250	$4,095.00	
5	Bendix/King KDR-610 XM WX Sat. Rcvr. w Interface for KMD-550/850	$5,889.00	
6	WSI InFlight AV-300 Certified Satellite Weather Data Link Receiver	$4,595.00	

(Continued)

7	XMD-75 XM WX Satellite Data Receiver	$3,889.00	
8	Bendix/King DATA MANAGEMENT UNIT	$53,998.00	Y
Intercom			
1	Garmin GMA-340 Audio Panel with Intercom	$1,989.00	
2	Garmin GMA-340 Audio Panel with Intercom	$1,095.00	
3	Garmin GMA-347 Audio Panel with Intercom	$2,695.00	
4	Bendix/King KMA-28 Audio Panel System	$2,249.00	
5	Bendix/King KMA-24H-70 Audio Panel with Intercom	$1,989.00	Y
6	Bendix/King KMA-24H-52 Audio Panel	$1,489.00	
7	Bendix/King KMA-24H Audio/Intercom 2 Comm Auto	$1,489.00	
8	Bendix/King KMA-24 Audio Panel	$1,389.00	
9	Bendix/King KA-134 Audio Panel	$2,129.00	Y
Warning System			
1	P2 6601AAS Landing Gear & Airspeed Warning System	$1,589.00	Y
2	L3 Avionics Systems WX-500 Stormscope Lightning Detection	$5,700.00	Y
Antenna			
1	Comant CI-105 DME/TXP Blade Antenna	$162.00	
2	Bendix/King KA-92 GPS Active Antenna	$389.00	
3	Comant CI-105-20 DME/TXP Antenna	$299.00	
4	Comant CI-212-2 V Dipole Int Mount Dual Output Antenna	$500.00	
5	Comant CI-120-200 GS/Dual Combiner Antenna	$1,054.00	
6	Comant CI-211-16 Comm 118-153MHz 6-Hole Mount Antenna	$857.00	
7	Comant CI-108-1 Comm Extended Band Antenna	$829.00	
8	Comant CI-480-1 Globalstar Antenna	$1,721.00	
9	Comant CI-2480100 GPS/ORBCOMM 26.5dB Antenna	$572.00	
10	Comant CI-2680100 GPS/ORBCOMM WX 26.5dB Antenna	$846.00	
11	Comant CI-2680504 GPS/Sat-Ent WX/VHF/ORBCOMM Antenna	$1,170.00	
12	Comant CI-2680500 GPS/VHF/ORBCOMM/SAT-ENT/WX Antenna	$1,170.00	
13	Comant CI-135-100 VOR High Performance Bal Loop Single Antenna	$4,924.00	
14	Comant CI-120200GS VOR/GS Bal Loop with/Leading Edge Antenna	$1,240.00	
15	Comant CI-268-30 VHF/ORBCOMM WX Antenna	$908.00	
Autoflight			
1	CENTURY 2000 Trim Prompter ValuePAK	$10,789.00	
2	CENTURY 2000 Autotrim ValuePAK	$12,589.00	
3	CENTURY 2000 Aviator PLUS ValuePAK	$16,589.00	
4	CENTURY 2000 Aviator ValuePAK	$13,489.00	
5	CENTURY TRIDEN Autotrim ValuePAK	$15,889.00	
6	CENTURY TRIDEN Aviator PLUS ValuePAK	$15,889.00	
7	CENTURY TRIDEN Aviator ValuePAK	$16,989.00	
8	CENTURY TRIDEN Trim Prompter ValuePAK	$13,889.00	
9	CENTURY TRIDEN Aviator PLUS ValuePAK	$19,989.00	Y
10	Bendix/King KA-52 Autopilot Adapter for the KI-525A HSI	$3,720.00	Y
Electronic Flight Bag			

(Continued)

1	Advanced Data Research Electronic Flight Bag PN FG-5000	$6,171.00	
2	Advanced Data Research Electronic Flight Bag PN FG-6000	$7,789.00	Y
3	Advanced Data Research Electronic Flight Bag PN FG-8000	$2,995.00	
Traffic Advisory System			
1	Avidyne Safety SystemsTAS-600 Traffic Advisory System	$9,990.00	
2	Avidyne Safety Systems TAS-610 Traffic Advisory System	$14,990.00	
3	Avidyne Safety Systems TAS-620 Traffic Advisory System	$20,990.00	
4	L3 Avionics Systems SKYWATCH Traffic Advisory System	$15,990.00	
5	L3 Avionics Systems SKYWATCH HP Traffic Advisory System	$20,990.00	
6	L3 Avionics Systems SKYWATCH HP Traffic Advisory System; TCAS 1 Configured	$24,340.00	
Communication Transceivers			
1	ICOM IC-A210	$1,299.00	
2	Garmin SL-40 COM	$1,589.00	
3	Bendix/King KY-97A 14V COM	$1,589.00	
4	Bendix/King KY-96A COM 28V	$1,489.00	
5	Bendix/King KY-196A COM 28V	$3,889.00	
6	Bendix/King KTR-900A Communication Transceiver (Recon.)	$1,289.00	
7	Collins/S-Tec VHF-251 COM (Recon)	$889.00	
8	MICROAIR M760 Communication Transceiver	$1,189.00	
9	Narco COM-810+	$1,722.00	
10	Narco COM-811+	$1,722.00	
EFIS			
1	Dynon Avionics EFIS-D100 Electronic Flight Information System	$2,400.00	
2	Dynon Avionics EFIS-D10A Electronic Flight Information System	$2,200.00	
3	Sandel SN-3500 MFD/EHSI/EFIS	$8,989.00	
4	Sandel SA-4550 High-Definition Electronic Attitude Display Indicator (EADI)	$24,989.00	
5	Sandel SN-4500 MFD/EHSI/EFIS	$19,989.00	
6	Aspen Avionics Evolution EFD-1000 ATP PFD (Primary Flight Display)	$17,289.00	
7	Aspen Avionics Evolution EFD-1000 MFD (Multi-Function Display)	$12,589.00	
8	Aspen Avionics Evolution EFD-1000 PILOT PFD (Primary Flight Display)	$10,689.00	
9	Aspen Avionics Evolution EFD-1000 PRO PFD (Primary Flight Display)	$14,489.00	
10	Aspen Avionics Evolution EFD-500 MFD (Multi-Function Display)	$9,789.00	
11	Blue Mountain Avionics EFIS Sport G4	$6,995.00	
12	Blue Mountain Avionics EFIS/Lite G4	$3,495.00	
13	Blue Mountain Avionics EFIS/Lite Plus G4	$4,595.00	
14	Blue Mountain Avionics EFIS/ONE G4 (Dual Display)	$14,975.00	
15	Blue Mountain Avionics EFIS/ONE G4 (Single Display)	$14,975.00	
16	Garmin G600 Glass Cockpit for Production Aircraft	$29,772.00	
17	Chelton Flightlogic Synthetic Vision EFIS 2-Display System	$74,889.00	
18	Chelton Flightlogic Synthetic Vision EFIS 3-Display System	$94,989.00	
19	Chelton Flightlogic Synthetic Vision EFIS 4-Display System	$114,989.00	

(Continued)

20	Chelton Flightlogic Synthetic Vision EFIS.1 Display System	$52,889.00	
21	Meggitt Avionics / S-Tec Magic 2100 Dfcs	$63,489.00	
22	Meggitt Avionics / S-Tec Magic EFIS-500 Copilot Side Package	$25,989.00	
23	Meggitt Avionics / S-Tec Magic EFIS-500 Full Panel Package	$139,989.00	Y
24	MEGGITT AVIONICS / S-TEC MAGIC EFIS-500 Pack	$51,989.00	
25	Meggitt MAGIC EFIS	$51,989.00	
Emergency Locator Transmitter			
1	Artex C406-1HSB ELT for Turbine Aircraft	$3,575.40	
2	Artex C406-2HSB ELT for Turbine Aircraft	$3,531.00	
Forward Looking Infra Red Systems			
1	Forward Vision Aviation FLIR	$17,989.00	
Glideslope			
1	Bendix/King KN-53 G/S NAV/Glideslope Receiver	$4,289.00	Y
2	Bendix/King KA-120 Converter for DME/Glideslope w/Rack	$1,971.00	
3	Bendix/King KX-155 GS NAV/COM with Glideslope	$3,289.00	
4	Bendix/King KX-155A NAV/COM w/ Glideslope 28V and KI 209A	$4,989.00	
5	Bendix/King KX-165 NAV/COM w/Glideslope 14Vor 28V	$4,329.00	
6	Comant CI-104 Glideslope Antenna V Wing	$329.00	
7	Bendix/King KCS-305 Slaved Remote Gyrocompass System	$10,449.00	Y
8	Bendix/King KG-102A Vertical Gyro System	$3,780.00	Y
AFIS			
1	Satellite AFIS Option	$63,689.00	Y
2	Bendix/King VHF AFIS Graphics Remote Processor Unit	$7,542.00	Y
Integrated Hazard Avoidance Systems			
1	Bendix/King KGP-560 EGPWS	$11,907.00	
2	Bendix/King KGP-560 EGPWS with KMD 550/850 interface	$14,448.00	
3	Bendix/King KGP-860 EGPWS	$15,121.00	
4	Bendix/King KGP-860 EGPWS with Interface for the KMD-550/850	$17,662.00	Y
5	Bendix/King KMH-880 Multi-Hazard Awareness System for the KMD 550/850	$41,233.00	Y
6	Bendix/King KMH-880 Multi-Hazard Awareness System for other Displays	$36,161.00	
7	Bendix/King KMH 980 TCAS I/EGPWS Multi-Hazard Awareness System with Traffic and EGPWS Modules for KMD 550/850	$50,677.00	Y
8	Bendix/King KMD-250 MFD with GPS	$5,694.00	
9	Bendix/King KMD-550 Color MFD	$9,181.00	
10	Bendix/King KMD-850 Color MFD with Radar Interface	$15,614.00	
11	Bendix/King KMD-250 MFD	$5,454.00	
12	Bendix/King KDR-610 XM Radio Satellite Data Link Weather Receiver	$6,559.00	
13	Bendix/King KDR-610 XM Radio Satellite Receiver w Interface for KMD-250	$4,095.00	
14	Bendix/King KAC 510 Weather Radar Module for KMD 550	$6,433.00	
15	Bendix/King KTA 870 TAS for other displays		
16	Bendix/King KTA 870 TAS with Traffic Module	$29,081.00	Y
17	Bendix/King KTA 970 TCAS I for KMD 550/850	$36,968.00	

(Continued)

18	Bendix/King KTA 970 TAS for other displays	$34,437.00	
19	Bendix/King KMH 980 TCAS I/EGPWS Multi-Hazard Awareness System for Other Displays	$45,605.00	
20	Bendix/King KAC 502 EGPWS Module for KMD 550/850	$2,541.00	Y
21	Bendix/King KTA 870 TAS with Traffic Module for KMD 550/850	$29,081.00	
22	Bendix/King MFRD Multifunction Radar Display,115V or 28V Black or Grey	$47,726.00	Y
Others			
1	Castleberry Emergency Power Supply EPU28-24rm4	$1,849.00	Y
2	Bendix/King KA-132 Accelerator Trim Switch	$7,623.00	Y
3	Bendix/King KN 40 VOR Composite Converter	$8,289.00	Y

B.4 Database Normalization Example

Some parameters required by research are missing even in the authorized data source. If the parameters of similar products are available, they can be estimated using statistical techniques.

An example is provided as following.

In the database of jet engines, the turbine temperature is a necessary parameter for establishing engine cost models. However, some parameters are missing even in the Type Certificate Data Sheet (TCDS). Here is an example:

Table B.1 – CF34-3B1 Data from TCDS (Original)

Maximum permissible temperatures: Interturbine temperature (T5), (°C)	CF34-1A	CF34-3A/-3A2	CF34-3A1	CF34-3B/-3B1
Maximum takeoff (5 min.)	857	871	899	
Maximum takeoff (2 min. transient out of a total of 5 minutes)	886	900	928	
Normal takeoff (5 min.)	842	856	884	
Normal takeoff (2 min. transient out of a total of 5 minutes)	864	878	906	
Maximum continuous	838	860	888	899
Dry Weight (lbs)	1625	(1640)*	1655	1670

Data Source: TCDS NUMBER E15NE from FAA

*Note: This number is not available in TCDS and estimated from other 3 variants.

CF34-3B1 is the variant needed by the research, which is used on CRJ-200 of Bombardier. However the first 4 temperatures are not available in the TCDS. But it can be observed that all parameters of other variants are readily available, and the trends from CF34-1A to CF34-3B/-3B1 on “Maximum continuous” and “Dry Weight” are clear. Thus, all parameter can be presented in a scatterplot as following:

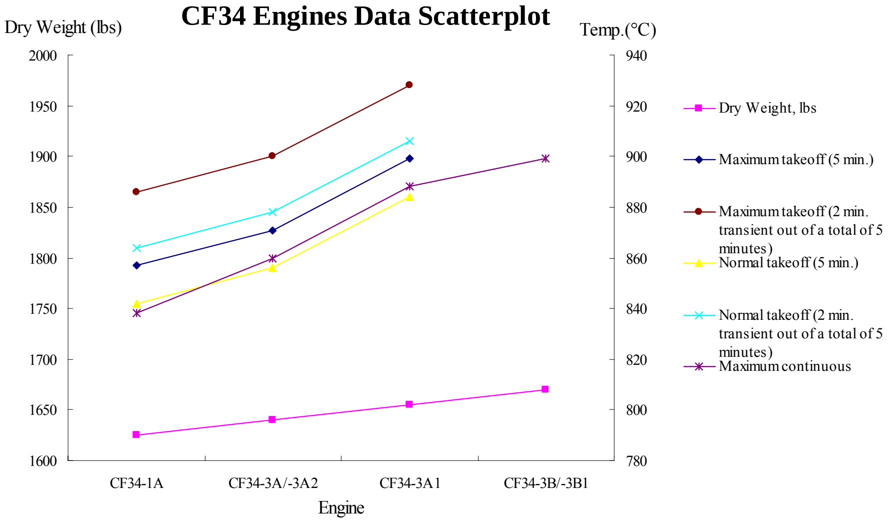


Figure B.1 – Data Scatterplot of CF34 Engines

It can be seen that each temperature parameter has similar trend from one variant to others. After making regression to each parameter series, the trends of all series can be observed mathematically.

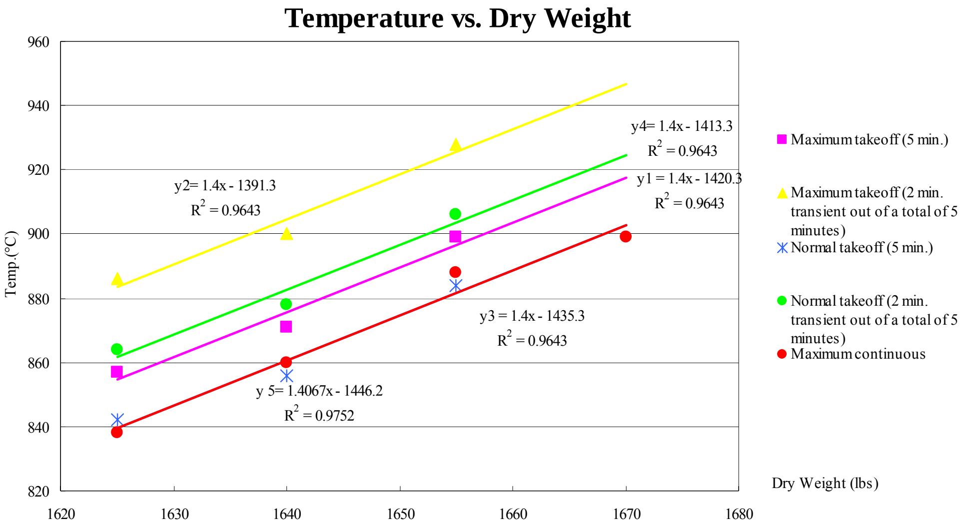


Figure B.2 – Temperature Regression of CF34 Engines

All regression equations have the same slope with similar intercepts and the R Squares of all regressions are greater than 0.96. So it can be concluded that the missing parameters are able to be estimated by those regression equations. Hence, blanks in the data list can be filled in as below.

Table B.2 – CF34-3B1 Data from TCDS (Normalized)

Maximum permissible temperatures: Interturbine temperature (T5), (°C)	CF34-1A	CF34-3A/-3A2	CF34-3A1	CF34-3B/-3B1
Maximum takeoff (5 min.)	857	871	899	(918)
Maximum takeoff (2 min. transient out of a total of 5 minutes)	886	900	928	(947)
Normal takeoff (5 min.)	842	856	884	(903)
Normal takeoff (2 min. transient out of a total of 5 minutes)	864	878	906	(925)
Maximum continuous	838	860	888	(899)
Dry Weight (lbs)	1625	(1640)	1655	1670

C - Questionnaire

The questionnaire has been sent to 30 persons and 26 replied their answers. Some results are summarized in Chapter 4 while all answers in form of percentage are presented here.

C.1 Questionnaire

QUESTIONNAIRE

Industrial Cost Situation in Asia

This questionnaire is a part of research "Acquisition Cost Estimating Methodology for Aircraft Conceptual Design". All information collected will be used only for this research and consequent thesis.

1. Please choose your working field.

   A. Design B. Manufacturing C. Operating D. Supplier E. Other_____(please describe)

2. Please choose your position.

   A. Design Engineer B. AdministratorC. Manufacture Engineer

   D. Project Manager E. Financier F. Other________(please describe)

3. Would you consider the costs resulting from your works?

   Yes☐ No☐ (go to question 5)

4. If YES, what are your reasons?

   A. It's one part of my job B. As procedures required

   C. There are no procedures but my supervisor told me to do it

   D. Nobody asks but I believe it's necessary E. Other_________(please describe)

5. If NO, what are your reasons?

   A. It's financial department's work B. I know nothing about cost

   C. There are procedures but I didn't perform D. No procedure related to cost

   E. Nobody told me to do F. Somebody told me to do but I didn't

   G. Other_________________(please describe)

6. How is your understanding about cost?

Professional	5	4	3	2	1	Nothing

7. If someone will tell you to consider costs in your work, the person possibly will be:

   A. supervisor B. financier C. manager D. subordinate E. colleague

   F. other_________(please describe)

8. Would you like to accept cost related training?

   Yes☐ No☐ (go to question 10)

9. If Yes, why?

A. Beneficial to work B. Beneficial to myself C. Other___________(please describe)

10. If No, why?

A. My work doesn't need it B. I don't need it C. Other___________(please describe)

11. Please choose one as the first in priorities of your work from following factors.

A. Performance B. Efficiency C. Feasibility D. Schedule E. Cost

F. Quality of product/service G. Safety H. Other________(please describe)

12. How is your knowledge about cost estimating?

Strong	5	4	3	2	1	Weak

13. What are the purposes of cost estimating in your understanding?

A. Making decisions B. Assessing economic performances C. Budgeting

D. Controlling cost E. Developing schedule F. Risk analysis G. Bidding

H. Market analysis I. Other_________________(please describe)

14. Is there independent cost estimating department in your company?

Yes☐ No☐ I don't know☐

15. How does your company treat cost estimating in projects?

Very important	5	4	3	2	1	Unimportant

16. Continue question 16, is it suitable in your opinion?

Yes☐ No☐ I don't know☐

17. In your own opinion, on what position should cost estimating be in your company?

Very important	5	4	3	2	1	Ignorable

18. What is the result of cost estimating in your company?

Significant	5	4	3	2	1	No any effect

19. What are the reasons if there is no any effect after cost estimating?

A. Data B. Method C. System D. Emphasis

E. Experience F. Professional G. Other______________(please describe)

20. Have you been involved in cost estimating for new product/programme?

Yes☐ No☐ (go to question 23)

21. Which methods did you use in cost estimating?

A. Empirical B. Expert judgement C. Analogue D. CERs E. Standard operation

F. Computer aided method G. Other______(please describe)

22. The top-priority method used by your company is:

A. Empirical B. Computer aided method C. Analogue D. CERs

E. Standard operation F. Expert judgement G. Other______(please describe)

23. What are the most difficult issues in cost estimating in your opinion?

A. Historic Data B. Uncertainty analysis C. Methodology

D. System in industry E. No enough emphasis from high level F. Accuracy

G. Professional H. Other_________(please describe)

24. Who were involved in cost estimating normally?

A. Design Engineer B. Manufacture Engineer C. Project Manager

D. Administrator E. Financer G. Other______(please describe)

25. Which field should the manager comes from?

A. Design B. Manufacturing C. Project management

D. Administrating E. Financial G. Other_____________(please describe)

26. Please score the importance of cost estimating in business.

must	5	4	3	2	1	unnecessary

27. Which issues are the most important for cost estimating?

A. Collecting data B. Methodology C. Analysis D. Professional

E. Accuracy F. Risk analysis G. Traceability H. Computer aiding

I. Other _______________(please describe)

28. Which phase is the most important one in that LCC estimating should be conducted?

A. RDT&E B. Production C. Operation D. Other________(please describe)

29. Please score each feature

A. Performance	Important	5	4	3	2	1	Unimportant
B. Safety	Important	5	4	3	2	1	Unimportant
C. Maintenance	Important	5	4	3	2	1	Unimportant
D. Schedule	Important	5	4	3	2	1	Unimportant
E. Cost	Important	5	4	3	2	1	Unimportant
F. Quality	Important	5	4	3	2	1	Unimportant
G. Other____(please describe)	Important	5	4	3	2	1	Unimportant

C.2 Questionnaire Interviewee

All people involved in the survey are listed in following table.

Interviewee	Position	Years in Aerospace	Major
1	Vice President	20	Manufacturing
2	Duty Engineer	14	Manufacturing
3	Manager	13	Manufacturing
4	Director	16	Manufacturing
5	Director	20	Manufacturing
6	Engineer	7	Manufacturing
7	Dispatcher	9	Manufacturing
8	Tooling Director	32	Manufacturing
9	Project Manager	20	Manufacturing
10	Project Manager	16	Manufacturing
11	Project Manager	20	Manufacturing
12	Manager	15	Manufacturing
13	Engineer	4	Manufacturing
14	Engineer	11	Manufacturing
15	Engineer	4	Manufacturing
16	Duty Engineer	13	Engineering
17	Engineer	11	Engineering
18	Engineer	12	Engineering
19	Duty Engineer	14	Engineering
20	Engineer	12	Engineering
21	Engineer	13	Engineering
22	Engineer	4	Engineering
23	Engineer	4	Engineering
24	Duty Engineer	12	Engineering
25	Duty Engineer	12	Engineering
26	Engineer	12	Engineering

There are 15 persons from manufacturing and others from engineering. The youngest ones have 4-year experience in aerospace industry while the experienced one has worked for 32 years.

One of them is the vice president of a company. Also, there are some project managers who concern cost more often. The majority are engineers in both manufacturing and engineering and their works will influence the costs of RDT&E and production in reality. Moreover, their knowledge and understanding about cost and cost estimating will consequently lead the trend of cost.

C.3 Questionnaire Results

Interviewee	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	B	C	Y	A		2	A	Y	A		D	2	ACDE	N	4	Y	4	1	F	N
2	B	B	Y	D		3	C	Y	A		A	3	C	Y	3	N	5	3	CDF	N
3	B	B	Y	D		3	C	Y	A		E	2	ABCGH	Y	4	N	5	1	C	Y
4	B	D	Y	A		4	A	Y	A		B	2	C	Y		N	3	2	C	N
5	B	C	Y	AD		3	C	Y	A		B	3	BC	N	3	N	3	2	BC	Y
6	B	B	Y	ABC		3	A	Y	A		E	3	ABCEGH	Y	2	N	3	3	ADEF	N
7	B	C	Y	D		1	A	Y	A		B	1	ABCF	NO IDEA	2	NO IDEA	3	2	CF	N
8	B	B	Y	AD		4	A	Y	A		G	4	F	Y		Y	4		CE	Y
9	B	C	Y	AC		3	C	Y	A		B	3	ABCFGH	N	4	N	5	4	ABCDF	Y
10	B	C	Y	AD		4	A	N		A	C	2	A	Y	3	N	4	3	C	N
11	B	C	N		D	1	C	Y	A		D	1	ABC	Y	2	N	2	2	B	N
12	B	D	Y	A		4	C	Y	A		E	4	D	N	3	Y	4	2	C	Y
13	B	B	Y	D		1	A	Y	A		A	1	BCGH	N	3	N	4	3	AEF	Y
14	B	B	Y	AC		3	A	Y	A		A	2	BC	Y	3	N	3	2	ABDF	N
15	B	B	Y	D		2	A	Y	A		C	1	BCEGH	Y	3	N	5	2	CD	N
16	A	A	Y	AC		3	A	Y	B		C	3	ACFG	Y	4	Y	4	3	CEF	Y
17	A	A	N		D	2	C	Y	A		C	2	A	NO IDEA	2	NO IDEA	2	2	C	N
18	A	A	Y	D		1	NONE	Y	AB		C	1	ALL	NO IDEA	2	N	3	1	ALL	N
19	A	A	Y	D		1	C	Y	A		G	1	CG	N	2	NO IDEA	2	2	F	N
20	A	A	Y	AD		4	A	Y	A		G	3	ABCFH	Y	3	N	4	2	ADEF	Y
21	A	C	Y	A		3	AC	Y	AB		C	2	ABCF	Y	5	Y	5	4	CD	N
22	A	A	Y	D		2	A	N		A	A	1	E	Y	4	Y	3	3	E	N
23	A	A	N		D	3	C	N		A	AB	3	A	Y	3	NO IDEA	4	2	D	N
24	A	A	Y	D		3	A	Y	AB		G	2	ALL	Y	4	N	5	3	CD	N
25	A	A	Y	A		5	C	Y	A		AB	4	ACE	Y	4	N	5	3	BF	Y
26	A	A	N		C	3	A	N		A	A	3	CG	NO IDEA	3	NO IDEA	2	2	AB	N

(Continued)

Interviewee	21	22	23	24	25	26	27	28	29					
									A	B	C	D	E	F
1		AB	AC	BCE	B	5	AB	B	4	5	3	4	3	3
2		A	G	ABCE	B	5	ACEG	A	5	5	4	4	4	5
3	A	A	ACDE	BCE	B	5	AB	A	5	5	5	5	5	5
4		A	E	BCE	C	5	ADF	A	4	5	3	3	4	2
5	CD	D	AD	AB	B	4	E	B	5	5	4	5	4	5
6		ABCDF	BCEFG	ABCE	A	5	ACEF	B	3	5	3	5	5	5
7		AC	BD	ABC	C	4	ACEF	A	3	3	2	3	3	4
8	B	A	D	ABCE	C	5	ABC	C	4	5	4	5	5	4
9	ACD	ACD	ABG	BCE	BCE	5	ABCDEFGH	B	4	5	4	4	5	4
10		AC	BE	CE	C	4	ABE	C	3	5	4	3	4	5
11		D	C	ESTIMATOR	E	4	AB	C	5	5	3	5	5	5
12	A	A	D	BE	E	4	G	B	4	5	5	3	5	4
13	C	ABC	A	ABC	C	3	AB	A	4	5	4	4	4	3
14		D	BE	CE	E	5	ACDEGH	A	5	4	3	4	5	3
15		ABC	DE	ABCDE	C	5	A	B	4	5	3	1	4	4
16	AC	ABC	DG	ACDE	C	5	ACD	C	4	5	3	3	4	4
17		NO IDEA	E	ABCDE	C	4	C	A	5	5	5	4	4	4
18		NO IDEA	DEG	C	C	4	ADG	A	4	4	4	4	2	5
19		AC	B	DE	CE	2	BE	A	4	5	3	3	4	4
20	BC	BC	AEG	ACD	C	4	ADF	A	4	5	4	3	4	3
21		ABCE	BE	ABCDE	CE	5	BEFG	A	5	5	5	5	5	5
22		B	A	D	C	3	A	A	5	4	3	4	2	3
23		B	E	CDE	C	4	D	A	5	5	5	5	5	5
24		ABC	DE	ABCDE	C	4	D	C	4	5	4	4	5	5
25	A	A	BD	ABC	E	5	AE	A	3	4	3	5	5	4
26		AB	BG	AC	A	3	AB	A	5	4	4	3	2	4

D - Labour Rate Validation

In this section, the assumed labour rates are to be validated by comparing estimated costs with actual costs. The estimated costs are derived from Roskam's (1990) and Burns' (1994) CERs respectively.

Considering the main manufacturers of commercial aircraft, labour rates in 3 main areas should be available for the research: western countries (including the U.S., Canada, and Europe; and assuming that labour rates in these regions are the same), Asia, and Brazil.

The labour rates of Asia are from China because the situations in Japan or Korea are close to western countries and not representative. Lower labour rare, skilled workers and experiences on aviation are the most competitive advantages of China for a long period.

With respect to western countries, a recent labour rate of aircraft servicing in the U.K. is around £60 ($90) per hour (Cotter & Blackah, 2008). Normally, the manufacturing labour rate will be lower than servicing. So the labour rate should be less than $90 per hour. Another evidence is the aerospace wage in the U.S. which can be found at "Bureau of Labor Statistics" website as following:

Table D.1 – Wages of Aerospace Occupations In USA (May 2007)

Occupation Title	Avg. Hourly Wage
Aerospace engineers	$41.74
Aerospace engineering and operations technicians	$26.49
Aircraft mechanics and service technicians	$22.87
Aircraft structure, surfaces, rigging, and systems assemblers	$21.34
Avionics technicians	$23.69
Engine and other machine assemblers	$20.53

Data Source: http://www.bls.gov/

As Raymer mentioned, the wage typically is a little less than half of the labour rate because labour rate includes overhead, administrative costs, and benefits (Raymer, 2006).

With this understanding and aforementioned U.K. labour rate & U.S. wages, the labour rates of western countries can be assumed as two times of these available U.S. wages. And a labour rate of $83.5/hour, obviously, can match $90/hour in the U.K. On the other hand, the labour rate of tooling normally is higher than manufacturing while quality control labour rate is almost the same. Therefore, following labour rate for western countries can be assumed (manufacturing labour rate is the base from which others are calculated):

Table D.2 – Estimated Labour Rates in Regions

Occupation	Labour Rate ($/hour)		
	USA, Canada & Europe		
Engineering	83	79	75.5
Manufacturing	55	52.5	50
Tooling	65	62	59
Quality Control	55	52.5	50

These labour rates are put into CERs to be validated with actual data of typical A319, B737-700, and CRJ-900 from three main western manufacturers respectively. The results are presented below:

Table D.3 – Validation of Western Labour Rates

Aircraft	A319		B737-700		CRJ 900		Base Labour Rate($/h)
Actual Cost($M)	70.3		62.25		33.9		
CERs	Estimates	Error	Estimates	Error	Estimates	Error	
Burns	69.07	-1.75%	67.34	8.18%	36.64	8.08%	55
Average	66.545	-5.34%	66.47	6.78%	37.415	10.37%	
Roskam	64.02	-8.93%	65.6	5.38%	38.19	12.65%	
Burns	67.5	-3.98%	65.83	5.75%	35.69	5.28%	52.5
Average	65.7	-6.54%	64.11	2.99%	36.355	7.24%	
Roskam	63.9	-9.10%	62.39	0.22%	37.02	9.20%	
Burns	65.93	-6.22%	64.33	3.34%	34.75	2.51%	50
Average	64.07	-8.86%	62.545	0.47%	35.3	4.13%	
Roskam	62.21	-11.51%	60.76	-2.39%	35.85	5.75%	

It can be seen that the assumed labour rates with base of $52.5 per hour are quite reasonable and can generate reliable estimates with all tolerances under 10 per cent.

Labour rates in Brazil are assumed as the mean value of China's and westerns' due to shortage of actual data. Then be validated with the ERJ aircraft as following:

Table D.4 – Validation of Brazil's Labour Rates

Aircraft	ERJ 170		ERJ 190	
Actual Cost($M)	29.47		35.12	
CERs	Estimates	Tolerance	Estimates	Tolerance
Burns	29.31	-0.54%	34.3	-2.33%
Average	29.875	1.37%	34.69	-1.22%
Roskam	30.44	3.29%	35.08	-0.11%

The results show that all tolerances are within 4 per cent. So the assumed labour rates are valid and can be used for the research.

Finally, following labour rates are estimated for the research.

Table D.5 – Estimated Labour Rates in Regions

Occupation	Labour Rate ($/hour)		
	USA, Canada & Europe	Brazil	China
Engineering	79	60	40
Manufacturing	52.5	36	20
Tooling	62	46	30
Quality Control	52.5	36	20

E - Regression

E.1 Acquisition cost of Aircraft

The processes of applying ordinary least-squares and partial least-squares regression, as introduced in chapter 3, are presented. Various CERs with different statistically explanatory variables are compared as well as analysed to choose the most suitable one.

E.1.1 Ordinary Least-Squares Regression

Ordinary Least-squares regression and stepwise regression are applied as below.

E.1.1.1 Linear Regression

At first, the CER is assumed to be:

$$\text{Cost} = p_0 + p_1{*}\text{Var}_1 + p_2{*}\text{Var}_2 + \ldots\ldots + p_n{*}\text{Var}_n$$

where p_n stands for the coefficient of n variable and Varn the cost-related variables, i.e. the aircraft parameters.

E.1.1.1.1 Simple Regression

The acquisition cost of aircraft is related to the mass and speed respectively, considering they are both explanatory variables in many CERs. The results are:

Table E.1 – Comparison of Simple CERs (Linear)

Simple Regression	R^2	Adjusted R^2	CER
Operational Empty Mass (OEM)	0.968	0.967	C=13.12+0.00135*OEM
Maximum Take-Off Mass(MTOM)	0.960	0.959	C=23.39+0.00063*MTOM
Maximum Speed V_{MAX}	0.730	0.721	C=-1914.94+2.254*VMAX

It can be seen from the table that the OEM is the best explanatory parameter while speed can not explain the cost mainly because all observations are civil transports with similar speed.

E.1.1.1.2 Multiple Regression

The mass or weight will not represent the cost completely. As various concepts with different parameters are available at aircraft conceptual design phase, the impacts of parameters are to be studied for optimizing cost. Hence, more parameters are introduced to figure out which parameters will affect cost. The results will help both engineers and managers when making decisions at conceptual design phase. Consequently, corresponding measures are able to be implemented to optimize design for cost reduction and resources allocation.

There are a total of 17 possible explanatory variables in the database, including range, thrust, passenger capacity, age, delivery number, wingspan, length, wing area, operational empty mass, maximum take-off mass, wing loading, power loading, maximum speed, cruise speed, take-off distance, landing distance, and typical labour rate base in different region (which is assumed and validated in section 5.1.2.2).

To identify the independent explanatory parameters and refine the cost model, stepwise regression technique is used to eliminate non-explanatory variables. The results are as follows:

CER Cost= -51.791 + 1.074*Wingspan + 1.572*Length + 0.00032*MTOM

Coefficient of Determination	$R^2=0.986$
Adjusted Coefficient of Determination	$R^2=0.985$

Standardized coefficients:

Wingspan	0.213
Length	0.302
MTOM	0.495

Other 14 parameters are eliminated statistically. However, one question is coming up: is it rational to reduce the acquisition cost by decreasing either aircraft length or wingspan? Although the length and wingspan will somewhat decide the size of aircraft, this CER can not satisfy cost estimators.

E.1.1.2 Exponential Regression

As shown in most existing CERs, the equation may be nonlinear equations.

E.1.1.2.1 Simple Regression

Again, the costs are related to the mass and speed respectively. This time exponential equation is chosen as the relationship between cost and parameter.

Table E.2 – Comparison of Simple CERs (Exponential)

Simple Regression	R^2	CER
Operational Empty Mass (OEM)	0.979	$C=0.0094*OEM^{0.843}$
Maximum Take-Off Mass(MTOM)	0.981	$C=0.0154*MTOM^{0.758}$
Maximum Speed V_{MAX}	0.737	C=-0.000015*VMAX2.361

The improvements in all three equations can be observed easily. It also proves that exponential equation is the best form of aircraft CERs.

E.1.1.2.2 Multiple Regression

For the same reason, more parameters are introduced to figure out cost-related variables using stepwise regression. The final CER is

Coefficient of Determination	$R^2=0.983$
Adjusted Coefficient of Determination	$R^2=0.982$

CER $C=0.12*Seat^{0.461}*Wingspan^{1.154}$

Standardized coefficients:

Seat	0.417
Wingspan	0.584

There are only two parameters remained in the CER.

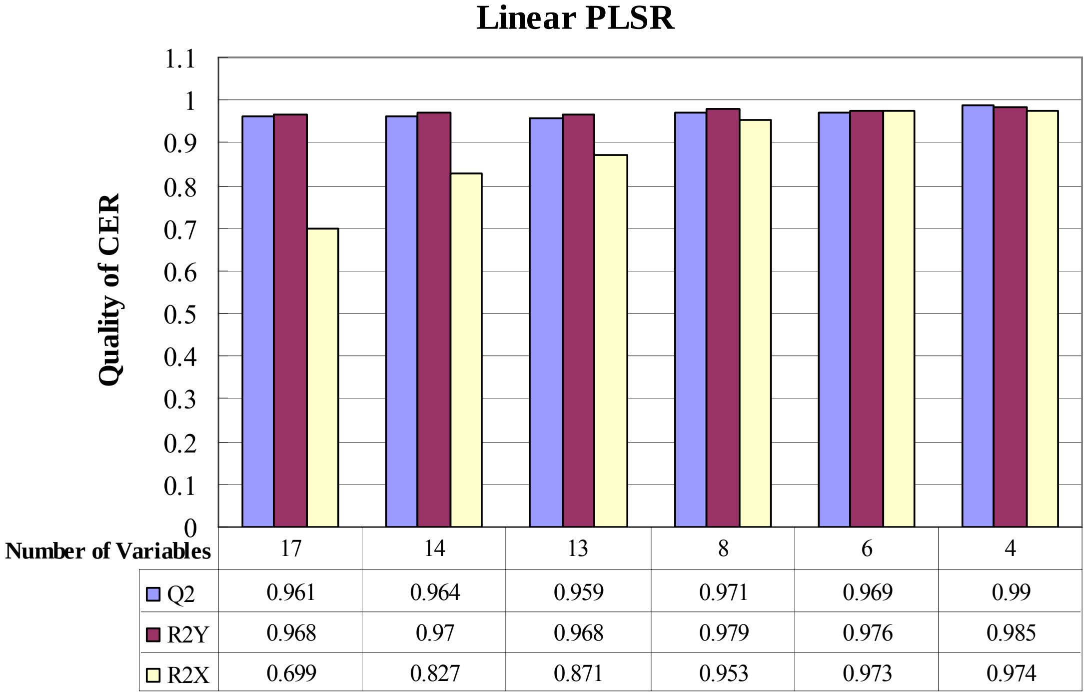
E.1.2 Partial Least-Squares Regression

From prior regression using ordinary least-squares techniques, no satisfied models are achieved because these equations do not provide the same variables although the goodness of each equation looks good.

As mentioned above, many of selected 16 parameters are related to other(s), some parameters are unavailable, and the observations are few considering number of parameters. Partial least-regressions regression (PLSR) is able to cope with these problems and better than multiple least-squares regression (Li et al, 2007).

E.1.2.1 Linear Regression

With the same form of equation as aforementioned, the results are:



Number of Variables	17	14	13	8	6	4
Q2	0.961	0.964	0.959	0.971	0.969	0.99
R2Y	0.968	0.97	0.968	0.979	0.976	0.985
R2X	0.699	0.827	0.871	0.953	0.973	0.974

Figure E.1 – Quality of CER – Linear PLSR

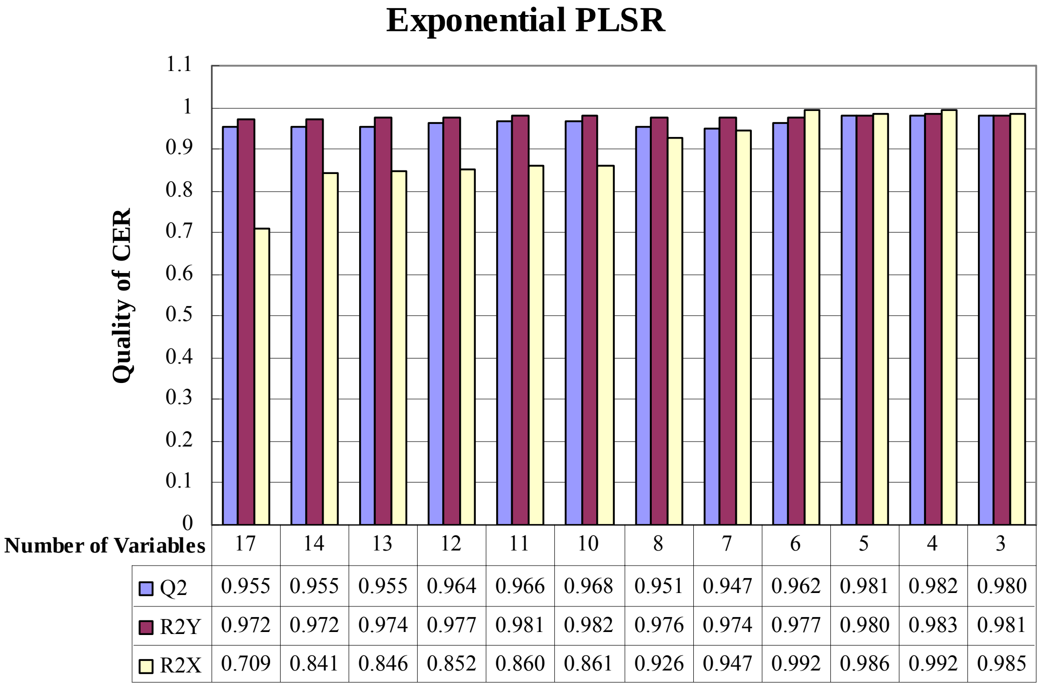
CER C=-50.05+1.28*Wingspan+1.32*Length+0.00033*OEM+0.000165*MTOM

E.1.2.2 Exponential Regression

The form of CER is assumed as:

$$Cost = p_0 \cdot Var_1^{p_1} \cdot Var_2^{p_2} \cdots\cdots Var_n^{p_n}$$

To do this in PLSR, all data are converted into denary logarithms to transfer the CER equation to exponential form. The process is presented as shown in figure E.2:



Number of Variables	17	14	13	12	11	10	8	7	6	5	4	3
■ Q2	0.955	0.955	0.955	0.964	0.966	0.968	0.951	0.947	0.962	0.981	0.982	0.980
■ R2Y	0.972	0.972	0.974	0.977	0.981	0.982	0.976	0.974	0.977	0.980	0.983	0.981
□ R2X	0.709	0.841	0.846	0.852	0.860	0.861	0.926	0.947	0.992	0.986	0.992	0.985

Figure E.2 – Quality of CER – Exponential PLSR

CER $C=0.0179*Seat^{0.292}*Wingspan^{0.516}*OEM^{0.233}*MTOM^{0.221}$

Although OEM is related to MTOM, removing one of them will cause impaired quality of model. Therefore, both of them are reserved for sound model quality.

E.1.3 Selection and Discussion

E.1.3.1 CER Selection

Totally 6 CERs are derived by using different statistical approaches and all of them passed the validation.

A $Cost=13.12+0.00135*OEM$

B $Cost= -51.791 + 1.074*Wingspan + 1.572*Length + 0.00032*MTOM$

C $Cost=0.0154*MTOM^{0.758}$

D $Cost=0.012*Seat^{0.461}*Wingspan^{1.154}$

E $Cost=-50.05+1.28*Wingspan+1.32*Length+0.00033*OEM+0.000165*MTOM$

F $Cost=0.0181*Seat^{0.290}*Wingspan^{0.518}*OEM^{0.232}*MTOM^{0.222}$

As shown in these CERs, the explanatory variables are mainly the parameters representing size and weight of aircraft.

To find out the most explanatory CER from those 6 equations, the average error percentage is introduced and compared as below.

Table E.3 – Comparison of CERs

CER	A	B	C	D	E	F
Number of Variables	1	3	1	2	4	4
R^2	0.968	0.978	0.997	0.981	0.985	0.982
Average Error (%)	15.17%	10.09%	14.31%	10.92%	19.76%	9.60%

It is clear that CER F has the lowest average error. Therefore, the exponential acquisition cost estimating model derived by PLSR is selected as the CER for aircraft conceptual design. And its features are as below:

Quality of Model

Q^2 cumulated index	0.982
R^2Y cumulated index	0.982
R^2X cumulated index	0.994

VIP (Variable Importance in the Projection)

Table E.4 – VIP of Explanatory Variables

Variable	VIP	Standardized coefficient
MTOM(kg)	1.010	0.253
Wingspan(m)	1.006	0.252
OEM(kg)	0.986	0.247
Seat	0.997	0.250

The trend is clear and two validation points are very close to the cost model as shown in figure E.3.

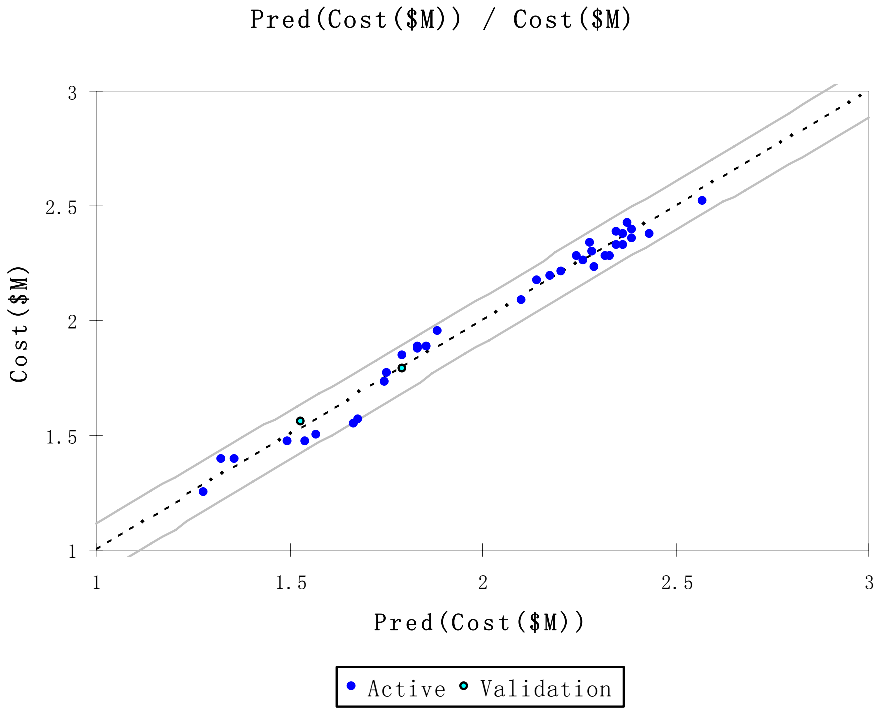


Figure E.3 – Predicted Cost vs. Actual Cost (PLSR, Exponential, 4 Variables)

The errors of estimates are listed by percentage in table E.5:

Table E.5 – CER Errors in percentage

Aircraft	Actual Cost($M)	Predicted Cost($M)	Error	Error Percentage
A318-100	59.1	57.10095	-1.99905	-3.38%
A319-100	70.3	62.286	-8.014	-11.40%
A320-200	76.9	68.59909	-8.30091	-10.79%
A321-200	90.3	77.2725	-13.0275	-14.43%
B737-600	53.5	56.41227	2.912266	5.44%
B737-800	74.5	68.27708	-6.22292	-8.35%
B737-900	77.285	71.97093	-5.31407	-6.88%
A330-200	180.9	183.8092	2.90915	1.61%
A330-300	200.8	192.5435	-8.25652	-4.11%
A380-800	327.4	375.2932	47.89316	14.63%
B747-400	238	273.6459	35.6459	14.98%
B767-200ER	121.7	127.3101	5.6101	4.61%
B767-300ER	149.25	139.2986	-9.95138	-6.67%
B777-200	191.54	209.5663	18.02631	9.41%
B777-200ER	212.5	223.4959	10.99594	5.17%
B777-300	228	244.1245	16.12454	7.07%
CRJ-100/200	24.85	22.87557	-1.97443	-7.95%
CRJ-700/705	29.5	31.62635	2.126351	7.21%
ERJ-135 ER	17.67	18.95994	1.289937	7.30%
ERJ-145 ER	25.04	21.29641	-3.74359	-14.95%
A350-800	169.3	196.8524	27.55238	16.27%
A350-900	188.15	214.145	25.99498	13.82%
A350-1000	210.83	231.2458	20.41579	9.68%
A340-300	215.5	191.5355	-23.9645	-11.12%
A340-500	237.1	232.625	-4.47499	-1.89%
A340-600	249.4	246.7356	-2.66435	-1.07%
B777-300ER	264.5	237.3743	-27.1257	-10.26%
B787-3	156.88	150.9728	-5.90723	-3.77%
B787-8	162	161.3845	-0.61555	-0.38%
B787-9	188.2	175.8945	-12.3055	-6.54%
E170 LR	29.47	34.9012	5.431197	18.43%
E175 LR	31.71	37.231	5.520999	17.41%
E190 LR	35.12	46.64384	11.52384	32.81%
E195 LR	37.09	48.14662	11.05662	29.81%
B777-200LR	243.8	222.5894	-21.2106	-8.70%
B737-700	62.3	62.23922	-0.06078	-0.10%
CRJ-900	33.9	36.22799	2.327986	6.87%
Average(Absolute Value)				9.60%

Thus, these four explanatory parameters can be emphasized during conceptual design phase to optimize the design.

E.1.3.2 Discussion

One interesting finding is about the particular pattern in a company. All Boeing and Airbus aircraft in database are studied separately by manufacturer. The results are compared as follows:

Table E.6 – CER for Manufacturer

Manufacturer		Airbus	Boeing
Quality	Q^2	0.976	0.984/987
	R^2Y	0.97	0.986/992
	R^2X	1.007	0.974/984
	R^2	0.97	0.992
Coefficient	Intercept	-44.596	-39.226
	Length(m)	1.345	2.369
	Wingspan(m)	1.395	-0.168
	OEM(kg)	2.52E-04	2.49E-04
	MTOM(kg)	1.51E-04	2.39E-04

The CERs are significantly different, especially the coefficient of wingspan in CER based on Boeing aircraft. It concludes statistically that there are different cost patterns in different companies. Due to lack of detail information, further research can not be performed. However, this issue must be taken into account when a company trying to build up its own cost estimating model for its own new programmes.

E.2 Acquisition Cost of Engines

As to jet engines, a similar regression process is applied to find explanatory parameters for engines at aircraft conceptual design phase. In addition, 7 independent variables are regressed separately to see the difference.

The unit of SFC is still lbs/lbs*hour for convenience.

E.2.1 Ordinary Least-Squares Regression

E.2.1.1 All Variables

E.2.1.1.1 Linear Regression

Stepwise regression is applied and the results are as following:

$$C_{ENG} = 0.343+0.0266*\text{Thrust(kN)}$$

R^2=0.766 adjusted R^2=0.760

It indicates that the engine cost will only related to its maximum thrust and the average estimates error is 35.08 per cent.

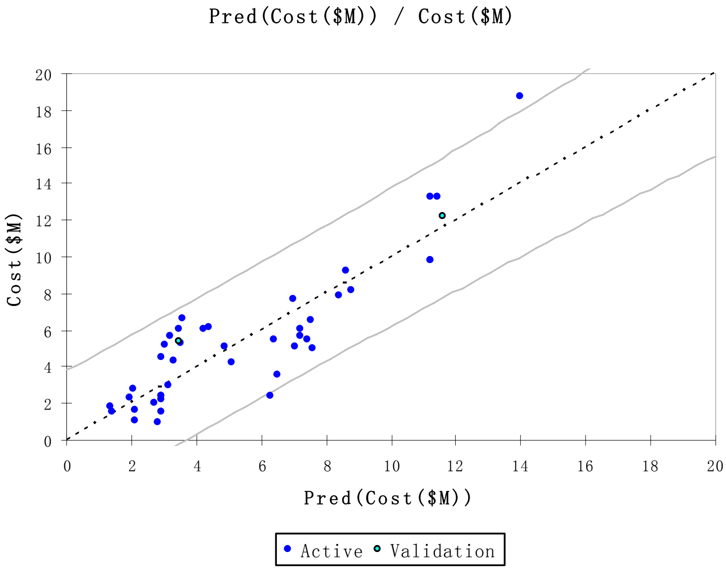


Figure E.4 – Quality of CER – Exponential PLSR

From the chart of predicted costs versus actual costs, the trend is not clear and departures of many observations can be seen obviously. The CER is not satisfied.

E.2.1.1.2 Exponential Regression

After converted all data into denary logarithms, stepwise technique is applied again and the exponential cost equation is:

C_{ENG} =1.286*Dia.$^{1.945}$

R^2=0.718 adjusted R^2=0.711

Only fan diameter is remained to explain the cost. The statistic quality is worse than linear equation.

E.2.1.2 Independent Variables

E.2.1.2.1 Linear Regression

Stepwise regression is applied and the results are as following:

C_{ENG} = -0.304+0.027*Thrust(kN)

R^2=0.761 adjusted R^2=0.741

The average error of predicted costs is 31.80 per cent.

E.2.1.2.2 Exponential Regression

Stepwise regression is applied to denary logarithms, the exponential cost equation is:

C_{ENG} =0.022*Thrust$^{0.736}$*BPR$^{0.908}$

R^2=0.820 adjusted R^2=0.788

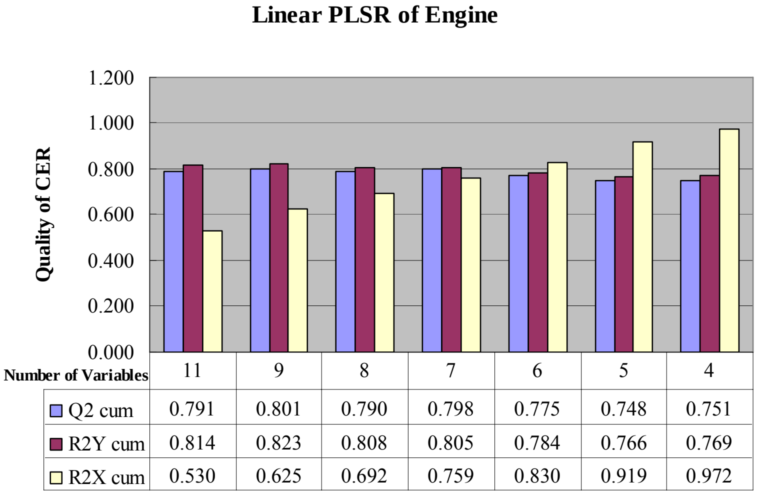
The statistic quality is improved and the average error of 23.48 per cent is much lower compared to equation above.

E.2.2 Partial Least-Squares Regression

E.2.2.1 All Variables

E.2.2.1.1 Linear Regression

PLSR technique is applied and the process of eliminating unimportant variables is illustrated as shown in figure E.5:



Number of Variables	11	9	8	7	6	5	4
🟦 Q2 cum	0.791	0.801	0.790	0.798	0.775	0.748	0.751
🟪 R2Y cum	0.814	0.823	0.808	0.805	0.784	0.766	0.769
🟨 R2X cum	0.530	0.625	0.692	0.759	0.830	0.919	0.972

Figure E.5 – Quality of CER – Exponential PLSR

Considering the quality of model, the CER with 6 variables is chosen as the cost model for engine because its features are more optimum than others. Hence,

$$C_{ENG} = 3.548 + 0.00536 * \text{Thrust} - 8.026 * \text{SFC} + 0.00162 * \text{Airflow} + 0.493 * \text{Length} + 1.073 * \text{Dia.} + 0.000346 * \text{Weight}$$

E.2.2.1.2 Exponential Regression

With the learning from CER for aircraft, the exponential equation may be more suitable for engine cost model as well. Some variables are eliminated for their low VIP (Variable Importance in the Projection).

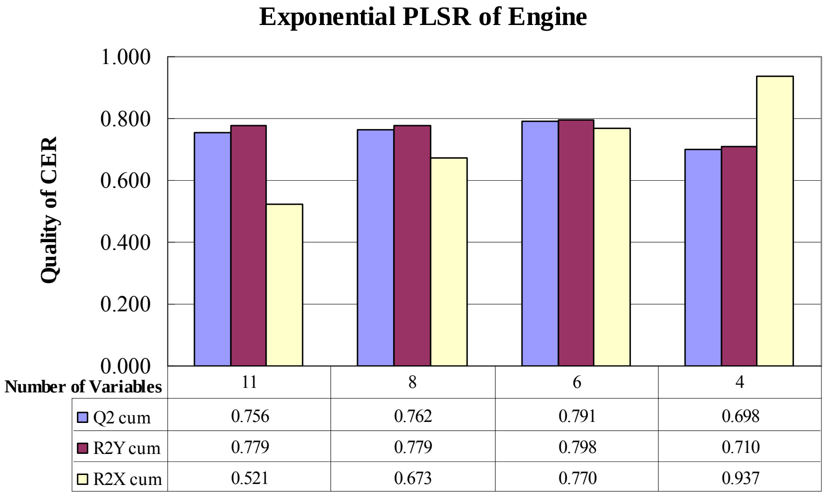


Figure E.6 – Quality of CER – Exponential PLSR

C_{ENG} =0.0236*Thrust$^{0.190}$*BPR$^{0.342}$*SFC$^{-1.166}$*Airflow$^{0.195}$*Dia.$^{0.433}$*Weight$^{0.211}$

E.2.2.2 Independent Variables

E.2.2.2.1 Linear Regression

PLSR technique is applied to 7 independent variables. Age and production number are identified to be not important to the cost. The results are as followings:

7 Variables Q^2 cum = 0.736 R^2Y cum = 0.863 R^2X cum = 0.453

C_{ENG}=-15.035+0.0206*Thrust(kN)+0.101*BPR+0.0000064*Number+0.0107*Temp(°C) -11.579*SFC(lb/lb hour)+16.961*Mach-0.0303*Age

5 Variables Q^2 cum = 0.770 R^2Y cum = 0.853 R^2X cum = 0.634

C_{ENG}=-18.144+0.0191*Thrust(kN)+0.193*BPR+0.011*Temp.(°C)-12.187*SFC(lb/lb hour)+20.174*Mach

So the equation with 5 variables is selected.

E.2.2.2.2 Exponential Regression

Using PLSR, the results are as below:

7 Variables Q^2 cum = 0.760 R^2Y cum = 0.795 R^2X cum = 0.382

C_{ENG}=5.066*Thrust$^{0.355}$*BPR$^{0.628}$*Num.$^{-0.060}$*Temp.$^{1.814}$*SFC$^{-2.14}$*Mach$^{4.13}$*Age$^{-0.059}$

When number and age are removed for their low VIP:

5 Variables Q^2 cum = 0.783 R^2Y cum = 0.813 R^2X cum = 0.503

C_{ENG}=0.978*Thrust$^{0.355}$*BPR$^{0.628}$*Temp.$^{1.814}$*SFC$^{-2.14}$*Mach$^{4.13}$

Thus, latter is chosen for improved quality.

E.2.3 Selection and Discussion

E.2.3.1 CER Selection

All derived CERs are compared as below.

Table E.7 – Comparison of Engine CERs

CER	A	B	C	D	E	F	G	H
Number of Variables	1	1	6	6	1	2	5	5
R^2	0.766	0.718	0.784	0.798	0.761	0.820	0.853	0.813
Average Error(%)	35.08	29.60	41.22	24.77	31.8	24.36	26.12	23.9

A C_{ENG}= 0.343+0.0266*Thrust(kN)

B C_{ENG}=1.286*Diameter$^{1.945}$

C C_{ENG}=3.548+0.00536*Thrust-8.026*SFC+0.00162*Airflow+0.493*Length +1.073*Dia.+0.000346*Weight

D C_{ENG}=0.0236*Thrust$^{0.190}$*BPR$^{0.342}$*SFC$^{-1.166}$*Airflow$^{0.195}$*Dia.$^{0.433}$*Weight$^{0.211}$

E C_{ENG} = -0.304+0.027*Thrust(kN)

F C_{ENG} =0.022*Thrust$^{0.736}$*BPR$^{0.908}$

G C_{ENG}=-18.144+0.0191*Thrust(kN)+0.193*BPR+0.011*Temp.(°C)-12.187*SFC(lb/lb hour) +20.174*Mach

H C_{ENG}=0.978*Thrust$^{0.355}$*BPR$^{0.628}$*Temp.$^{1.814}$*SFC$^{-2.14}$*Mach$^{4.13}$

Finally, the CER G is selected for its highest coefficient of determination and relatively low average estimate error.

E.2.3.2 Discussion

The qualities of all derived engine cost models are not satisfied as expected, and the accuracy is quite lower than that of aircraft cost model. However, five independent variables are identified, which appear in many existing turbine engine cost models. As reviewed in literature, the accuracy of cost estimates for conceptual design ranges from -30 to 50 per cent. Thus, the turbine engine CER can be used at concept design phase to derive rough estimating, especially when quotations are available to be references.