CRANFIELD UNIVERSITY

DEXIN XU

ANALYSIS AND MODELLING OF COST OF QUALITY IN AIRCRAFT TAILPLANE ASSEMBLY

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

MSc by Research Thesis
Academic Year: 2014 - 2015

Supervisor: Salonitis, Konstantinos
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ABSTRACT

With production quality playing a more and more important role in keeping the competitive power of company, Cost of Quality (CoQ) are paid more and more attention in manufacturing industries. Especially in aircraft manufacturing industry, due to the more stringent requirements on quality, the CoQ has been a serious issue for manager. However, due to the specificity of the industry, such as high-tech, low-volume, low degree of automation, the traditional generic CoQ models are not applied directly which make most of the aircraft manufacturing companies are lack of systematic method and efficient tool to analysis and manage CoQ. it is essential to develop a CoQ model which can be used to analyse and estimate the CoQ in the aircraft manufacturing industry.

This research aims at developing a CoQ model for tailplane assembly which can help the quality manager to collect and store the quality issue and cost information, and estimate the CoQ and analyse the benefit of cost spent on quality. The CoQ elements are identified and defined based on the comparing results of the literature and actual operation data. Prevention-Appraisal-Failure (P-A-F)/ Activity-Based-Costing (ABC) system is applied to develop the CoQ estimation system. And Cost-Benefit-Analysis (CBA) is applied to analyse the benefit brought by the cost spend on quality. In order to collect enough professional data for the model, an industry survey is designed. Moreover, some GUIs are designed using VBA in MS Excel to improve the operability and practicability. Furthermore, two different cases and expert judgements are used to validate the developed CoQ model.

The validation result illustrates that the developed model can help the user to estimate and analyse the CoQ in tailplane assembly, and supply a method to analyse quality issues quantitatively. And the overall performance of the model is approved by the experts in aircraft industry. The model is suit for aircraft industry and worth popularizing in this field.

Keywords:

Cost of Quality, CoQ Model, Cost Benefit Analysis, Tailplane Assembly

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ABC	Activity Based Costing
CBA	Cost Benefit Analysis
CoQ	Cost of Quality
CoQES	Cost of Quality Estimation System
FIRR	Financial Internal Rate of Return
FRR	Failure and Rejection Report
FOD	Foreign Object Damage
GUI	Graphical User Interface
NPV	Net Present Value
P-A-F	Prevention-Appraisal-Failure
VBA	Visual Basic for Application

LIST OF NOMENCLATURE

C_{pre}	Prevention Cost
C_{qdm}	Quality Design and Management Cost
C_{eat}	Education and Training Cost
C_{etu}	Equipment and Tool Update Cost
C_{app}	Appraisal Cost
C_{itd}	Inspection and Test Design and Management Cost
C_{ito}	Inspection and Test Operation
C_{eva}	Evaluation Cost
C_{inf}	Internal Failure Cost
C_{scr}	Scrap Cost
C_{rew}	Rework Cost
C_{rep}	Repair Cost
C_{del}	Delay Cost
C_{exf}	External Failure Cost
C_{ffr}	FRR Compensation Cost
C_{ddc}	Delivery Delay Cost
C_{qm}	Quality Management Cost
C_{the}	Theory Education and Training Cost
C_{pra}	Practice Education and Training Cost
C_{nep}	New Equipment and Tool Purchasing Cost
C_{hau}	Hardware Updating Cost
C_{sou}	Software Updating Cost
C_{itse}	Set up Cost
C_{iteq}	Inspection and Test Equipment Cost
C_{itto}	Inspection and Test Tool Cost
C_{itla}	Inspection and Test Labour Cost

C_{iev}	Internal Evaluation Cost
C_{eev}	External Evaluation Cost
C_{scr_mat}	Material Cost of Scrap
C_{scr_com}	Component Cost of Scrap
C_{scr_act}	Activities Cost of Scrap
C_{coq}	Total Cost of Quality
C_{ucoq}	Unit Cost of Quality

1 INTRODUCTION

1.1 Background

Quality is generally thought as one of the core factors for achieving competitiveness in manufacturing or service industries. Any serious attempt to improve quality must take into account the costs associated with achieving quality, and generally quality costs are reported to be between 5% and 30% of sales (Giakatis et al., 2001). The significant influence on profit makes reducing Cost of Quality (CoQ) to be a serious issue for manufacturing industries.

Aircraft manufacturers have to pay more attention and spend more money on product quality than any other manufacturing industries due to the special requirements of airworthiness which is inevitable to bring amount of CoQ. However, not all the aircraft manufacturers attach importance to the CoQ, especially those start-up companies as most of them are generally lack of systematic methods for the CoQ management and benefit analysis.

CoQ modelling is researched and reported as an effective method to analysis and estimate CoQ. And many researchers have made great contribution in this field (Juran, 1952; Crosby, 1979; Feigenbaum, 2001; Curran, 2006). However, the generic CoQ models were researched to analyse the CoQ in the whole lifecycle of product, especially in design phase, and most of generic models developed based on the high-volume and low-technology progress. These models could hardly to use directly in the high-technology and low volume manufacturing process, such as aircraft manufacturing, due to the specificity of these industries. Additionally, though spend millions of money on quality, most of companies do not know how many benefits the investment will bring and have on idea about whether the investment on quality is right due to the lack of effective method.

Hence, it is clear that a CoQ model which can be used to analyse and estimate the CoQ in manufacturing progress for aircraft manufacturing industry is necessary, and effective method to simulate benefit of investment on quality should be researched, either.

1.2 Problem Statement

Aircraft manufacturing is a very complex process, involving approximately more than ten thousands components, dozens of processes, inspections and tests. So it will be a very big project to research the whole manufacturing process in such a short period. Tailplane assembly is a typical assembly process in the aircraft manufacturing. The assembly process is very similar to the wing assembly and connection, therefore it will be easy to transfer the application of the method and models from tailplane to wing, and even the whole aircraft. So for this research, the tailplane assembly was chosen as the breakthrough point of C model in aircraft manufacturing.

CoQ identification and definition are the basic of the framework development of CoQ model. Though many generic models have been developed, the detail categories of CoQ are still based on the actual application background. Hence, finding out the specificity of CoQ in tailplane assembly is the premise of CoQ development.

The difficult point of CoQ estimation is that many kinds of CoQ are difficult to quantify as they are sometimes too abstract. And the influence of the production factors on CoQ is generally complex which make it difficult to calculate at times. Hence, identify and if possibly quantify the drivers of CoQ in the tailplane assembly is the key of the CoQ estimation.

A widely used method on benefit analysis is Cost Benefit Analysis (CBA), but it is scarcely used on quality analysis as it is difficult to estimate the benefit in financial. It is really a challenge to simulate the benefit and represent the relationship between cost and benefit in a manufacturing system as there are too many influencing factors for the results. However, as most of CoQ are caused by quality issues and most of investments focuses on solving them, CBA can be used to evaluate the investment of quality improvement as it will be simply to identify and estimate the benefit for single quality issue. And It may be very important and useful for quality managers in decision-making of quality issues management and quality improvement.

1.3 Aim and Objective

This research aims at developing a CoQ model which suits for the low-volume and high-technology manufacturing industry such as aircraft industry. The model can be used as a tool to estimate and analyze the CoQ in an aircraft tailplane assembly process, and a tool to simulate and analyze the benefit of investment on quality improvement. It will be very useful for quality manager to collect and analyze data.

To achieve the aim, a number of research objectives were set for this research which are shown as follow:

a) To identify the CoQ elements in a high value added assembling process such as the tailplane assembly.

b) To identify and if possibly quantify the drivers of quality cost for such assembling processes.

c) To identify and quantify the benefit of investing in the modelling of the cost of quality.

d) To develop a CoQ model to quantify and estimate the cost of quality in tailplane assembly process.

e) To apply CBA on quality issue improvement.

f) To validate the developed CoQ model through case studies and expert judgement.

1.4 Thesis Structure

The structure of the thesis is illustrated in Figure 1-1. Except this chapter, there are other five chapters in the thesis. In Chapter 2, the related researches on CoQ, Cost Estimation and CBA are reviewed to identify the research gap. Chapter 3 discusses the methodology and its procedure for this research. The process of developing CoQ Model is stated in Chapter 4, and Graphical User Interface (GUI) based on Visual Basic Application (VBA) is introduced at the same time. Chapter 5 focuses on the validation of the developed model. Two kinds of case studies based on tailplane assembly are conducted to validate the CoQ model, and the suggestions from expert judgment are used for the improvement of the model. In the final chapter, the achievements and limitations of present model, key findings and future work are discussed and concluded.

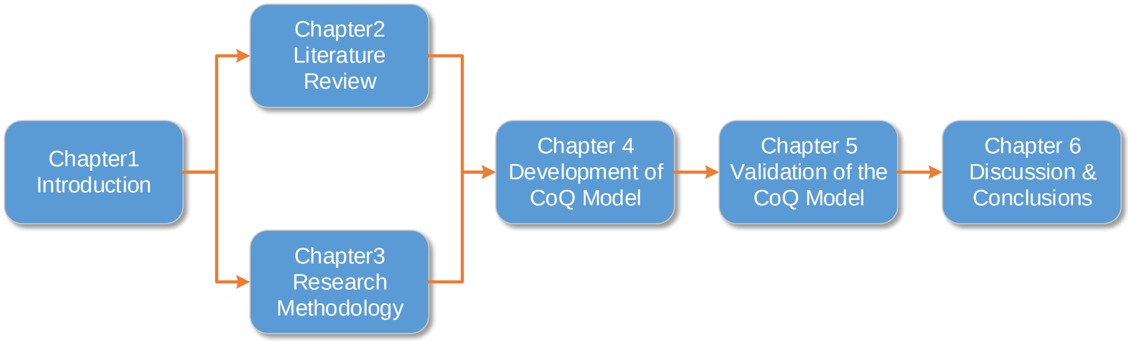


Figure 1-1 Thesis Structure

1.5 Summary

This chapter firstly introduced importance and necessity of CoQ management in manufacturing industries, and the CoQ current situation in aircraft manufacturing industries. Then the problems of CoQ model used in aircraft manufacturing were stated. And challenges for CoQ modelling and benefit analysis in aircraft manufacturing industries were discussed. Then the research aim and objectives were proposed. Developing a CoQ model for tailplane assembly is the target of the research and many objectives need to achieve for the target. In the end, the thesis structure was summarized.

2 LITERATURE REVIEW

2.1 Introduction

In order to understand the context and gain the fundamental knowledge for the research, the literature which is associated with major topics and research field are studied. A brief review of these literature will be presented in this chapter. As illustrated in Figure 2-1, the related literature includes four main parts: Cost of Quality, Cost Estimation, Cost Benefit Analysis and Aircraft Manufacturing.

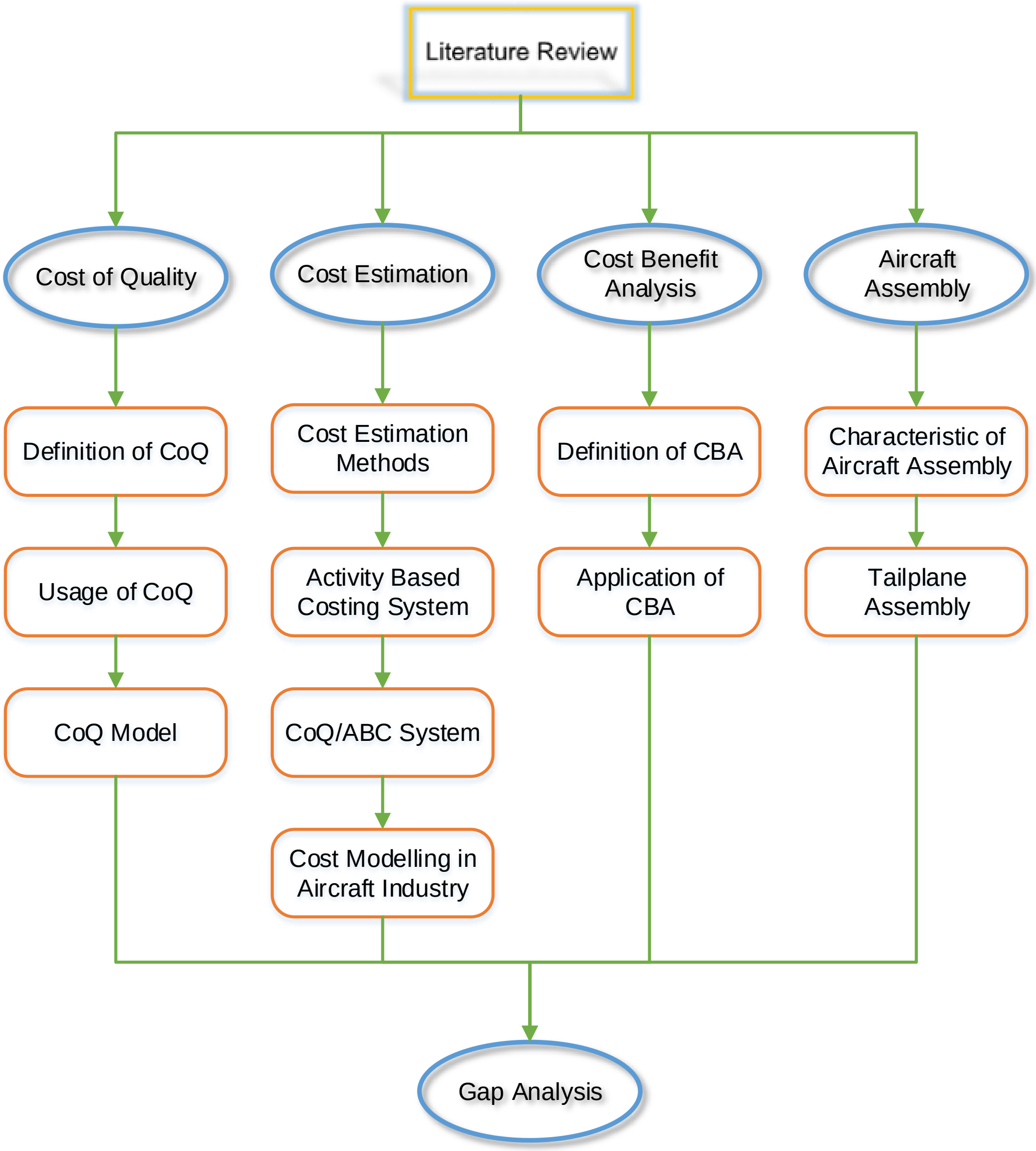


Figure 2-1 Literature Review Structure

In order to identify the CoQ precisely, the knowledge on CoQ were studied first. In Section 2.2, definition and usage of CoQ were introduced first, then the classical CoQ models were discussed, and the advantages and limitations of three main kinds of models were compared and discussed. According to the review results, the definitions and classifications of the CoQ model were determined. After identifying the CoQ, the methods for quantifying and calculating these CoQ were researched. In Section 2.3, various methods for cost estimation were illustrated and compared. Then activity based costing (ABC) system were introduced. After that, CoQ/ABC system which is an effective method to estimate CoQ was presented. As a consequence, estimation method for CoQ was selected. Then CBA method was stated in next section as it was necessary to understand this method well before using it on quality. The characteristics and application of CBA were summarized. And the advantages and limitations were discussed either. Based on the results, the method to identify and quantify the benefit of investing in the modelling of CoQ were decided. As the CoQ model was designed for using in aircraft manufacturing industry, especially in tailplane assembly, so the relevant literature was focused on in Section 2.5. Aircraft manufacturing industry were introduced and its characteristics were summarized through the comparison with other industries, then tailplane assembly was presented in brief. After the review of the literature, research gaps in this field were discussed in Section 2.6. And the final section was the summary of the literature review.

2.2 Cost of Quality

2.2.1 Definition of Cost of Quality

Cost of Quality(CoQ), sometimes called quality costs, which first appeared in Juran's Quality Control Handbook (Juran & Gryna, 1951) in the early 1950s, has been extensively researched by many quality experts in order to improve product quality and reduce costs (Lim et al., 2015). But there is no general agreement on a single broad definition of the CoQ. So various definitions for the CoQ were found in literature (Yang, 2008).

Campanella (1999) defined quality costs as the difference between 'ideal' situation (no failures occur) costs and actual situation costs. Krishnan et al. (2000) and Giakatis et al. (2001) defined CoQ as the costs to prevent a failure and ensure the products meet the requirements. However, some quality researchers called quality cost as ‘cost of poor quality’. Chen & Tang (1992) thought that cost of poor quality includes cost spend on inspection, prevention and cost incurred by corrective actions and imperfect quality. Bland et al. (1998) defined the cost of poor quality as the difference between the actual operating cost and the operating cost with no failures or mistakes in systems and staffs.

The different terminology and descriptions being different may result in the difference of identification and classification of CoQ. However, it is apparent that the term ‘cost of quality’, ’quality cost’ and ‘cost of poor quality’ are similar when calculate the total CoQ. In other words, the cost spend on the activities which are different from the ‘ideal situation’ to meet requirements are CoQ or contribution to the cost of poor quality. So these various definitions are essentially synonymous (Chiadamrong, 2003). The American Society for Quality Control (ASQC, 1970) and the British Standard Institute (BS 6143, 1990) defined CoQ as the costs incurred in ensuring quality, together with the loss incurred when quality is not achieved. This definition is widely accepted and used in many fields. So it can be used to discuss and identify CoQ in this thesis.

2.2.2 Usage of Quality Costing

CoQ is used as a progress indicator in measuring the overall performance of the organization, and organization can gain competitive advantage is that the CoQ is adequately measured and controlled (Omurgonulsen, 2009). Juran (1952) characterized the poor quality and its related costs as ‘gold in mine’. The importance of the quality costs has been realized by more and more companies in recent years as the quality costs represent a considerable proportion of a company’s total costs and sales (Giakatis et al, 2001). Many researchers (Wheelright and Hayes, 1985; Albright and Roth, 1992; Feigenbaum, 2001; Kent, 2005) reported the CoQ they estimated in different companies. Generally, quality costs are between 5 and 30% of sales (Yang, 2008). Reducing 10% of quality cost, the company may get hundreds of millions profit. That is why more and more experts and companies focus on the research of CoQ.

Quality costing not only can be used to reflect the profit, but also can be a useful method to help the top leader to manage the company (Hwang & Aspinwall, 1996). First, quality costing can be the first step to set up a quality system for many start-up companies. Secondly, quality costing can be the power for the top management to determine improvement project because the monetary data will be easier to arouse manager's feelings. At last, quality costing will establish a channel between the production line and top manager as quality costs integrate all the separate quality activities into a total quality system (Yang, 2008).

2.2.3 CoQ Model

Many experts analyzed the CoQ and set up CoQ models. Schiffauerova and Thomson (2006) summarized the main models in use, and Mohamed & Sharmeeni (2014) updated the information as detailed in Table 2-1. In all these models, P-A-F model, Process model and Taguchi Loss Function are the three main kinds of models which are wildly used in many fields.

Table 2-1 Generic Cost Models and Categories (Mohamed & Sharmeeni, 2014)

<table>
<tr><th>Genetic Model</th><th>Cost/Activity Categories</th></tr>
<tr><td>P-A-F Model</td><td>Prevention + Appraisal + Failure</td></tr>
<tr><td>Crosby's Model</td><td>Conformance + Non-conformance</td></tr>
<tr><td rowspan="4">Opportunity or Intangible Cost Models</td><td>Prevention + Appraisal + Failure + Opportunity</td></tr>
<tr><td>Conformance + Non-conformance + Opportunity</td></tr>
<tr><td>Tangibles + Intangibles</td></tr>
<tr><td>P-A-F (Failure Cost includes Opportunity Cost)</td></tr>
<tr><td>Process Cost Models</td><td>Conformance + Non-conformance</td></tr>
<tr><td>Taguchi Loss Function Model</td><td>Loss of sales revenue due to poor quality + Process inefficiencies + Losses when a quality characteristic deviates from a target</td></tr>
</table>

2.2.3.1 P-A-F Model

The P-A-F model is the oldest CoQ model, which is one of the best known and widely accepted models among quality practitioners and has been used in both manufacturing and service industries. Feigenbaum's and Juran's P-A-F scheme has been adopted by the American Society for Quality Control (ASQC, 1970), and the British Standard Institute (BS6143, 1990).

- ***Prevention cost:*** the costs of all activities specifically designed to prevent poor quality in products and services.
- ***Appraisal cost***: the costs associated with measuring, evaluating, or auditing products or services to assure conformance to quality standards and performance requirements.
- ***Internal failure cost***: the costs resulting from products or services not conforming to requirements or customer/user needs occur prior to delivery or shipment to the customer.
- ***External failure cost***: the costs resulting from products or services not conforming to requirements or customer/user needs occur after delivery or shipment of the product, and during or after furnishing of a service to the customer.

Table 2-2 shows the general categorization and examples of CoQ in P-A-F model. Yang (2008) summarized the results of former researchers, and analysed the detailed cost of quality in the manufacturing (assembling) process (see Table 2-3). The categories of CoQ from Yang were based on P-A-F model, but additional extra resultant costs and estimation hidden costs were identified.

P-A-F models are widely used in many industries. The United Technologies Corporation, Essex Telecommunication Products Division, established CoQ measurement based on a P-A-F model, and Fruin (1986) examined the costs elements calculation and their relationship to financial performance in detail. Thompson and Nakamura (1987) proposed a plan based on P-A-F quality costing structure, which is currently being used at AT&T Bell Laboratories, Transmission Systems Division. Denzer (1978) presented a description of a P-A-F CoQ system used in an electronics manufacturing facility.

The traditional P-A-F model held that there was an optimum economic level of quality at which the cost of securing higher quality would exceed the benefits of the improved quality (BS4778, 1987). However, the concept is challenged by many researchers (Fox, 1989; Marcellus & Dada, 1991), and some empirical evidence was found to support the idea about no economic level of quality. So there may be some limitations in using P-A-F model to discuss the quality level.

Table 2-2 General P-A-F Model for Categorization (Srivastava, 2008)

CoQ Categories	Examples
Prevention Costs	• New product review • Quality Planning • Supplier capability surveys • Process capability evaluations • Quality improvement team meetings • Quality improvement projects • Quality education and training
Appraisal Costs	• Incoming and source inspection/test of purchased material • In-process and final inspection/test • Product, process or service audits • Calibration of measuring and test equipment • Associated supplies and materials
Internal Failure Costs	• Scrap • Rework • Re-inspection • Re-testing • Material review • Downgrading
External Failure Costs	• Processing customer complaints • Customer returns • Warranty claims • Product recalls

Table 2-3 Cost of Quality in Manufacturing (Assembly) (Yang, 2008)

CoQ Categories	Examples
Prevention Costs	● Operations process validation ● Operations quality planning ● Design and development of quality measurement and control equipment ● Operations support quality planning ● Operator quality education and training ● Operator SPC/process control ● Salaries of quality administrators ● Administrative expenses for quality planning and control ● Quality program planning ● Quality performance reporting and analysis ● Quality education ● Quality improvement ● Quality system audits ● Investment in tools and equipment of quality control
Appraisal Costs	● Planned operations inspections, tests and audits ● Salaries of checking labours ● Miscellaneous quality evaluations ● Inspection and test materials ● Set-up inspections and tests ● Process control measurements ● Laboratory support ● Investments and maintenance expenses of measurement (inspection and test) equipment ● Salaries of maintenance and calibration labours ● External appraisal costs ● Field performance evaluation ● Review of test and inspection data
Internal Failure Costs	● Material review and corrective action costs ● Disposition costs for defects in the process ● Troubleshooting or failure analysis costs (operations) ● Costs of operations corrective actions

	• Operations rework costs • Operations repair costs • Investigation support costs • Re-inspection/retest costs • Costs in labour hours associated with scraps in process • Costs in materials associated with scraps in process
External Failure Costs	• Costs of complaint handling • Costs of handling and repair of returned goods • Costs of scraps of returned goods • Warranty claims • Liability costs
Extra Resultant Costs	• Waste of labour hours and scrap of other parts destroyed, which were caused by failure operations in the process • The increase costs of downtime, additional inventory due to the poor quality in process • The resultant costs of the defect bypass the quality control system • Freight and insurance premium costs • The resultant costs by inadequate quality, delivery and reliability • The increase costs caused by the delayed order delivery Penalties of customer damage caused by defective goods
Estimated Hidden Costs	• The lost sales owing to poor quality in the past • Loss-of-reputation costs • The opportunity cost of lost customer loyalty • The delay launch of new product due to the poor quality in process • Brand image damage

2.2.3.2 Process Cost Model

The concept of the process cost model was originally developed by Crosby (1979) who defined the CoQ as the sum of the price of conformance (POC) and the price of non-conformance (PONC). BS6143 (1990) accepted the concept, but replaced the world ‘price’ with ‘cost ’.

The process cost model was first used for quality costing by Marsh (1989) which represents quality cost systems that focus on process rather than products or services. Process cost is the total cost of conformance and non-conformance for a particular process. The structure of the model is shown in Figure 2-2. The cost of conformance is the actual process cost of producing products or services first time to the required standards by a given specified process, and cost of non-conformance is the failure cost associated with the process not being executed to the required standard. These costs can be measured at any step of the process. Accordingly, it can be determined whether high non-conformance costs show the requirement for further expenditure on failure prevention activities or whether excessive conformance costs indicate the need for a process redesign (Porter and Rayner, 1992).

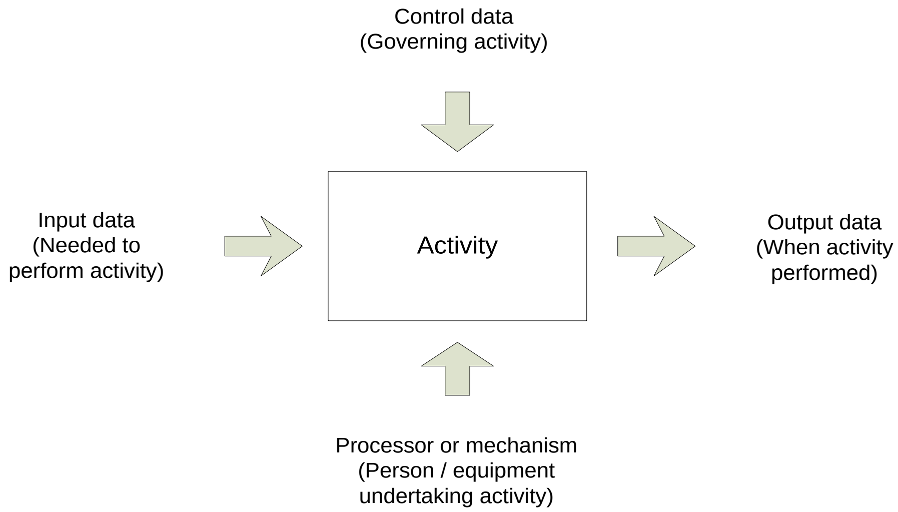


Figure 2-2 Process Cost Model Structure (Hwang & Aspinwall, 1996)

A successful example in using process cost model is design and implement in the power systems division of GEC Alsthom Engineering Systems. Goulden and Rawlins (1995) describe this hybrid process model by using flowcharts.

The process modeling method called IDEF (the computer-aided manufacturing integrated program definition methodology) developed by Ross (1977) is useful for experts in system modeling; nevertheless, for common use by managers or staff it is too complex. Though some researchers (Crossfield & Dale, 1990; Goulden & Rawlins, 1995) tried to develop simpler methods to overcome this limitation, the process cost model is not in widespread use.

2.2.3.3 Taguchi Loss Function Model

Traditionally, it has been accepted that quality losses are not incurred within specification limits but outside them. Therefore, products or services whose characteristics are within specifications should not produce any external failure costs. The reality, however, is different. These products can incur opportunity costs associated with lost sales, or customer dissatisfaction after delivery. Taguchi (1987) formulated these external quality losses into a loss function based on his own industrial experience. The function is parabolic, with the loss increasing continuously as the characteristic moves away from the nominal point; there is no discontinuity at the specification limits. The loss function curve (see Figure 2-3) is

$$\mathrm{L} = \mathrm{C}\,(X - T)^2 \tag{2-1}$$

Where L = loss (£), C= cost coefficient, X = quality characteristic and T = target.

The Taguchi loss function is considered a breakthrough in describing quality, and helped fuel the continuous improvement movement that since has become known as lean manufacturing. And it can help engineers better understand the importance of designing for variation. But it does not include avoidable costs and quality costs incurred within the manufacturing plant, reflecting only the impact of the finished product. At the same time, it does not directly show relationships between prevention and quality improvement in-house. In addition, the model is difficult to apply because of the problems associated with correctly identifying the probability distribution of the product defects which influence the loss after delivering to the customer.

From the literature summarized above, it can be found that CoQ which has significant influence on profits need to be paid more attention. Though there are various definitions for the CoQ, most of them are essentially synonymous. Though there may be some limitations in discussing quality level, the P-A-F classification is still the widely accepted and may be suit for the CoQ model in this research.

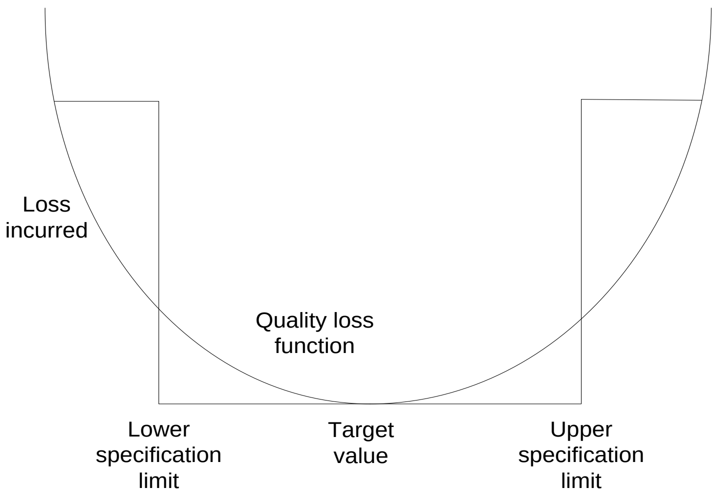


Figure 2-3 Taguchi Loss Function (Hwang & Aspinwall, 1996)

2.3 Cost Estimation

The importance and potential benefits of the measurement of CoQ has been emphasized by many researchers (Giakatis et al., 2001; Prickett & Rapley, 2001; Chen & Yang, 2002). However, the quantification of CoQ has been neglected by most organizations (Harry & Schroeder, 2000). Cost estimation is an effective method to quantify the CoQ within a defined scope.

2.3.1 Cost Estimation Techniques

Liebers (1998) recommended three sub layers to effectively estimate and control cost in manufacturing environments, which are “production monitoring”, “cost calculation and evaluation” and “cost modelling” respectively. Cost modelling which has been applied to support cost estimation, business analysis and planning, project management, profitability analysis is a significant useful method to get support data for business decisions (Curran et al. 2004). Many researchers and industrialists (Roy and Palacio 2000, Rush and Roy 2000, Agyapong-Kodua 2009) have proposed and experimented with different cost-modelling techniques and suggested it was necessary to develop structured enterprise models to scientifically support cost estimation and control.

Boehm (1984) classified and described seven cost-modelling techniques in his research on the economics of software engineering, which are Parametric, Expert judgment, Analogy, Parkinson, Price to win, Top down, Bottom-up respectively. Shehab and Abdalla (2001) showed another categorization: intuitive, parametric, variant-based and generative. Some researchers (Layer et al. 2002, Foussier 2006) suggested cost-modelling techniques may be classified as qualitative and quantitative from a methodological point of view. And quantitative cost-modelling methods were further classified into statistical, analogous, generative or analytical and feature based (Layer et.al, 2002; Caputo and Pelagagge, 2008). The widely reported cost-modelling techniques were summarized (Niazi et al., 2006), and the key advantages, limitations for each cost modelling technique can be found in Table 2-4.

Table 2-4 Advantages, Limitations for Cost Modelling Technique (Niazi et al., 2006)

<table>
<tr><th colspan="4">Product Cost Estimation Techniques</th><th>Key Advantages</th><th>Limitations</th></tr>
<tr><td rowspan="6">Qualitative Cost Estimation Techniques</td><td rowspan="4">Intuitive Cost Estimation Techniques</td><td colspan="2">Case-Based Systems</td><td>Innovative design approach</td><td>Dependence on past cases</td></tr>
<tr><td rowspan="3">Decision Support Systems</td><td>Rule-Based Systems</td><td>Can provide optimized results</td><td>Time-consuming</td></tr>
<tr><td>Fuzzy Logic Systems</td><td>Handles uncertainty, reliable estimates</td><td>Estimating complex features costs is tedious</td></tr>
<tr><td>Expert Systems</td><td>Quicker, more consistent and more accurate results</td><td>Complex programming required</td></tr>
<tr><td rowspan="2">Analogical Cost Estimation Techniques</td><td colspan="2">Regression Analysis Model</td><td>Simpler method</td><td>Limited to resolve linearity issues</td></tr>
<tr><td colspan="2">Back Propagation neural network model</td><td>Deal with uncertain and non-linear problems</td><td>Completely data-dependence, Higher establishment cost</td></tr>
<tr><td rowspan="3">Quantitative Cost Estimation Techniques</td><td colspan="3">Parametric Cost Estimation Techniques</td><td>Utilize cost drivers effectively</td><td>Ineffective when cost drivers hard to define</td></tr>
<tr><td rowspan="2">Analytical Cost Estimation Techniques</td><td colspan="2">Operation-based cost models</td><td>Alternative process plans can be evaluated to get optimized results</td><td>Time-consuming, required detailed design and process planning data</td></tr>
<tr><td colspan="2">Break-down cost models</td><td>Easier method</td><td>Detailed cost information required</td></tr>
</table>

		Cost tolerance models	Cost effective design tolerances can be identified	Require detailed design information
		Feature-based cost models	Features with higher costs can be identified	Difficult to identify costs for small and complex features
		Activity-based cost models	Easy and effective method using unit activity costs	Require lead-times in the early design stages

2.3.2 Activity-Based Costing System

The Activity-Based Costing (ABC) system focuses on calculating the costs incurred on performing the activities to manufacture a product (Niazi et al., 2006). It is presented as a useful means to distribute the overhead costs in proportion to the activities performed on a product to manufacture it. And it proved a good alternative to traditional estimation techniques since it provided more accurate product manufacturing cost estimates (Andrade et al., 1999). Tornberg et al. (2002) investigated the capabilities of the ABC with a particular emphasis on providing useful cost information to product designers. Yang et al. (1998) used process planning, scheduling, and cost-accounting information to estimate manufacturing and machining cost through an activity-based approach.

Some other researchers used the ABC approach to model the manufacturing costs in a specific manufacturing setup. For example, Koltai et al. (2000) estimated costs for flexible manufacturing systems based on the ABC analysis. The implementation procedure of ABC costing system is as follows (Curran et al., 2004):

- Determine the activity centres that relate to certain cost aspects of the product development cycle.
- Determine the activity pools that relate to sets of activities.
- Determine the allocation base per activity pool as the cost driver.
- Determine the overhead costs per activity pool.
- Calculate the overhead costs per cost driver (rate).

ABC method can provide more logical, detailed and hence more comprehensive and accurate estimates of cost, especially when overhead cost are significant or when the product range is very diverse (Qian & Ben-Arieh, 2008). It is easy to understand the cause and effect of every activity, which allows the identification of valued-added and non-value-add manufacturing operations and how resources are consumed.

But ABC method requires amounts of specific and accurate data (Curran et al., 2004), which means that a detailed design definition is needed. Developing and implementing such an accounting system is also time consuming, expert knowledge may be required.

2.3.3 CoQ/ABC System

ABC is an alternative approach that can be used to identify, quantify and allocate quality costs among products, and therefore, helps to manage CoQ more effectively. Tsai (1998) proposes an integrated CoQ-ABC framework, in which ABC and CoQ systems are merged and share a common database in order to supply various cost and non-financial information for related management techniques. The long-term goal of ABC system is to eliminate non-value added activities and to continuously improve processes, activities and quality so that no defects are produced (Özkan & Karaibrahimoğlu, 2013).

CoQ/ABC, as an alternative costing method overcomes the deficiencies of traditional cost accounting, by analysing the activities of the production process, determining the costs of the resources consumed by each activity and allocating activity costs using an appropriate cost driver for each quality-related (according to PAF scheme) and quality unrelated cost.

Figure 2-4 shows a P-A-F/ABC system framework. The first step in CoQ measurement under ABC is the activity analysis and categorization of activities as value-added or non-value-added. In the second step, each activity of ABC is categorized as quality-related or quality-unrelated activities using the PAF. In the third step, resource costs (including overheads) are traced to quality-related and quality-unrelated activities. Where the resources are used in a single quality-related activity, they are traced directly, and where used in several activities, they are assigned among the activities using a resource driver. CoQ is measured as the sum of the costs of quality-related activities. After activity costs are calculated, they are traced to cost objects using activity drivers.

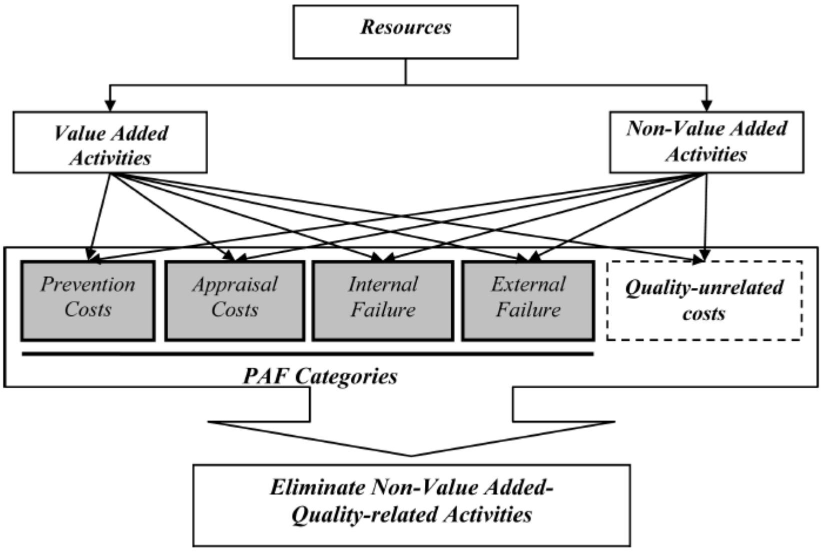


Figure 2-4 P-A-F/ABC Framework (Özkan & Karaibrahimoğlu, 2013)

2.3.4 Cost Modelling in Aerospace Industry

Cost modelling is nevertheless largely based on experience rather than science, because it lacks a consolidating theory (Curran et al., 2006). Cost estimation requires knowledge capture from various disciplines and it is affected by unpredictable factors, so it is 'information sensitive' (Langmaak et al., 2013).

The aerospace industry is a typical example of high-tech but low-volume manufacturing, where it is very challenging to obtain well documented and comprehensible costing information (Curran et al., 2004). The sparse and inaccurate data often increases the challenge of creating objective cost estimates and validating these (Collopy & Curran, 2005). Therefore, many researchers tried to use various methods to estimate cost in aerospace industry.

Banazadeh and Jafari (2012) summarized the common cost estimation methods for main steps in the life cycle of an aerospace system in their research (see Figure 2-5). And complexity index theory is utilized to develop a heuristic complexity-based method to estimate various costs of aerospace systems. The model shows a better R^2 value, as a statistical measure of regression quality, than an already existing successful model by Technomics

Corporation, regarded as a pioneer in this field.

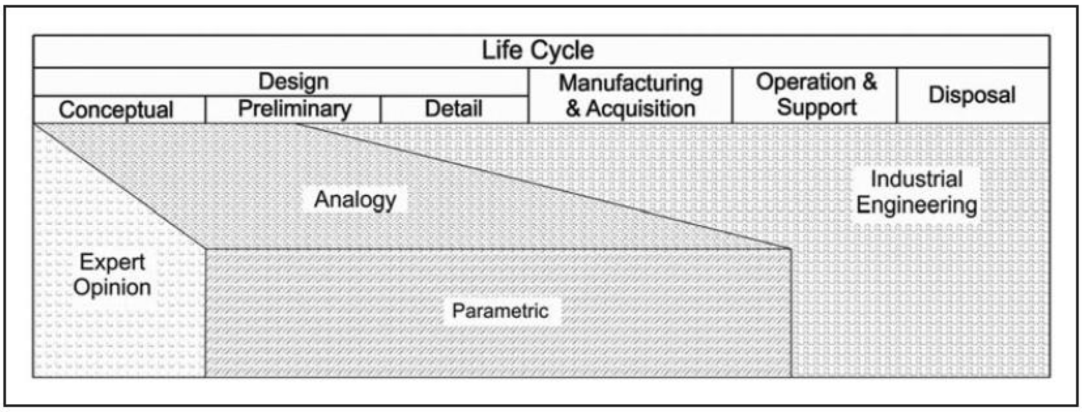


Figure 2-5 Common Cost Estimation Methods for Main Steps in the Life Cycle of an Aerospace System (Banazadeh & Jafari, 2012)

The parametric estimating technique (Roy et al., 1999) use is widespread within aerospace and varies greatly from being based on purely statistical significance to being more causal in nature; being either linear, exponential (logarithmic linearity) or polynomial in form. Zhang et al. (2014) established the aircraft development project cost estimation model based on the parametric cost estimating method and multiple nonlinear regression analysis method, and gave recommendations of using the parametric cost estimating method to estimate cost of China's aviation aircraft development project.

The analogous costing methodology is characterized by adjusting the cost of a similar product relative to differences between it and the target product. The principle is widely used within aerospace costing. An example of analogous costing details one methodology that was developed for the costing of nose-cowls on engine nacelles (Taylor, 1997). Zhou et al. (2014) related the activity based costing method used in calculating cost in a china-based aviation manufacturing enterprise. The results showed that ABC in more accurate than the conventional volume-based product-costing system. However, most of researches are focused on the design phase because many researchers suggested that 70 - 80% of the total avoidable cost was controllable at the design stage and conceptual design wielded the greatest cost influence (Rush and Roy, 2001).

From the above, cost estimation is a predicting process to quantify the CoQ in defined scope. Various methods are applied in cost modelling, and ABC method which can provide more logical and detailed accurate estimation of cost. Moreover PAF/ABC system is an effective method to estimate the CoQ in manufacturing industry. Furthermore, though various cost estimation techniques are used to estimate the cost in aerospace industry, ABC are rarely used. So the PAF/ABC system used to estimate the CoQ in aircraft manufacturing industry may be a beneficial research.

2.4 Cost Benefit Analysis

2.4.1 Definition of Cost Benefit Analysis

Cost Benefit Analysis (CBA) which sometimes called benefit–cost analysis (BCA) is a systematic approach to estimating the strengths and weaknesses of alternatives that satisfy transactions, activities or functional requirements for a business. It is a technique that is used to determine options that provide the best approach for the adoption and practice in terms of benefits in labour, time and cost savings etc.

CBA is an analysis of the expected balance of benefits and costs, it can help predict whether the benefits of a policy outweigh its costs, and by how much relative to other alternatives. CBA usually tries to put all relevant costs and benefits on a common temporal footing using time value of money calculations. Generic CBA includes 9 steps (Boardman, 2006):

- List alternative projects/programs.
- List stakeholders.
- Select measurement(s) and measure all cost/benefit elements.
- Predict outcome of cost and benefits over relevant time period.
- Convert all costs and benefits into a common currency.
- Apply discount rate.
- Calculate net present value of project options.
- Perform sensitivity analysis.
- Adopt recommended choice.

2.4.2 Application of Cost Benefit Analysis

CBA is a method to identify the risk mitigation strategies which supply an optimal trade-off between the cost estimation and risk reduction. It can be widely used in many different fields such as engineering, health management, and policy making (Špačková & Straub, 2015). One of the typical application of CBA is economic assessment of natural hazard mitigation projects (Rose et al., 2007; Defra, 2009; Hochrainer-Stigler, 2011). Additionally, CBA can be used in risk-based optimization of climate change and the management of man-made risks (Paltrinieri, 2012). Another important application of CBA is to evaluate the effect of policies and regulations in many field such as terrorist prevention estimation (Stewart & Mueller, 2013), earthquakes resistance improvement through retrofitting of buildings (Li et al., 2009), air pollution control (Fann et al., 2011) and medicine test (Meckley et al., 2010).

Quality management is a field which need amounts of investments. However, the CBA is rarely used in this filed as it is difficult to estimation the benefit in the complex manufacturing process. Only few experts tried to apply CBA in quality management. Porter and Rayner (1992) suggested a simple cost benefit model to monitor the effect of a TQM program without reflecting the dynamics of the quality activities. Bajpai (1989) developed a simulation model over time with system dynamics techniques, which enumerated different elements of costs and benefits relating to preventative activities in a manufacturing company. Merino (1988) also developed a detailed cost benefit model related to technology, which considered the types of quality problems encountered and their possible solution using engineering economics. But the model did not explain the interacting effect between different activities or departments because of dealing with them independently.

The CBA can supply support to the manager in the decision-making phase before investment. And the main limitations for its application are benefit identification and estimation. Though some of experts had tried to apply CBA on quality, quantitative estimation in benefit was still a difficult issue and the application in aircraft manufacturing industry had not been reported. So it may be a beneficial and necessary attempt to apply CBA on the quality management in aircraft manufacturing industry in this research.

2.5 Aircraft Assembly

Aircraft assembly (see Figure 2-6) is the final phase of aircraft manufacturing. Generally, aircraft assembly includes subassembly and final assembly. Figure 2-7 show the overview of structural assembly of aircraft. In the subassembly phase, all the sub-assembly components used in final assembly will be assembled, the part of work generally finished by different suppliers all over the world. In the final assembly phase, these sub-assembly components will be assembled together through some special process such as riveting and welding, this part of work generally finished by aircraft manufacturing companies such as Boing and Airbus.

Figure 2-6 Aircraft Assembly (Michael, 2009)

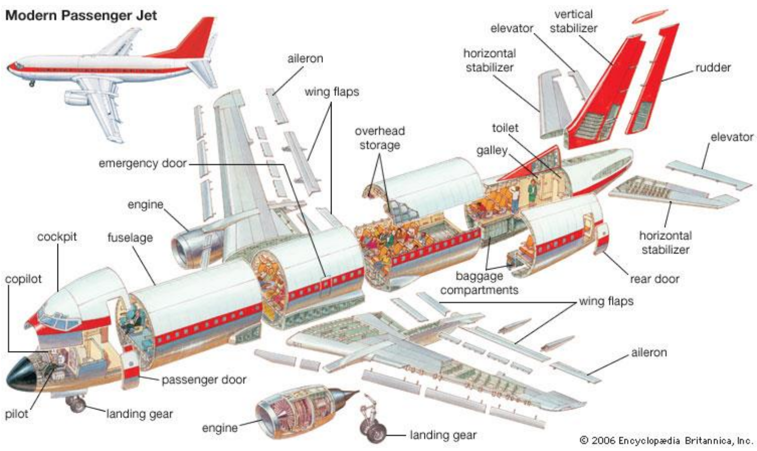


Figure 2-7 Overview of Structural Assembly of Aircraft (Encyclopaedia, 2006)

2.5.1 Characteristic of Aircraft Assembly

Aircraft assembly is a very complex set of process and it is different from other manufacturing industry in many aspects. This tremendous amount of drilling and fastening, along with demanding tolerances makes aerospace assembly one of the most challenging but at the same time exciting fields in aircraft manufacturing. Compared with other manufacturing or assembly industry, the characteristic of aircraft assembly can be summarized as '3-high, 1-low'.

2.5.1.1 High Complexity

Aircraft may be the most complex product in the world. Generally a typical automobile is composed of approximately 20,000 components, while a 150 seat airplane is composed of approximately 2 million components, and in some large plane such as A380, the amount of components may exceed 4 million (Ekinci, 2013). It is well known that the more components are used, the more difficulty of coordination and tolerance distribution are brought. And the increasing trends are generally not linear, sometime it will increase exponentially. And the more components are used, the more process are required. The manufacturing process of Airbus wings requires the drilling of over 40 million holes in aircraft structures per annum (Ekinci, 2013). Even that the error rate for equipment and operator is very low, facing to such large base, the quality problem could hardly be controlled in a low level. So the possibility of occurring quality issue will be much higher than other manufacturing industry.

2.5.1.2 High Precision

Aircraft is a complex product, but the precision requirement of the assembly process is much higher than other manufacturing process which can reduce the possibility of problem occurred in the operation. The more complex it is, the more precision it needs. In general, a spot weld gun in car assembly is positioned within +/- 1.2 mm; while a drilling machine in aircraft assembly requires positioning within +/- 0.2 mm and sometimes with higher tolerance

(Ekinci, 2013). High precision requirement means low error-tolerant rate which result in the increase of possibility of quality issue in the assembly process.

2.5.1.3 High Cost

Aircraft may be the most expensive product in the world. The average price of one A320 is approximately 40 million pounds while one BMW X5 is only 50 thousand pounds. The high price reflects the high cost of aircraft manufacturing. One reason is the components, equipment, tools and labour used in aircraft manufacturing are high cost. Only the cost of one of engine is approximately 4 million pounds. Another reason is the CoQ. Due to the high cost of these main factors, the failure cost and investment on quality certainly will be high. Assembly can take up to as much as 40% of the total cost of manufacturing an aircraft. So aircraft assembly is really a high cost process. And the cost of quality certainly will be very high in this process either.

2.5.1.4 Low Degree of Automation

Aircraft assembly is not a high-volume process. Compared with automobile, the yield of aircraft is too low. Even in Boing which may be the biggest aircraft manufacturing company, the annual yield can hardly be more than 5000, while annual yield of Ford automobile is more than 5 million. One of the reasons is the degree of automation. Though some automation equipment such as automatic assembling line have been used in the aircraft assembly, but due to the complexity of the assembly process and the input-output ratio, much of the work in aircraft assembly is still depend on the manual. The 40 million holes which are on the Airbus wings, approximately 80% of total, were drilled manually (Ekinci, 2013). There are too many influence factors in the manual operation which may result in quality issue in different ways. So low degree of automation may affect the improvement of quality assurance.

2.5.2 Tailplane Assembly

Tailplane, also known as horizontal stabiliser, is a small lifting surface located on the tail behind the main lifting surfaces of a fixed-wing aircraft as well as other non-fixed-wing aircraft such as helicopters and gyroplanes (see Figure 2-

8). The structure of tailplane is similar as wing, the difference is that tailplane is smaller and the internal structure of tailplane is simpler.

Tailplane is generally composed of one central section and two symmetrical overhanging sections (Figure 2-9). Central section is composed of spindle joint of front girder and back girder, side rib, 3 upper siding, 3 under siding, mast section of actuator joint (Figure 2-10). Overhanging section is composed of front girder, back girder, upper siding, lower siding, wing rib, leading edge, trailing edge cabin, wing end fairing, wing root fairing, hinge brackets of elevators (See Figure 2-11).

Figure 2-8 Position of Tailplane in an Aircraft (Brady, 2014)

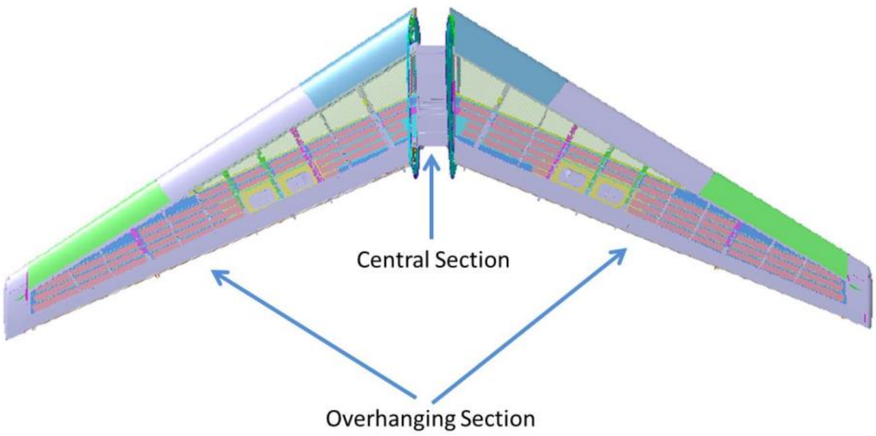


Figure 2-9 Tailplane

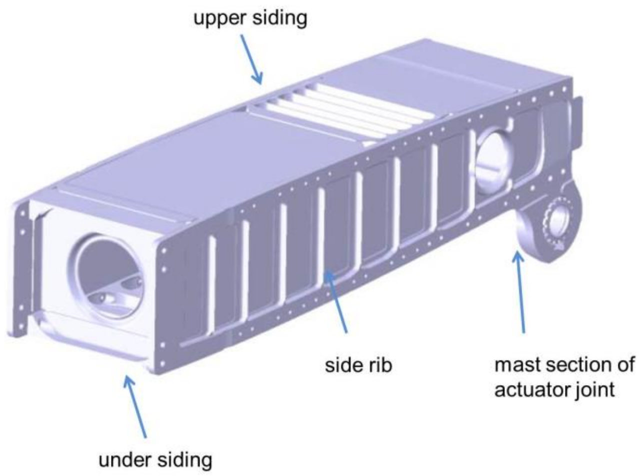


Figure 2-10 Central Section

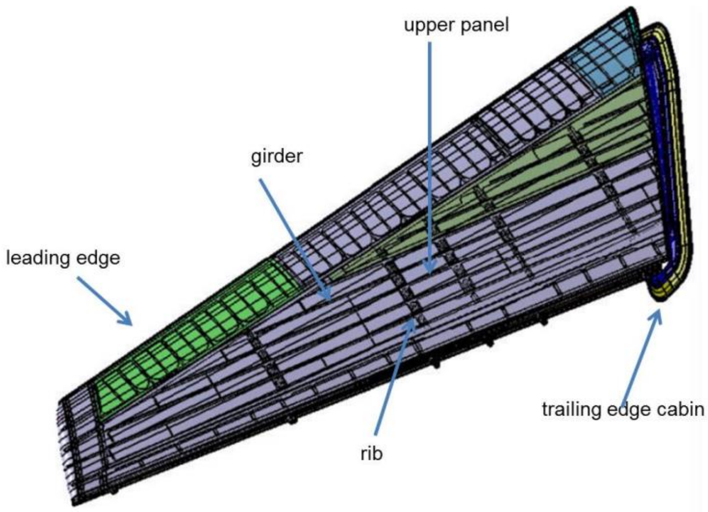


Figure 2-11 Overhanging Section

Tailplane assembly process includes five main phases: left overhanging section assembly, right overhanging section assembly, centre section assembly, elevator assembly and final assembly. Each phase consists of a series of sub-assembly process. The schematic diagram and process map of the tailplane assembly process are shown in Figure 2-12 and Figure 2-13 respectively. The process involves thousands of components, tens of technologies (Wang, 2012). The main technologies are summarized in Table 2-5. Additionally, quality issues are normal in such a complex process (Yang, 2014), and the main quality issues are summarized in Table 2-6.

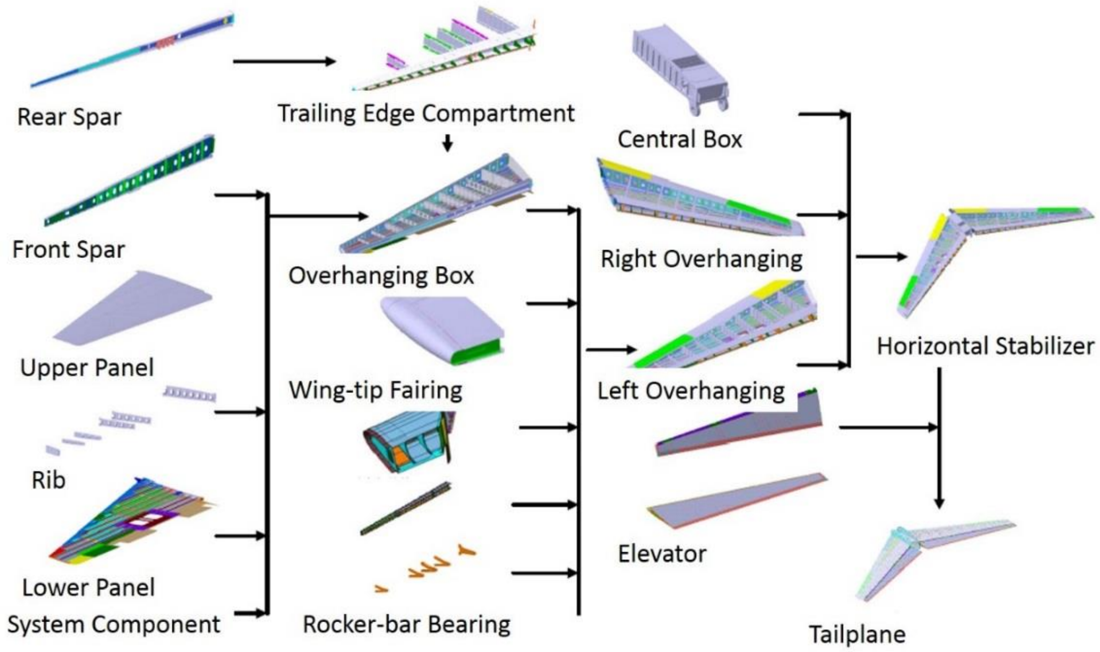


Figure 2-12 Schematic Diagram of Tailplane Assembly

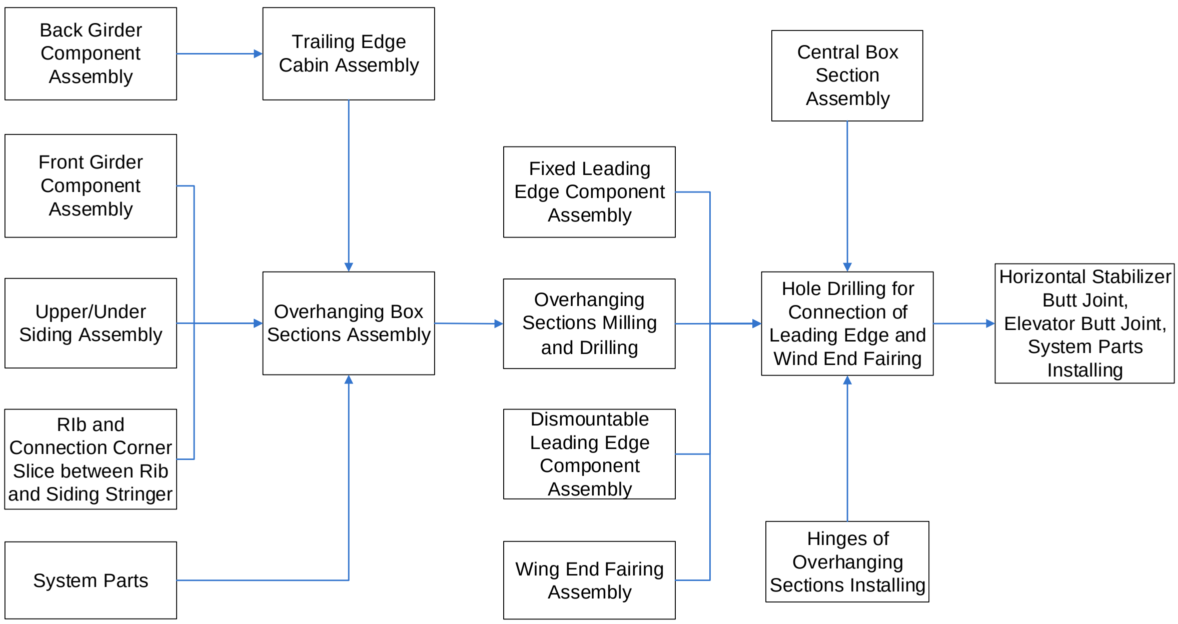


Figure 2-13 Process Map of Tailplane Assembly

Table 2-5 Main Technologies in Tailplane Assembly (Wang, 2012)

Process	Drilling, Dimpling, Bearizing, Boring, Burring, Riveting, Positing, Installing, Cementing, Cleaning, Sealing, Fixing, Hoisting, Reaming, Weighting, Milling, Trimming
Inspection	Part Check, Hole Diameter Inspection, Position Inspection, Foreign Object Damage (FOD) Inspection, X-ray Inspection, Laser Measurement, Painting Inspection, Cementing Inspection
Test	Axial Force Test, Push-out Test, Pipe Pressure Test.

Table 2-6 Main Quality Issues in Tailplane Assembly (Yang, 2014)

Hole Problem	Hole diameter too small, Hole diameter too big, Wrong position, Wrong shape
Riveting Problem	Wrong rivet, Wrong position, Wrong angle
Sealing Problem	Leak
Cementing Problem	Wrong glue, Wrong position
Positioning Problem	Wrong position
Roughness Problem	Too coarse
Painting Problem	Wrong paint, Wrong temperature, Wrong thickness

2.6 Research Gap Analysis

Based on the literature review above, it can be seen that several researchers have done lots of contributions on CoQ models. And some of the theories can be applied in aircraft manufacturing industry.

However, there are still some limitations in these researches. Firstly, though P-A-F model had been used in some aerospace company, there is rare report to show the parameters and data used in the models which made it difficult to use for reference. Secondly, CBA is an effective method to supply support data for decision-making before investment. But it is scarcely used in the field of quality management, and little research only gave some qualitative discussion on the relationship between cost and benefit, but how to quantitatively represent and analyze the benefit were not mentioned and the application of CBA on quality management in aircraft manufacturing industry had not been reported.

In general, it is hardly to find a ready-made CoQ model to estimate and analyze the CoQ in aircraft assembly process. So it is necessary to develop a CoQ model which suits for the actual aircraft assembly and includes the quantitative cost benefit analysis which is the target area of this research.

2.7 Summary

In this chapter, the literature, which is associated with the major topics and research field are studied and reviewed. The literature review indicates that many researches have been done on cost of quality model, cost estimation and cost benefit analysis. And some of studies have been conducted on the topic of cost of quality model used in aircraft industry. Though some of these results can be used for reference, it is difficult to find a CoQ model which can be used in aircraft assembly directly and can analyse the benefit of investment of quality. So based on the research gap, this research will focus on developing a CoQ model which suit for tailplane which is an exploration for the CoQ model for the whole aircraft assembly process.

3 RESEARCH METHODOLOGY

3.1 Introduction

Prior to conducting research, it is essential for the researcher to develop a CoQ model which can be used to estimate and analyse the CoQ and simulate the benefit of cost on quality in aircraft manufacturing industry. It is imperative to select the correct methods for fulfilling the research. Firstly, in order to obtain a comprehensive body of knowledge on the research and reduce bias due to the researcher’s personal interest or preferences, literature which is related to the topic need to be studied. Literature review can help the researcher to comprehensive the context better. Secondly, the reported models and parameters are the important references for the development of the CoQ model, the theory data can be collected through literature review. Meanwhile, actual parameters and records in aircraft manufacturing industry are the guideline of the model development, the actual data can be collected from aircraft companies. However, data from one company may not reflect the characteristic exactly in this industry, industry survey is an effective method for data collection as it is simple and convenient to collect data from amount of sources. Thirdly, there may be some difference between the data collected from literature and industry survey, so contrastive analysis is very important in determining the parameters and calculation method which can improve the applicability of the model. Fourthly, the CoQ model is designed to be a tool for quality management, so it is necessary to be used simply and conveniently. As MS Excel is the most commonly used statistics and calculation software in office, the model is set up base on it. Moreover, in order to improve the operability of the model, Graphical User Interface (GUI) which can supply user friendly interfaces are designed using the VBA in MS Excel. Finally, validation is the indispensable progress for the model development. Real system measurement can test the applicability of the model directly, so case studies based on the actual assembly progress are used for the validation. Additionally, expert intuition is an accepted method which can judge the advantage and limitation of the model according to the experience of the experts which is very important in aircraft manufacturing industry. So the expert judgment is selected as another method for validation.

3.2 Adopted Research Methodology

As shown in Figure 3-1, the research methodology adopted for CoQ modelling includes four main phases: understanding the context, data collection and analysis, development of CoQ model and validation. The activities and outputs in each phase are elaborated as follow:

Phase 1: Understanding the Context

This phase involved gaining a contextual understanding of the research topic and related knowledge. Industry requirement were analyzed based on the quality reports and operation condition from the data supplied by a tailplane assembly company, then the CoQ issues in tailplane assembly were stated. Then a detailed literature review was conducted, starting with a classification of papers according to research objectives. The literature on CoQ was firstly conducted from journals, books and thesis. A literature review on cost estimation was followed to introduce the generic cost modelling technologies and the cost estimation method used in aerospace industry. Then the applications of CBA were summarize. The last main part literature review was on aircraft assembly. The characteristic and specificity of aircraft assembly were stated and the tailplane assembly was introduced in this part. After the review, research gap was discussed and the research contents of this project were determined. The output of this phase was a literature review report, which was incorporated into Chapter 2.

Phase 2: Data Collection and Analysis

This phase aims to collect the necessary data for CoQ modelling and validation. The data involved materials, parts, processes, equipment, tools and labor which were used in tailplane assembly. The data can be divided into two parts: theory data and practice data. The theory data were mainly gathered from literature and database which was reported. And the practice data mainly came from actual manufacturing. An industry survey was designed to collect the practice data from five aircraft design and manufacturing companies in China. After data collection, theory data and practice data was compared to determine the parameter used in the model, then the structure of CoQ model were developed based on the P-A-F/ABC system. The output of this phase was the analysis result of the questionnaires, parameter list and model structure.

Phase 3: Development of CoQ Model

Phase 3 is the core of this research. The CoQ model was developed based on the MS Excel as it was the main calculated software applied in quality management. It involved three main modules. Cost of Quality Estimation System (CoQES), Quality Issues Analysis module and CBA module. The CoQES focused on the calculation of the CoQ, which included GUI, data collection module, CoQ estimation module and CoQ reporting module. The GUI was designed based on the VBA in MS Excel, and the production factors databases (material, equipment, tool and labor), the CoQ databases (prevention, appraisal, internal failure and external failure) and the calculator in other modules were developed based on the store and calculation function in MS Excel. The Quality Issues Analysis module was designed to analyze the quality issues based on Pareto Analysis. However, it was not the main work of this research. The reason for developing it was that the analysis results quality issues were the necessary support data of CBA. This module included data collection module and quality issues analysis module, and the developing method was the same as CoQES. CBA module was designed to evaluate the investment on quality management. And the benefit of investment on quality management was mainly simulated based on the analysis results of history data which was estimated through CoQES. Contrastive analysis was the main method applied in CBA. After the development of the CoQ model, debugging were carried out to check the operation of the system.

Phase 4: Validation

In this phase, a validation of the CoQ model was fulfilled through case studies and expert judgements. Two case studies were used to test the model. One was used to validate the reliability of the CoQES and the other was used to validate the application of CBA on quality management. Otherwise, some industry experts were invited to use and analysis the CoQ model, and assessments to this model were gathered. Based on the results of case studies and expert judgement, the capacity and the reliability of the CoQ model were validated. And the model would be reviewed, revised and improved in the future work.

3.3 Summary

This chapter introduced the research methodology used in the CoQ model development in tailplane assembly. Literature review was conducted to obtain the basic knowledge and theory data, and industry survey was used to collect practice data from the aircraft manufacturing industry. Case studies and expert judgements were the methods to validate the CoQ model. Main methods and output in every phase were summarized.

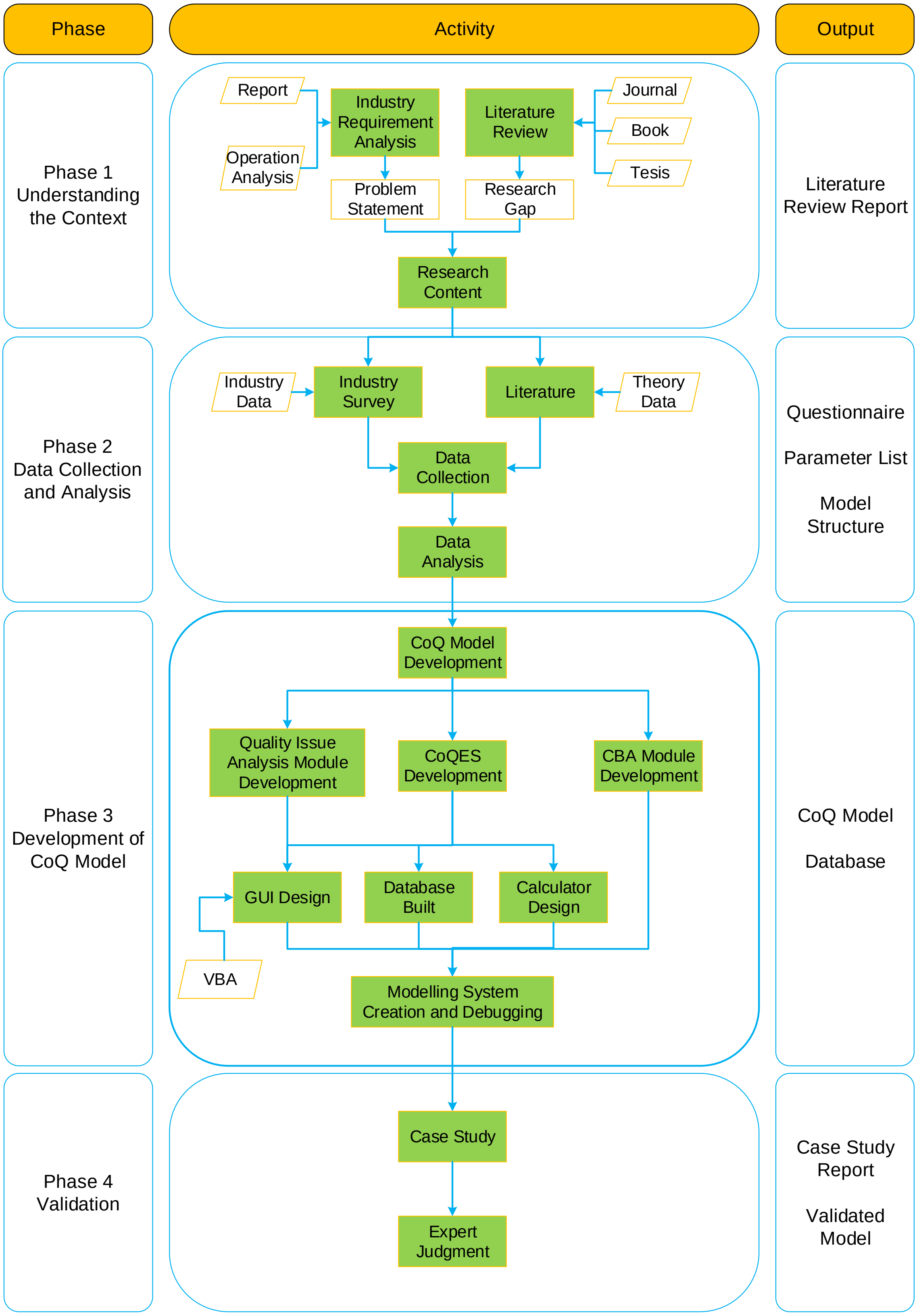


Figure 3-1 Research Methodology

4 DEVELOPMENT OF COST OF QUALITY MODEL

4.1 Introduction

The development approach of the CoQ model was introduced in this chapter. Firstly, industry survey was designed to collect the necessary data for the model. Then, based on analysis results of the survey and literature, CoQ in tailplane assembly were identified and defined according to P-A-F classification. Moreover, cost drivers for each activity involved in the model were analysed. Then the CoQ model was developed based on the parameters determined above. Finally, the main modules in the CoQ model were introduced and analysed.

4.2 Industry Survey

The questionnaire aims at collecting necessary data which used in the CoQ model and cases. As the reported data is limited, the support of actual data is necessary for this research. However, data only from one company may not reflect the real condition of this industry, so collect data from as many companies as possible in this field can reduce the risk resulted from company bias. And industry survey is widely accepted and used method for data collection in wide-range. The collected data can provide support for identifying the quality issues and cost drivers, and collect industrial data for analyzing and calculating the CoQ and the potential benefit in tailplane assembly.

The survey was made among five aircraft design or manufacturing companies in China as these companies all involved tailplane assembly for civil or military aircraft and they were the leaders in this field in China. They could be considered as the representatives of tailplane assembly as they owned the most advanced technology and richest experience in this field. The participants who took part in the survey are all from the departments related to quality issues or CoQ in their companies, including structure design, process design, quality management, project management, manufacturing department. The questionnaire and results were sent and collected by a questionnaire tool in a Chinese public website which named “Wen Juan”. For confidential reasons, the names the companies were not shown in this thesis, and the code names would be used in necessary places.

4.2.1 Questionnaire Design

The questionnaire was designed as a closed questionnaire. Compared with open questionnaire, closed questionnaire have many advantages. Firstly, in a close questionnaire, all the answers are designed which make it is easy to answer. Moreover, it obliges the respondent to answer particular questions, providing a high level of control to the questioner. Furthermore, it can save the answer time. Finally, it can provide better information than open-ended questions, particularly where respondents are not highly motivated (Rossi, et al., 2013). So closed questionnaire is the better selection. However, there are still some limitations for closed questionnaire. For example, closed questions are appropriate only when the set of possible answers are known and clear-cut, and the answer list cannot involve all the possible answers for the questions. In order to solve the issue, two quality management experts with more than 10 years working experience were invited to audit the questionnaires in the design phase and the questionnaire was improved based on their suggestions before sending out. Otherwise, as the answer list of some questions may be not integrated, option which named 'Other' was put into the answer list to collect the special answers and suggestions for the questions.

There are four main sections in the questionnaire (see Appendix A). The first section focuses on gathering the general information of the participants and their companies. Section two is designed to find out the quality issues and the root causes in tailplane assembly. The third section is set to collect the CoQ estimation parameters and cost drivers in the tailplane assembly. The last section is to get ideas on benefit simulation. There are total twenty-two questions in this questionnaire and it may be completed within an hour.

There are four questions in Section 1. These questions all focus on the general information of participants, including company, department, responsibility and working experience. This information is the basis for the classification of participants. The questions in the other sections involve different professional fields which need professional knowledge and experience to answer, but it is impossible for one person to give very accurate answer for every question. For example, a process designer may know well on process cost but may be not know well about the quality issues; quality issue handle department may be familiar with the handle results of quality issues but may not be familiar the cost drivers of the process. However this inaccuracy or the potential of wrong answering may affect the precision of analysis result. So in order to reduce the influence of such data, weighted approach is applied in the process of data analysis. The general information in Section 1 is the basis for applying the weights in each answer. Detail application is discussed in Chapter 4.2.2.

In Section 2, seven questions are designed to understand the quality issues in tailplane assembly. It is obvious that quality issues will result in the failure cost such as rework and scrap. Meanwhile, the prevention costs are generally spent on solving quality issues. So it is important to know quality issues when discussing the CoQ. Question 5 aims to find out the phase in which the quality issues occur most frequently. As tailplane assembly is a very complex progress, and every assembly phase involves hundreds of procedures. It is a huge project to collect data and calculate the whole CoQ of tailplane assembly. So choosing one phase as the template is reasonable in such a short period, and the phase with most quality issue may be a good choice. Question 6 and 7 focus on the categories of quality issues in tailplane assembly and their proportion in total quality issues. As there are various quality issues in tailplane assembly, it is impossible to analyse all of them. So these quality issues which occur most frequently are focused on. Questions 8 to 11 are related to the causes of quality issues. Finding out cause is the premise of solving quality issues, and CoQ are generally based on the solution of quality issues. So it is very imperative to know the causes of quality issues. As mention above, it is impossible to discuss every cause, so the main causes are focused on. That is the reason of estimating the proportion of these causes.

Section 3 aims at determining the main activities and cost drivers in tailplane assembly. The high cost and frequent used activities significantly affect the CoQ, so four questions are designed to find out these activities. Question 12 focus on the six processes with the highest cost and Question 13 focus on the six processes most frequently used. The data from these two questions will be combined to determine six main processes which affect the CoQ significantly. The aims of Question 14 and 15 are same as Question 12 and 13, the difference is these two questions focus on inspections and tests. Four main inspections or tests which have remarkable influence on CoQ will be determined. Question 16 and 17 are designed to find out the main cost drivers for these activities which are the basis of the calculation of CoQ. Question 18 aims at gathering information about the proportion of CoQ in tailplane assembly which are used to compare with the analysis result of case studies.

The final section is related to benefit identification. As there is limited report about CBA applied in quality analysis. It is a difficult to identify and represent the benefit of cost on quality. Hence, Question 19 to 22 are designed to gather ideas on how to represent benefit. Benefit of some investments can reflect in a short period, such as training. But some of them need a long time to see their profit, such as high cost equipment purchasing. So the benefits in this research are divided into short-term benefit and long-term benefit. Questions 19 to 20 are designed to collect data about the representation of short-term benefits and their reflection period. And Questions 21 to 22 are designed for long-term benefit.

4.2.2 Survey Result Analysis

100 questionnaires were sent out and 42 completed ones were collected. The response rate is 42%. The data of survey is mostly based on the individual experience of respondents. The main survey results were summarized as follows. Based on the data, the survey results were analysed as follow.

4.2.2.1 General Information and Weighted Approach

General information of participants is summarized in Table 4-1. It can be seen that most of people who responded to the survey come from aircraft manufacturing companies. And more than 80% of them work in the department related to assembly process. Moreover 75% of respondents are operators. Furthermore, approximate 67% of them have worked more than 3 years.

Based on this information, weighted approach is used to distinguish answers from different participants. Company, department, responsibility and working experience are the four factors for judging the reliability of the answers. The reliability of the answer are evaluated by the author based on the working experience and the comments from the quality experts who audited the questionnaire. The more the reliability is, the higher the weighted value of answer is. For example, questions 12 to 18 focus on cost estimation in tailplane assembly, and the participants from aircraft manufacturing company may be more familiar with activities costs than the one from aircraft designing company, so the answer from the former will be more credible than the latter's. Hence, the basic weighted value to the answers on question 12 to 18 which given by participants from aircraft manufacturing company is higher than the one which given by participants from aircraft designing company. Similarly, the participants from quality management may be more familiar with quality issues than the ones from project management; and the answer from supervisor may be more credible than the one from operator; and the more working experience participant has, the higher reliability answer he can supply.

Every question can be given a basic weighted value according to each of the factors, and the final weighted value is the product of the four basic weighted values. The weighted value for each question was shown in Table 4-2. The basic value for each questions were determined by the experience of the authors and the quality experts who attended the audition of the questionnaire. In order to make the calculation more simply and convenient, all weighted values were the multiple of 0.5. The calculation process of the final weighted value was shown as follow. For example, a structure design supervisor from aircraft designing company with 3 to 5 years working experience who responded to this survey, according to the company factor, the basic weighted value of answers to question 5 to 11 is 1; based on the department factor, the basic weighted value of answers to question 5 to 11 is 2; on the basic of responsibility factor, the basic weighted value of answers to these questions is 2 and in the light of working experience, the basic weighted value is 1. Hence, the final weighted value can be calculated as: Weighted Value=1×2×2×1=4. So each answer on question 5 to 11 of this participant will be counted by four times. This method may reduce the influence of inaccurate data.

Table 4-1 General Information of Participants

Company		Department		Responsibility		Working Years	
Aircraft Design	12%	Manufacturing	24%	Supervisor	29%	< 3	33%
Aircraft Manufacturing	76%	Quality Management	21%	Operator	71%	3 - 5	36%
Aircraft Design & Manufacturing	12%	Project Management	7%			6 - 10	14%
		Process Design	36%			>10	17%
		Structure Design	12%				

Table 4-2 Weighted Value of Questions

Factors	Weight Value	Weighted Value		
		Q5 - Q11	Q12 - Q18	Q19 - Q22
Company	Aircraft Design	1	1	1
	Aircraft Manufacturing	1	2	2
	Aircraft & Manufacturing	1	2	2
Department	Structure Design	2	1	1
	Process Design	1	2	1
	Quality Management	2	1	1
	Project Management	1	2	2
	Manufacturing	2	1	1
Responsibility	Supervisor	2	2	2
	Operator	1	1	1
Working Years	No more than 3	0.5	0.5	0.5
	3-5	1	1	1
	6-10	1.5	1.5	1.5
	Above 10	2	2	2

4.2.2.2 Quality Issue Analysis

The phase with the most quality issues in tailplane assembly is Final Assembly Phase which can be seen in Figure 4-1. Approximately 41% of the participants support this statement. In the final assembly phase, there is not enough tolerance to distribute in the assembly process generally. So there will be many matching problems which may result in amount of rework and repair, even scrap. That is why most quality issues occur in the final assembly phase. Hence, the CoQ and the case used in this research will be on the basis of this phase.

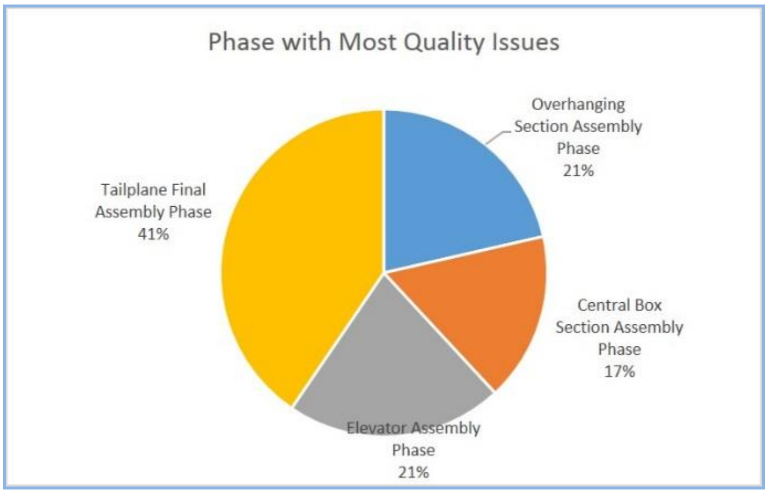


Figure 4-1 Phase with Most Quality Issues in Tailplane Assembly

Figure 4-2 shows the results of quality issues in the tailplane assembly. Graph a) is about the main quality issue in the tailplane assembly, and it reflects the number of different answers. It can be seen that the most frequently occurred quality issues are hole problem, position problem and riveting problem. It reflects the number of different answers. Graph b) reflects the proportion of these quality issues in total quality issues. The proportions of the three main quality issues are totally above 50%. Drilling and Riveting are two main processes in assembly process, and there may be more than ten thousand holes and rivet in an aircraft. Moreover, as mentioned in Chapter 2, aircraft assembly significant relies on manual work. Approximately 80% of drilling and riveting are finished manually. Hence, it is not difficult to explain why hole problem and riveting problem are the most frequent ones. Otherwise, matching is very important in assembly process. The more components are used, the more difficult to put these components in right place. Especially in final assembly phase, positioning problem may be the most frequently and most difficult quality issues to handle. Therefore, hole problems, riveting and positioning problems are the main quality issues discussed in this research.

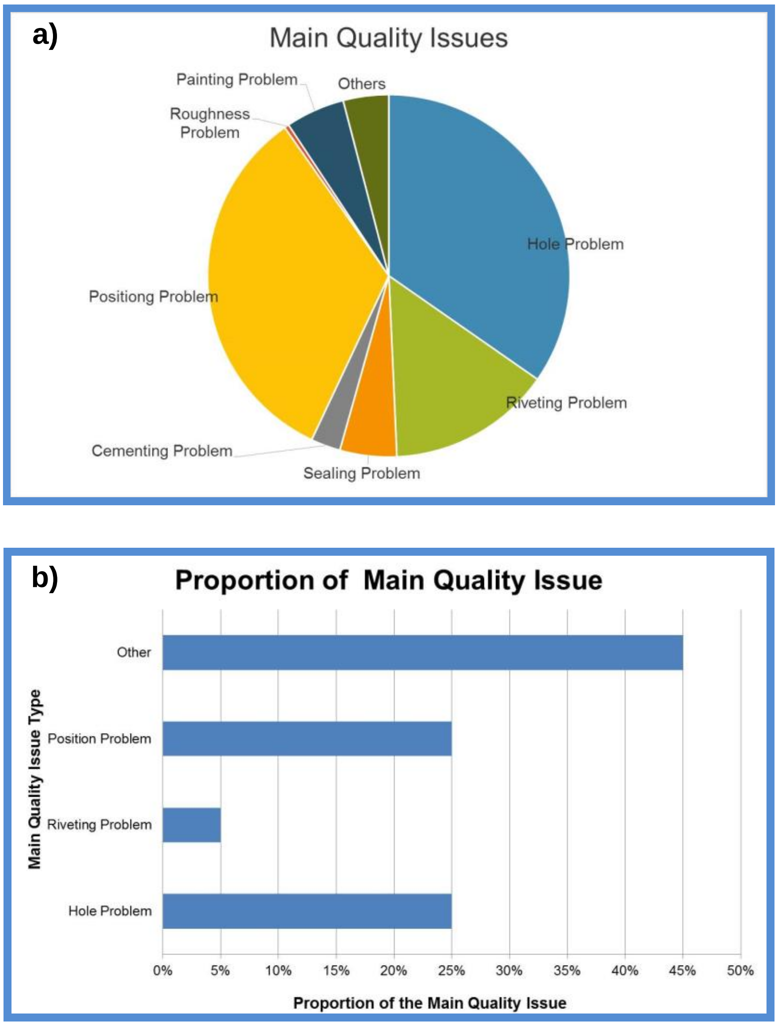


Figure 4-2 Main Quality Issues in Tailplane Assembly

The causes for these quality issues are analyzed based on the results which are shown in Figure 4-3. Graph a) illustrates the proportion of three main immediate causes in total immediate causes. Similarly, graph b) shows the results on root causes. It is clear that misoperation is the main immediate cause for quality issues in tailplane assembly. And the main root cause is identified to be the lack of professional skill. Due to the low degree of automation, too much work in tailplane assembly is finished manually, so quality issues will occur unavoidably. Moreover, using too much young workers in designing and manufacturing is another reason. Lack of skill and experience may result in the high error rate in manufacturing.

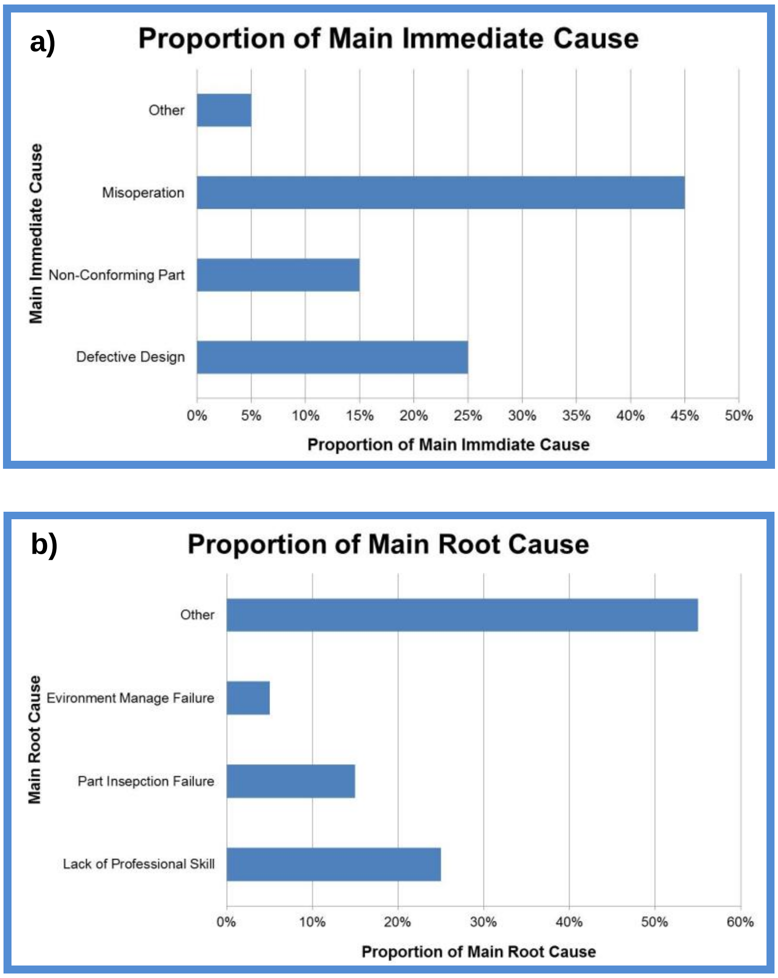


Figure 4-3 Main Cause for Quality Issues

4.2.2.3 Cost Estimation

Figure 4-4 reflects the processes with most significant influence on cost in tailplane assembly. Graph a) shows the main processes with highest cost and graph b) shows the main processes which are used most frequently. It can be seen that the highest cost processes are riveting, reaming, drilling, sealing, dimpling and installing and the most frequently used processes are drilling, position, riveting, dimpling, sealing and cleaning. In order to identity the processes which can affect cost significantly, the influence proportion on cost of one process are calculated using the proportion of this process in graph a) multiplied by the proportion of this process in graph b), the results are shown in graph c). Hence, the six processes with most significant influence on cost are Riveting, Drilling, Position, Dimpling, Sealing and Reaming. These processes are the main concern objective in this research.

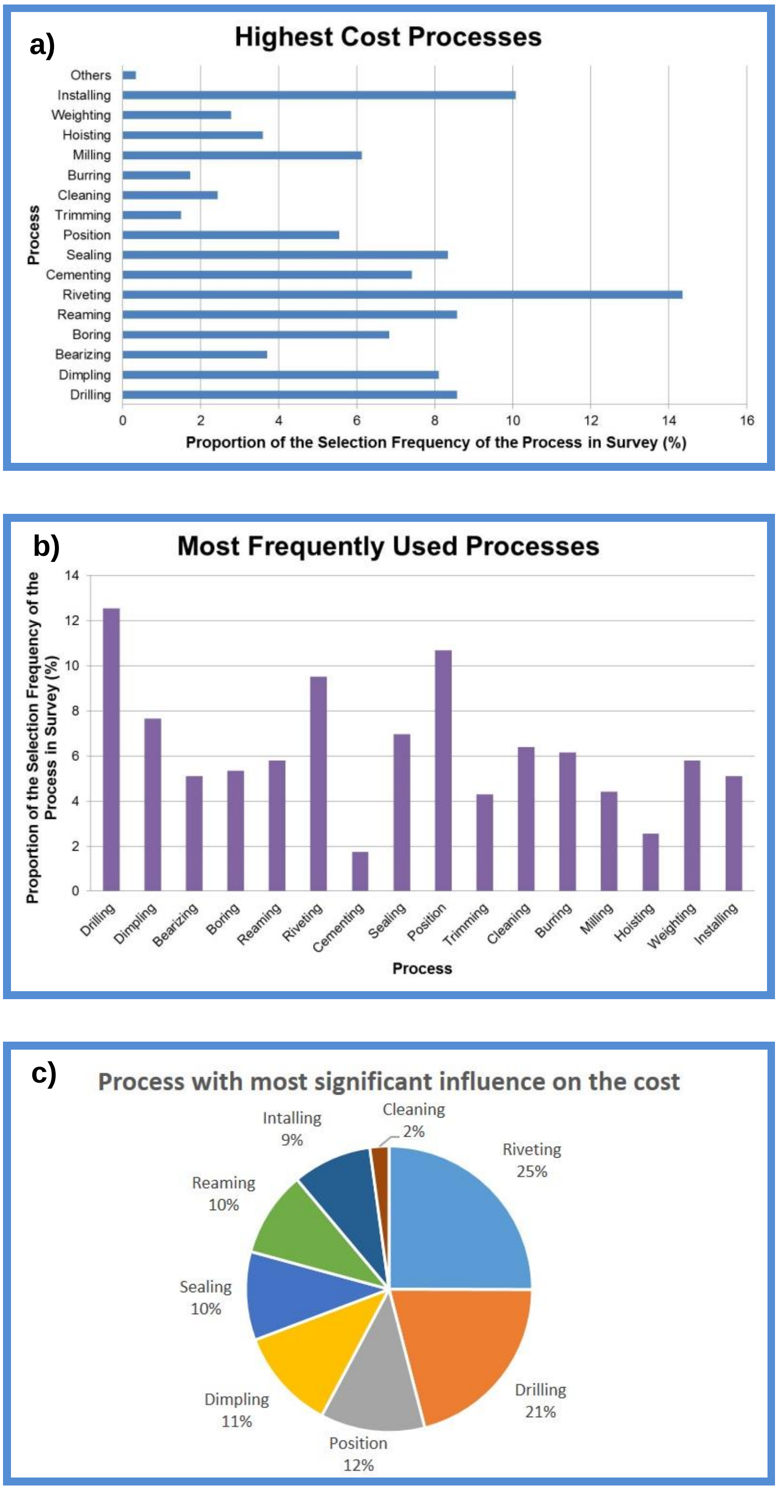


Figure 4-4 Processes with Most Significant Influence on Cost

The analysis method to identify inspections and tests which can affect cost significantly is same as process (See Figure 4-5). Hence, the four inspections and tests with most significant influence on cost in tailplane assembly are Laser Measurement, Hole Diameter Inspection, X-ray Inspection and Foreign Objective Damage (FOD) Inspection. These inspections and tests are mainly focused on in this research.

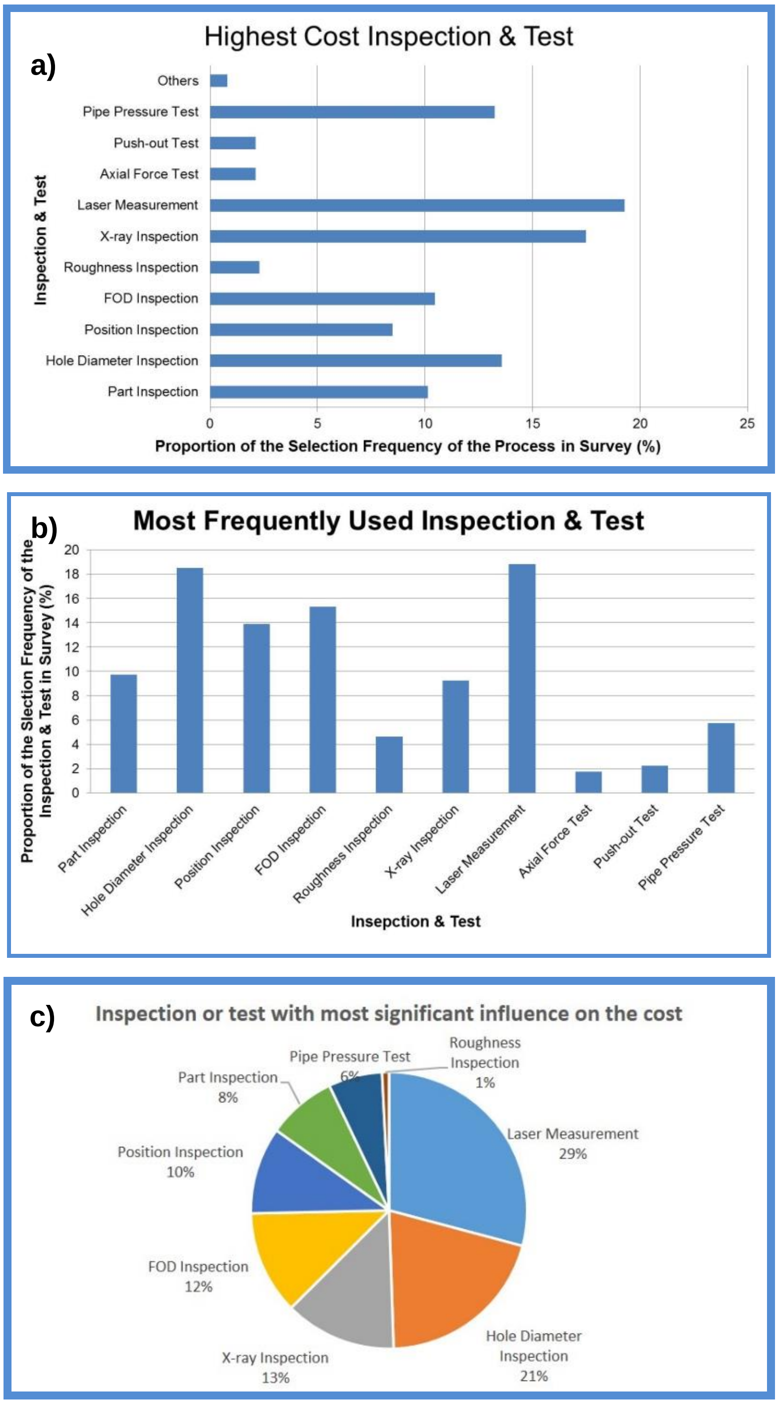


Figure 4-5 Inspections and Tests with Most Significant Influence on Cost

The main cost drivers for the activities in tailplane assembly are illustrated in Figure 4-6. Graph a) shows the main cost drivers and graph b) shows the proportion of the main cost drivers in total cost drivers. It can be seen that labor is the most important cost drivers. It is normal in an industry which relies on manual production. Additionally, depreciation of equipment and tool is thought as a main cost driver. The cause may be that the equipment and tools used in tailplane assembly are very expensive, thus the influence of depreciation is remarkable. Accidentally, the energy consumption is not thought as a main cost driver which is a very important driver in many manufacturing industries (Mouzon et al., 2007). Low consumption which results from low output and cheap price of energy in China may be the reason. In brief, based on the result, labor and depreciation will be the main cost drivers considered in calculation in this research.

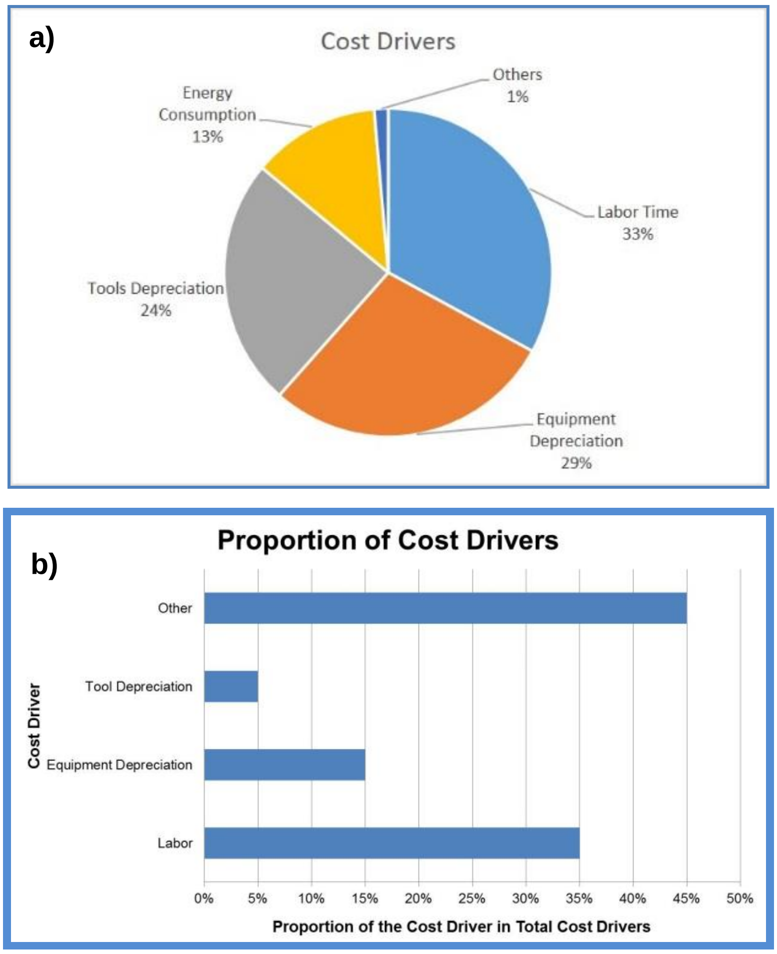


Figure 4-6 Main Cost Drivers for Activities in Tailplane Assembly

Survey result shows that the proportion of CoQ in total cost is most thought as 21% to 30% which is in accord with some reported results (Sower et al., 2007). It will be the reference parameter to analyze the result of cases.

4.2.2.4 Benefit Identification

Based on the survey result, shown in Figure 4-7 and 4-8, reducing number of quality issues is thought as the main way to represent the short-term benefit of the cost on quality, and the period for the benefit to reflect is about 7 to 12 months. Meanwhile, improving customer satisfaction is thought as the main way to represent the long-term benefit of the cost on quality, and the period for the benefit to reflect is about 3 to 4 years. These ways to represent benefit are all abstract, how to using quantitative method to represent these parameters will be discussed in chapter 4.6. The period of the benefit reflection may be the reference when collecting the necessary data in CBA and case study.

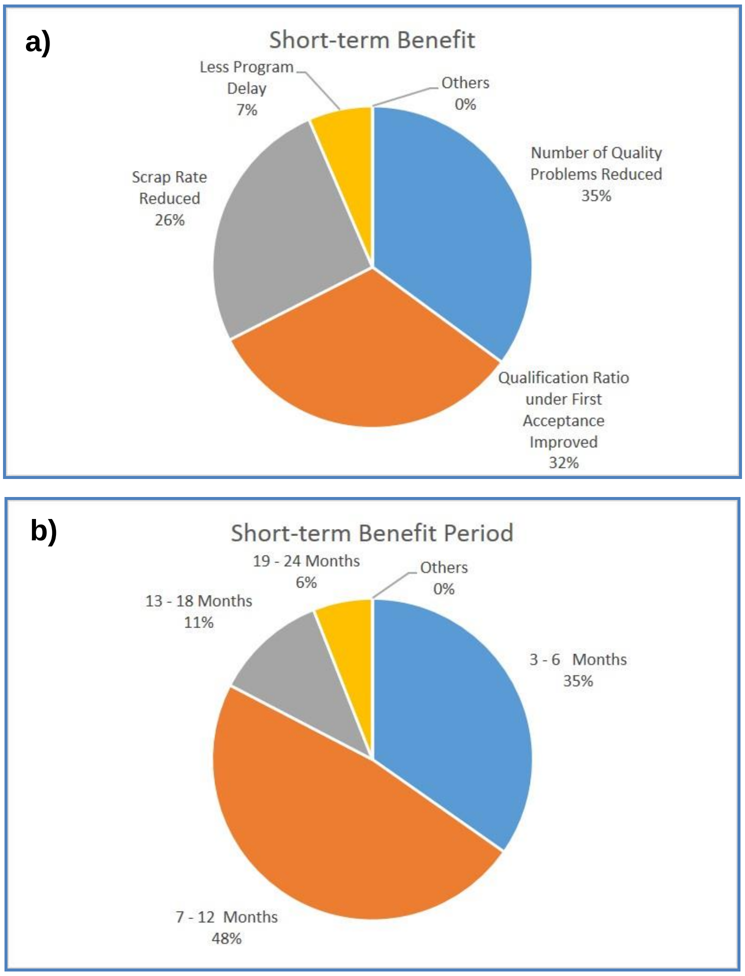


Figure 4-7 Method to Represent Short-term Benefit

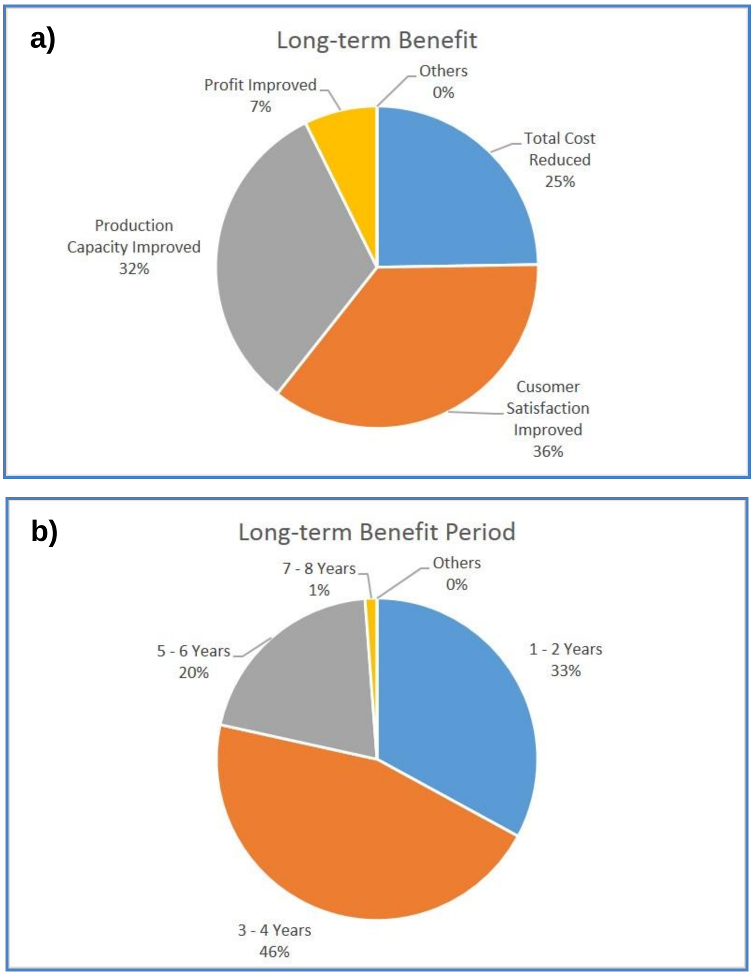


Figure 4-8 Method to Represent Long-term Benefit

4.3 CoQ Elements Identification and Definition

4.3.1 Breakdown Structure of CoQ

In order to reduce CoQ, the most important thing is to set priorities for the effective use of resources and this can be done by the identification of those factors which contribute a lot in CoQ (Ali et al., 2012). In this research, classification of CoQ is based on the traditional P-A-F model, which means that the total CoQ includes prevention cost, appraisal cost, internal failure cost and external failure cost. As summarized in Chapter 2, it has been some examples for different kind of CoQ. However, it is difficult to use these examples directly as not all of these are suit for tailplane assembly. For example, new product review and supplier capability surveys are two kinds of previous cost of a product. But they may not be considered when calculating the CoQ in the assembly process. Moreover, in this research, CoQ in tailplane assembly need to be quantified and calculated, so the examples which is impossible to quantify will not be considered, such as laboratory support. Furthermore, the research focus on the assembly phase which is only part of the lift cycle of the production. So only part of CoQ which is related to the assembly phase will be considered, most of external failure such as costs of complaint handling will not be involved. In conclusion, comparing the reported examples of CoQ with the actual data collected through the industry survey and supplied by a tailplane assembly company in China. The CoQ in this research can be identified and defined, as illustrated in Figure 4-9. The detailed definitions are discussed as follow.

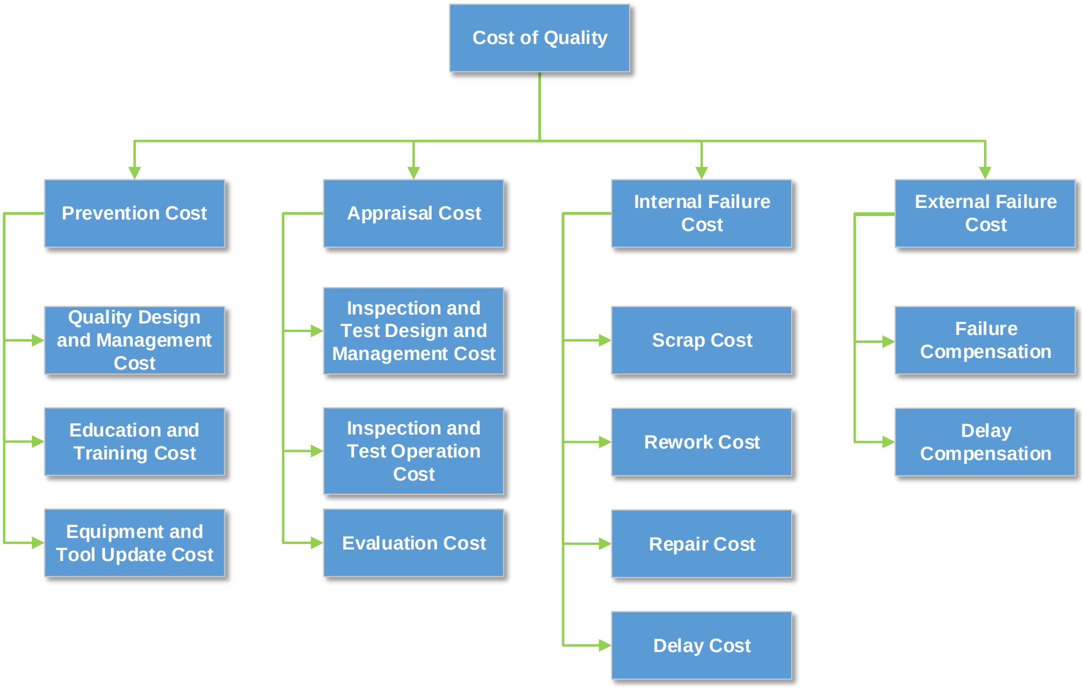


Figure 4-9 Breakdown Structure of CoQ in Tailplane Assembly

4.3.2 Definition of Prevention Costs

Prevention costs are the costs of all activities specifically designed to prevent poor quality in products or services. Prevention costs in tailplane assembly includes Quality Design and Management Cost (C_{qdm}), Education and Training Cost (C_{eat}), Equipment and Tool Update Cost (C_{etu}), as shown in Equation (4-1).

$$C_{pre} = C_{qdm} + C_{eat} + C_{etu} \tag{4-1}$$

Quality Design and Management Cost is the cost which is spent on quality design and management before or during the assembly process, including: Operations quality planning cost, Operations support quality planning cost, Operator SPC/ process control cost, Quality program planning cost, Quality performance report and analysis cost, etc.

Education and Training Cost is the cost which is spent on quality education and training in order to ensure the people get the necessary skills and knowledge, including: Quality education cost, Quality training cost, Assembly basic knowledge education cost, Professional skills training cost, etc.

Equipment and Tool Update Cost is the cost which is spent on new equipment or tool purchasing, manufacturing or old equipment updating in order to keep or improve the product quality, including: Equipment or tool purchasing cost, Hardware updating cost, Software updating cost, etc.

4.3.3 Definition of Appraisal Costs

Appraisal costs are the costs associated with measuring, evaluating or auditing products or services to assure conformance to quality standards and performance requirements. Appraisal costs in tailplane assembly process includes Inspection and Test Design and Management Cost (C_{itd}), Inspection and Test Operation Cost (C_{ito}), Evaluation Cost (C_{eva}), as shown in Equation (4-2).

$$C_{app} = C_{itd} + C_{ito} + C_{eva} \quad \textbf{(4-2)}$$

Inspection and Test Design and Management Cost is the cost which is spent on the inspection and test design, research and management, including: Planned operations inspections, tests and audits cost, Review of inspection and test data cost, etc.

Inspection and Test Operation Cost is the cost which is spent on operating inspection and test, including Part acceptance inspection cost, In-process inspection cost, Final inspection cost, Function test cost, etc.

Evaluation Cost is the cost which is spent on quality evaluations in order to check whether the quality system operation is well enough to ensure product quality, including: Internal evaluation, External evaluation, etc.

4.3.4 Definition of Internal Failure Costs

Internal failure costs occur prior to delivery or shipment of the product, or the furnishing of a service, to the customer. Internal failure costs in tailplane assembly process includes Scrap Cost (C_{scr}), Rework Cost (C_{rew}), Repair Cost (C_{rep}), and Delay Cost (C_{del}), as shown in Equation (4-3).

$$C_{inf} = C_{csr} + C_{rew} + C_{rep} + C_{del} \tag{4-3}$$

Scrap Cost is the cost which is spent on the scraped components, including: Materials cost, Component cost, Equipment cost, Tool cost, Labour cost, etc.

Rework Cost is the cost which is spent on working which can ensure the failed part meet the design requirement, including: Materials cost, Part cost, Equipment cost, Tool cost, Labour cost, etc.

Repair Cost is the cost which is spent on the working which can ensure the failed part be used again though not meet the design requirement, including: Materials cost, Part cost, Equipment cost, Labour cost, etc.

Delay Cost is the additional cost to finish the planned work due to the delay which may result from quality issues or other reasons. The main delay cost in tailplane assembly is waiting cost.

4.3.5 Definition of External Failure Costs

External failure costs occur after delivery or shipment of the product, and during or after finishing of a service to customer, including: Cost of complaint handling, Warranty claims, Cost of handling and repair of returned goods, Costs of scraps of returned goods, etc. However, these kinds of external failure cost are not be involved in the tailplane assembly progress. So some unreported external failure cost need to be considered in this model. The repaired components used on tailplane are not meet the requirements of design drawings, though they were evaluated by the designers before used, the potential risk of occurring quality issue is more than normal components, and the failure cost for these quality issue will be undertaken by the customers. So compensation is required for these components when sell the product to customers. This kind of cost occurs after delivery of the product, so it can be seen as one of external failure cost, as all the problems are handled through Failure and Rejection Report (FRR), this kind of cost can be named FRR compensation. Additionally, quality issues may result in the delay on delivery which may result in the compensation due to the breach of contract. This kind of cost can be seen as another external failure cost in tailplane assembly. So the external failure cost in this model can be represented as the sum of the FRR compensation (C_{frr}) and delivery delay compensation (C_{ddc}), as shown in Equation (4-4).

$$C_{exf} = C_{frr} + C_{ddc} \tag{4-4}$$

4.4 Activities Identification and Cost Drivers Analysis

4.4.1 Activity Identification

Based on P-A-F/ABC framework, after the definition of CoQ, the activities need to be identified and analysed. And the cost drivers for these activities need to be determined. According to the results of the literature review and industry survey, the main activities which result in CoQ in tailplane assembly can be divided into two groups. One group is the activities which involved in the assembly process directly. These activities can be called as ‘Productive Activities’, including inspection, test, rework, repair and scrap. These activities generally refer to one or more manufacturing processes which require amount of resource to fulfilling. So there are many cost drivers for these activities such as material, component, equipment, tool and labour.

The other group is the activities which involves no assembly process. These activities can be called as ‘Non-productive Activities’, including Quality design and management, education and training, inspection and test design and management and evaluation. These activities mainly belong to quality management and quality assurance which do not rely on production factors such as material, part, equipment, etc. The main cost drivers for these activities are labour. The cost drivers for activities are illustrated in Table 4-3.

Table 4-3 Cost Drivers of Activities

CoQ	Activities	Cost Drivers
Quality Design and Management Cost	Non-productive	Labour
Education and Training Cost	Non-productive	Labour
Equipment and Tool Purchasing Cost	None	None
Hardware Updating Cost	Non-productive	Labour
Software Updating Cost	None	None
Inspection and Test Design and Management Cost	Non-productive	Labour
Inspection and Test Operation Cost	Productive	Equipment, Tool, Labour
Evaluation Cost	Non-productive	Labour
Scrap Cost	Productive	Component, Equipment, Tool, Labour
Rework/Repair Cost	Productive	Material, Component, Equipment, Tool, Labour
Delay Cost	Non-productive	Labour
FRR Compensation Cost	None	None
Delivery Delay Compensation Cost	None	None

4.4.2 Cost Drivers Analysis

It can be seen from Table 4-3 that the main cost drivers for the activities can be divided into five groups: material, part, equipment, tool and labour. The characteristic and influence degree of these cost drivers are discussed and summarized as follow:

Material is a very important basic production factors in manufacturing industry. It can be divided into raw material and support material. Generally the influence of raw material to cost is far more significant than support material due to the difference of consumption and price. However, in assembly process, the consumption of raw is too little to ignore. Hence, in this research, material can be only thought as support material. And the influence of material on cost may be far less than the other cost drivers.

Component is another important basic production factors in manufacturing industry. It can be divided in subassembly and standard component in assembly. As the amount of component in tailplane is large and the costs of the component are very expensive, component costs accord for a high proportion in total CoQ. Hence, component is one of the main cost drivers for CoQ in tailplane assembly.

Equipment and tools are used widely in processes, inspection and test. Almost every activity needs one or more relative equipment and tool. Generally the main influencing factors to equipment and tool cost are depreciation and energy consumption. However, based on the result of industry survey, energy consumption is not thought as the main cost driver. So in this research, depreciation is thought as the only driver for equipment and tool. There are various methods to calculate the depreciation, such as Straight Line Depreciation Method, Declining Balance Depreciation Method and Sum of the Years Digits. In all these methods, the straight-line depreciation is the simplest and most often used one (Eisele, 2002). The salvage value is deducted from the asset and divided by the number of years of the depreciation period. The only two factors need to consider are cost and period. So the depreciation can be calculated through Equation (4-5).

$$D = \frac{P}{L \times T} \tag{4-5}$$

Where:

D = Depreciation of Equipment or Tool;

P = Unit Price of Equipment or Tool;

L = Lifetime of Equipment or Tool (Year);

T = Annual Available Working Time of Equipment or Tool.

Labour is one of the most important production factors in the manufacturing industry which rely on manual work significantly. Generally labour can be classified into direct labour and indirect labour. Direct labour is production or services labour that is assigned to a specific product. In manufacturing process, direct labour is considered to be the labour of the production crew that produces goods, such as machine operators, assembly line operators and inspectors. In this research direct labour can be thought as all the process operators, including drilling workers, riveting workers, FOD inspectors, etc. Indirect labour is the labour who supports the production process, but not directly involved in the activities to finish products, such as production supervisor and quality control staff. This part of cost is difficult to calculate for a single activity. The best method to estimate this kind of cost is to calculate accumulated cost in a period, such as annual quality management cost. In this research, the indirect labour can be thought as manufacturing management labour, process design labour and quality management labour. Based on the literature and industry survey, labour is thought as a main cost driver in activity in tailplane assembly. And with the increasing of labour cost these years, the influence of labour to CoQ is more and more remarkable.

4.5 Development of the CoQ Model

4.5.1 Overall Structure of the CoQ Model

The Developed CoQ model includes three main modules: Cost of Quality Estimation System (CoQES) module, Quality Issues Analysis module and CBA module, as shown in Figure 4-10. The CoQES module consists of cost information collection module, cost estimation module and CoQ reporting module. The modules in the CoQES are all composed of interfaces and databases. The cost information collection module consists of five interfaces and four databases, it is used to collect and store the necessary data for the CoQES. The cost estimation module consists of one interface and one calculator and four production factor databases (material, equipment, tool and labour), when the estimation period and some annual information, such as yield, annual evaluation cost, is input through the interface, different kind of CoQ will be calculated based on the information model, then the total CoQ will be the sum of all these CoQ elements, and unit CoQ will be the ratio of total CoQ to the yield. Finally, the proportion of CoQ in sales will be estimated by the ratio of unit CoQ to product price. All the estimation will be stored into the database of CoQ report in the CoQ reporting module, the interface in that module will show all these results to the user.

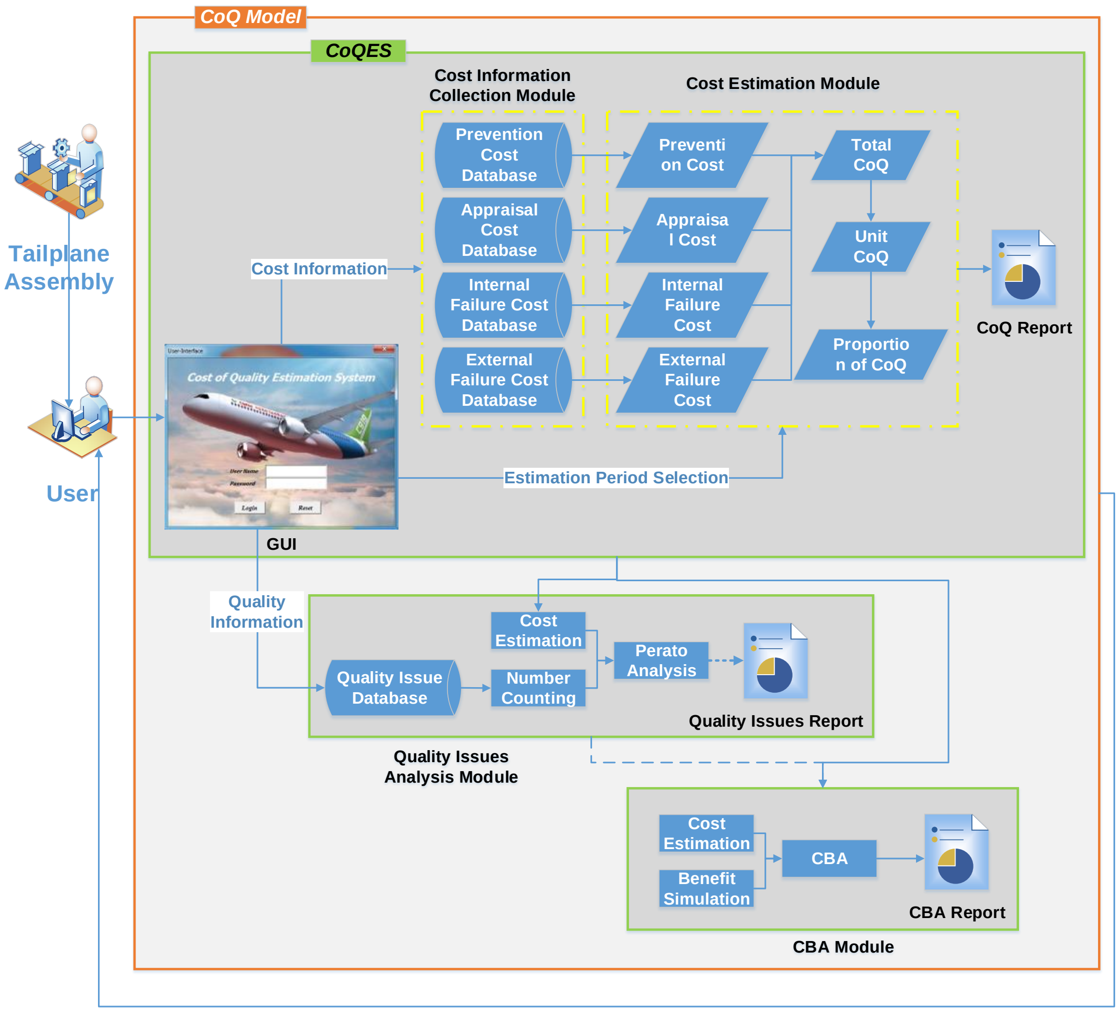


Figure 4-10 Overall Structure of the CoQ Model

The Quality Issue Analysis module includes two interfaces (quality problem information input and quality problem analysis) and one database (quality issue). In this module, quality issues information are collected and input into the database, and the number of different quality issues can be counted in the selected year. And the failure cost of these quality issues can be estimated based on the CoQES. Pareto Analysis will be used to determine the main quality issue from these two aspects. And a quality issue report can be summarized after the analysis. However, as this part is not the main work of this research, so it will not be discussed in- depth in this thesis and it may be improved in the future work.

The CBA module is mainly an analysis process of the cost and benefit. So the operation environment is not based on the interfaces. But the results of cost and benefit used in CBA are all calculated through CoQES. The CBA generally focuses on the main quality issues as most of investment on quality aims at solving them. They can be found through the quality issues analysis module. When the quality issues are determined, the cost and benefit can be estimated based on the CoQES. Then the ratio of cost and benefit will be analysed and a CBA report will be generated finally.

4.5.2 Cost of Quality Estimation System (CoQES)

The CoQES is a digital tool to estimate the cost of quality which can improve the operability of the CoQ model. It consists of GUIs, databases and algorithmic.

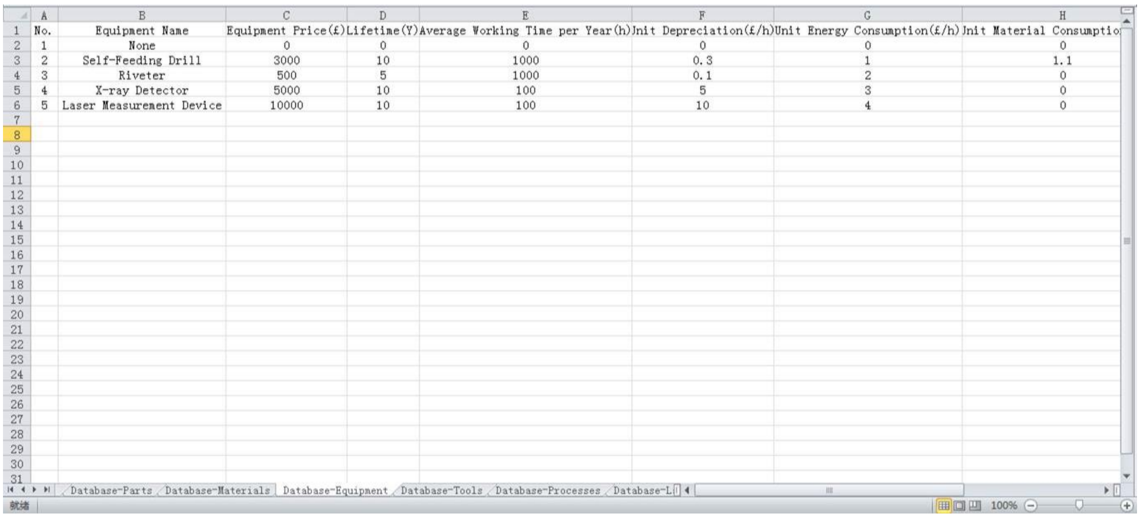
4.5.2.1 GUI Design

The GUIs are designed using VBA based on MS Excel to improve the operability of the model. The GUIs in the model involves eleven interfaces: Login Interface, Main Menu, Cost Information Input Menu, Prevention Cost Input, Appraisal Cost Input, Internal Failure Cost Input and External Failure Cost Input, Annual CoQ Estimation, CoQ Report, Quality Problem Information Input and Quality Problem Analysis.

4.5.2.2 Database

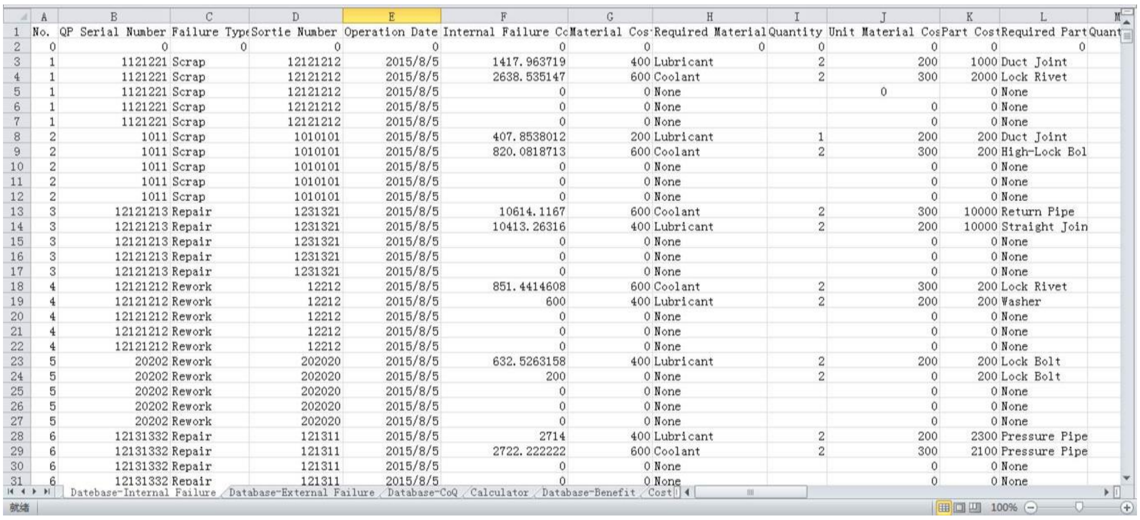
There are two kinds of databases in this model. One is basic information database (see Figure 4-11), which is used to store the basic production information in the tailplane assembly process, including material database, component database, equipment database, tool database and labour database. The information stored in these databases, such as unit component price, equipment depreciation and unit labour salary, should be collected based on the actual production condition before the CoQES used for estimation. And it is necessary in the calculation process.

The other kind of database is CoQ information database (see Figure 4-12), which is used to store the cost of quality information in the tailplane assembly process, including prevention cost database, appraisal cost database, internal failure cost database, external failure cost database and total cost of quality database. The information stored in these databases, such as training cost, inspection and test cost, scrap cost and FRR compensation cost, will be input and estimated when the CoQES used for estimation. And it is the basis of the CoQ report.



	A	B	C	D	E	F	G	H
1	No.	Equipment Name	Equipment Price(£)	Lifetime(Y)	Average Working Time per Year(h)	Unit Depreciation(£/h)	Unit Energy Consumption(£/h)	Unit Material Consumptio
2	1	None	0	0	0	0	0	0
3	2	Self-Feeding Drill	3000	10	1000	0.3	1	1.1
4	3	Riveter	500	5	1000	0.1	2	0
5	4	X-ray Detector	5000	10	100	5	3	0
6	5	Laser Measurement Device	10000	10	100	10	4	0

Figure 4-11 Equipment Database



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	No.	QP Serial Number	Failure Type	Sortie Number	Operation Date	Internal Failure Co	Material Cos	Required Material	Quantity	Unit Material Cos	Part Cost	Required Part	Quant
2	0	0	0	0	0	0	0	0	0	0	0	0	
3	1	1121221	Scrap	12121212	2015/8/5	1417.963719	400	Lubricant	2	200	1000	Duct Joint	
4	1	1121221	Scrap	12121212	2015/8/5	2638.535147	600	Coolant	2	300	2000	Lock Rivet	
5	1	1121221	Scrap	12121212	2015/8/5	0	0	None		0	0	None	
6	1	1121221	Scrap	12121212	2015/8/5	0	0	None		0	0	None	
7	1	1121221	Scrap	12121212	2015/8/5	0	0	None		0	0	None	
8	2	1011	Scrap	1010101	2015/8/5	407.8538012	200	Lubricant	1	200	200	Duct Joint	
9	2	1011	Scrap	1010101	2015/8/5	820.0818713	600	Coolant	2	300	200	High-Lock Bol	
10	2	1011	Scrap	1010101	2015/8/5	0	0	None		0	0	None	
11	2	1011	Scrap	1010101	2015/8/5	0	0	None		0	0	None	
12	2	1011	Scrap	1010101	2015/8/5	0	0	None		0	0	None	
13	3	12121213	Repair	1231321	2015/8/5	10614.1167	600	Coolant	2	300	10000	Return Pipe	
14	3	12121213	Repair	1231321	2015/8/5	10413.26316	400	Lubricant	2	200	10000	Straight Join	
15	3	12121213	Repair	1231321	2015/8/5	0	0	None		0	0	None	
16	3	12121213	Repair	1231321	2015/8/5	0	0	None		0	0	None	
17	3	12121213	Repair	1231321	2015/8/5	0	0	None		0	0	None	
18	4	12121212	Rework	12212	2015/8/5	851.4414608	600	Coolant	2	300	200	Lock Rivet	
19	4	12121212	Rework	12212	2015/8/5	600	400	Lubricant	2	200	200	Washer	
20	4	12121212	Rework	12212	2015/8/5	0	0	None		0	0	None	
21	4	12121212	Rework	12212	2015/8/5	0	0	None		0	0	None	
22	4	12121212	Rework	12212	2015/8/5	0	0	None		0	0	None	
23	5	20202	Rework	202020	2015/8/5	632.5263158	400	Lubricant	2	200	200	Lock Bolt	
24	5	20202	Rework	202020	2015/8/5	200	0	None	2	0	200	Lock Bolt	
25	5	20202	Rework	202020	2015/8/5	0	0	None		0	0	None	
26	5	20202	Rework	202020	2015/8/5	0	0	None		0	0	None	
27	5	20202	Rework	202020	2015/8/5	0	0	None		0	0	None	
28	6	12131332	Repair	121311	2015/8/5	2714	400	Lubricant	2	200	2300	Pressure Pipe	
29	6	12131332	Repair	121311	2015/8/5	2722.222222	600	Coolant	2	300	2100	Pressure Pipe	
30	6	12131332	Repair	121311	2015/8/5	0	0	None		0	0	None	
31	6	12131332	Repair	121311	2015/8/5	0	0	None		0	0	None	

Figure 4-12 Internal Failure Database

4.5.2.3 Input and Output

The input and output of CoQES will be introduced in this section. Firstly, the user opens the CoQES in Microsoft Excel, and inputs user name and password in the login interface, as illustrated in Figure 4-13. The login interface is designed to control the scope of the user as there are too much important data stored in the system.

Figure 4-13 Login Interface

Secondly, the user will enter the main menu interface (see Figure 4-14) to select the function in the system. Then the user can choose the "Cost Information Input" button, and the interface will convert to another cost information input menu, shown as Figure B-15. In the step, the user needs to input different necessary data for CoQ estimation.

Four main kinds of CoQ information need to be inputted into the system through different interfaces which are illustrated in Figure 4-16 to 4-19. The unit cost information for each kind of CoQ are inputted through these interfaces and stored in the corresponding databases in the system. As it is difficult and meaningless to estimate CoQ for single quality issue, the model is developed to estimate total CoQ in a year. So the annual cost is the sum of the unit cost in a year. Actually, information inputting will be a general work for the quality managers who use this model. So the user needs to record all the useful data before the estimation step.

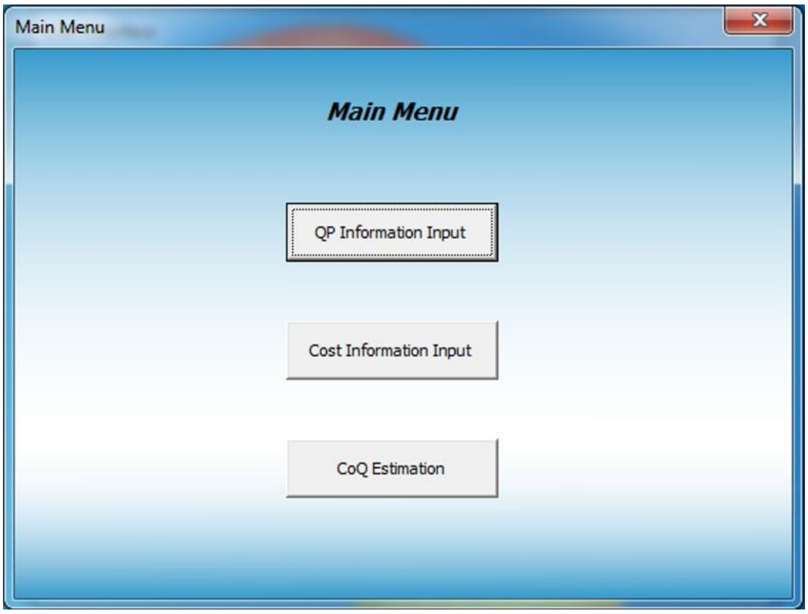


Figure 4-14 Main Menu Interface

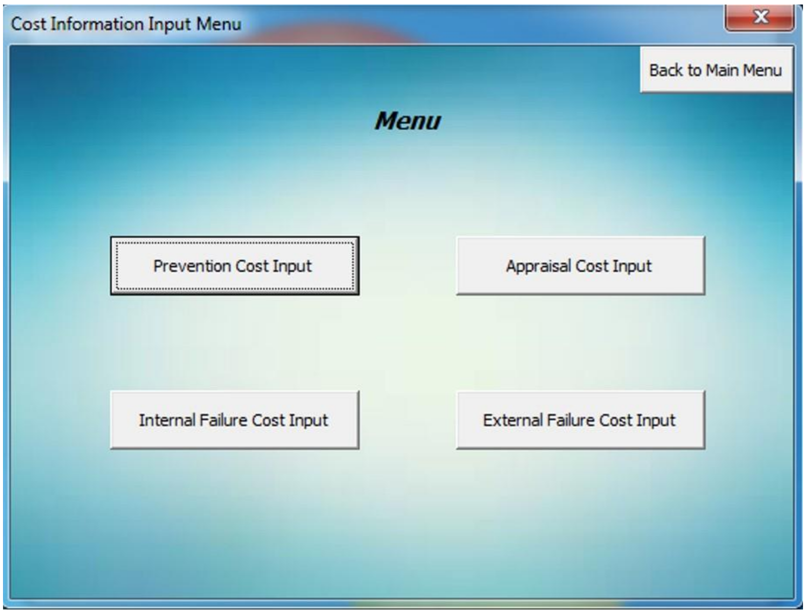


Figure 4-15 Cost Information Input Menu Interface

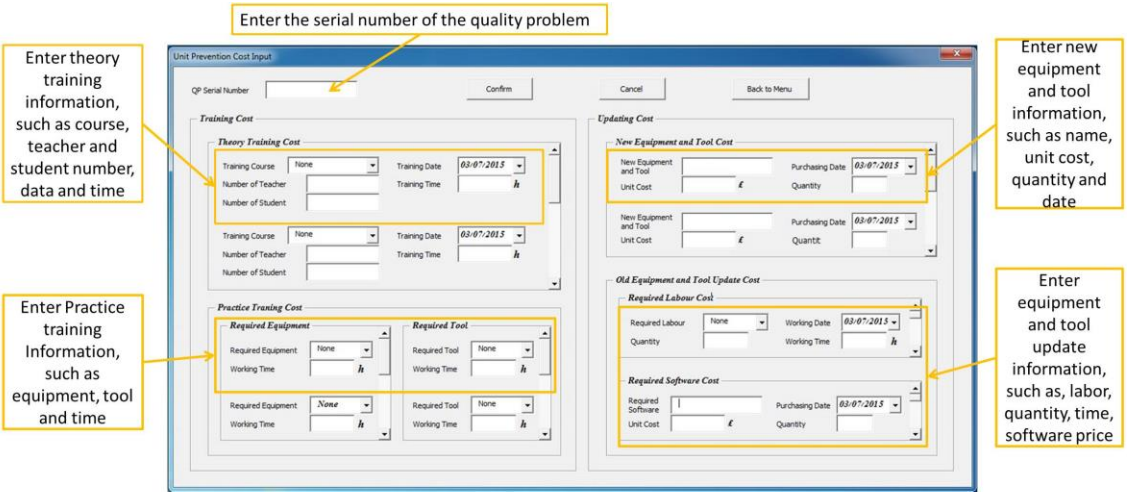


Figure 4-16 Prevention Cost Information Input Interface

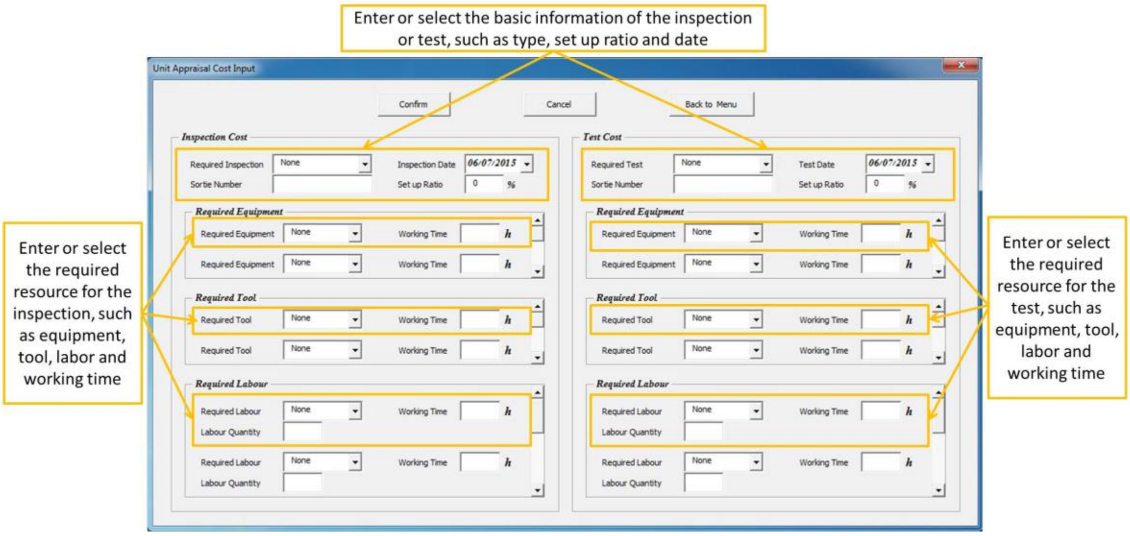


Figure 4-17 Appraisal Cost Information Input Interface

Fourthly, when the necessary data is collected and input into the system, the user can go to the estimation interface (See Figure 4-20) through the "CoQ Estimation" button in Main Menu interface. In estimation phase, the estimation year need to be selected. Then some necessary data in this year which is generally collected by year need to be inputted. Finally, the estimation process will start through the "Estimation" button. The estimation result will be illustrated in Cost of Quality Estimation Report (See Figure 4-21). The total CoQ, unit CoQ and every main kind of CoQ will be shown in the report.

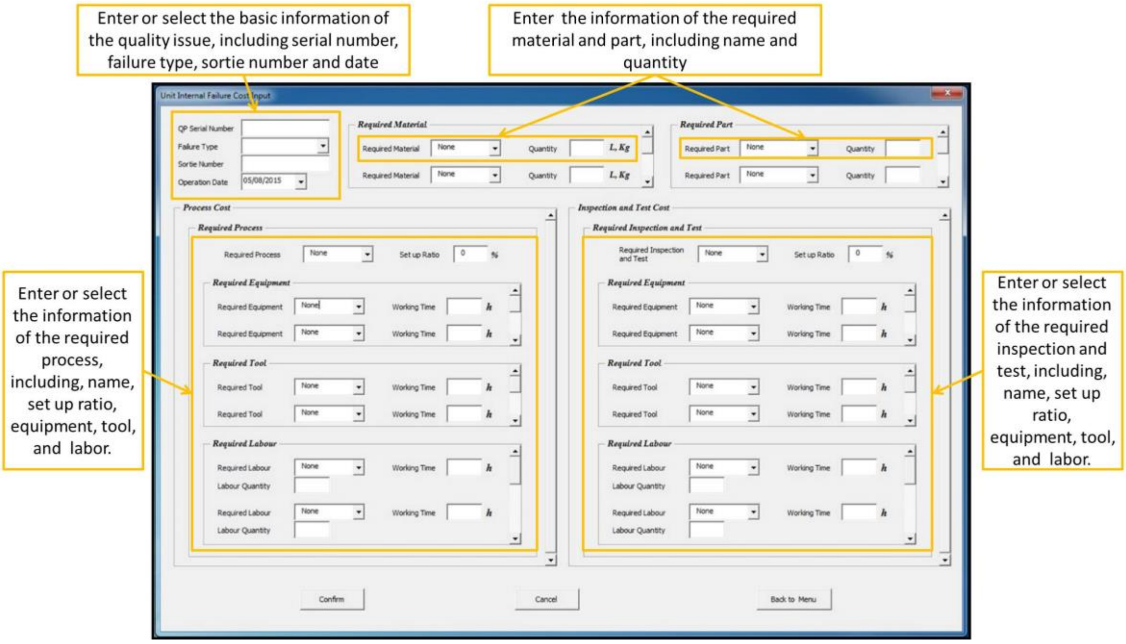


Figure 4-18 Internal Failure Cost Information Input Interface

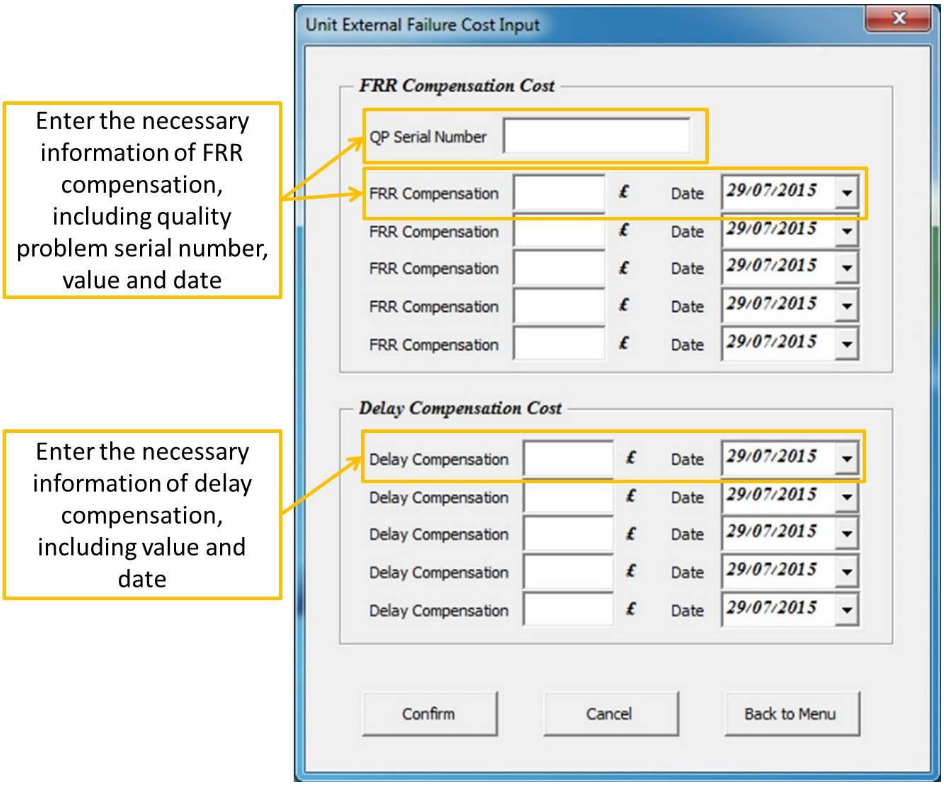


Figure 4-19 External Failure Cost Information Input Interface

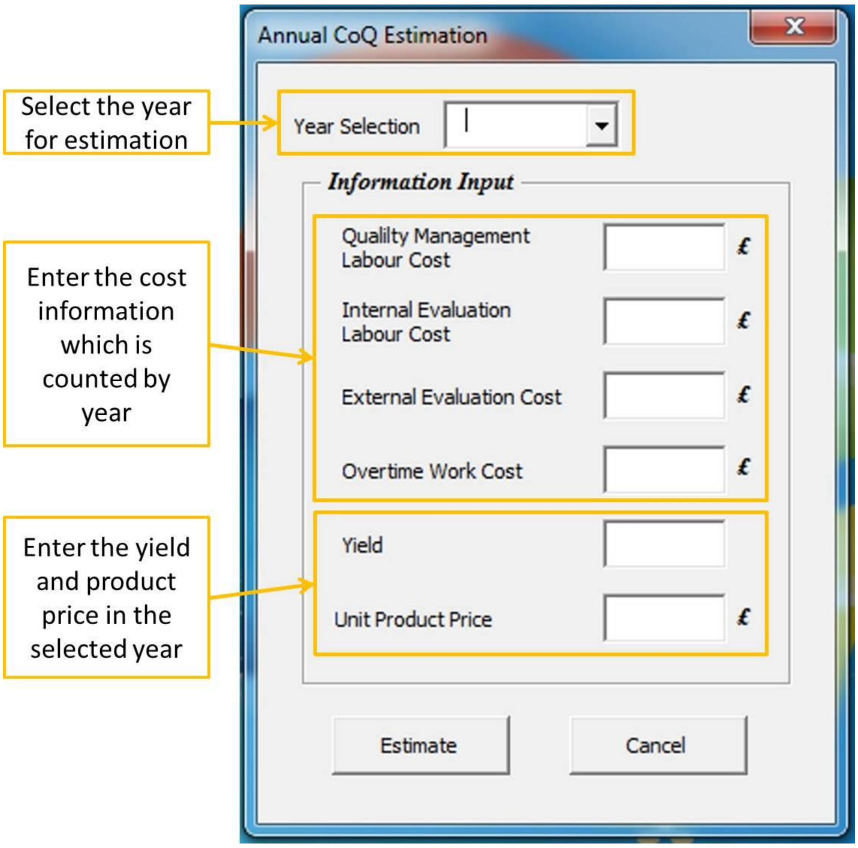


Figure 4-20 Annual CoQ Estimation Information Input Interface

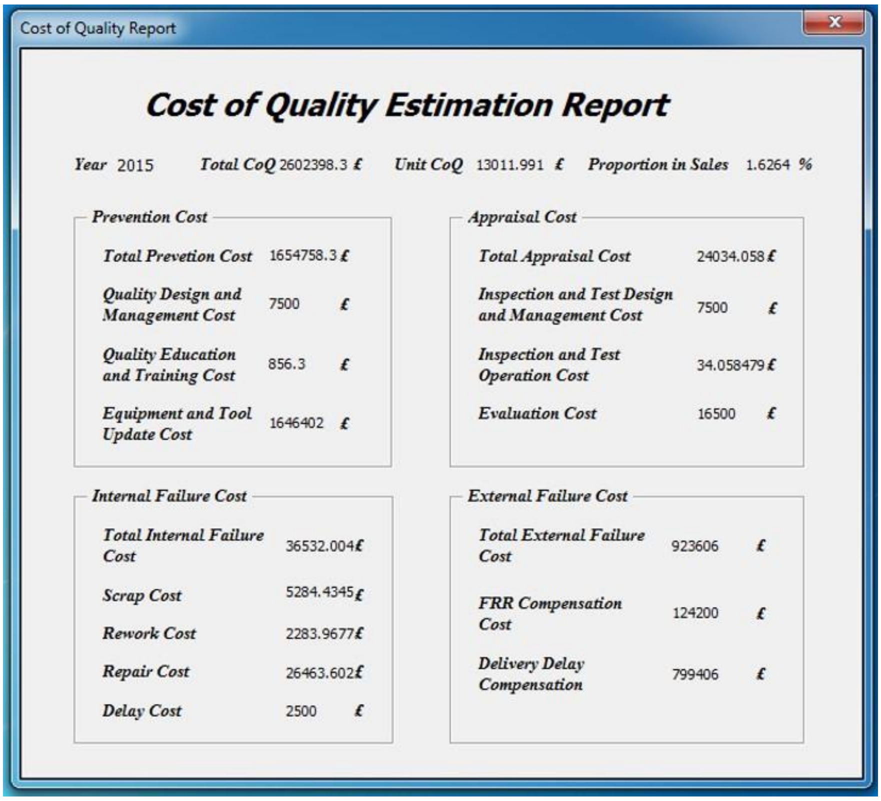


Figure 4-21 Cost of Quality Report Interface

4.5.2.4 Algorithmic

Prevention Cost Calculation

According to the Equation (4-1), prevention costs are the sum of consists of Quality Design and Management Cost (C_{qdm}), Education and Training Cost (C_{eat}), Equipment and Tool Update Cost (C_{etu}).

Quality Design and Management is part of the work for quality management, and it is the daily work of the quality manager. Another part of work for quality manager is Inspection and Test Design and Management in this model. As mentioned before, the cost driver for quality management is labour. So the cost of quality management (C_{qm}) can be calculated through Equation (4-6). As there are only two kinds of work for quality manager, and it is difficult to identify the proportion of each work, so it can be assumed that the proportion of each kind of work is 50%, then the Quality Design and Management cost can be estimated based on Equation (4-7).

$$C_{qm} = \sum_{i=1}^{n} S_{qmi} \times T_{qmi} \tag{4-6}$$

$$C_{qdm} = \frac{1}{2}\sum_{i=1}^{n} S_{qmi} \times T_{qmi} \tag{4-7}$$

Where:

$\boldsymbol{n}$ = Number of quality managers;

S_{qmi} = Unit salary for quality manager $\boldsymbol{i}$;

T_{qmi} = Working time for quality design and management.

Education and Training Cost can be categorized into two groups, theory education and training cost (C_{the}) and practice education and training cost (C_{pra}) which can be shown as Equation (4-8). The cost driver for theory education and training cost is labour, including the teacher cost and student cost. So theory cost can be calculated through Equation (4-9). Practice education and training is similar as 'Productive Activity', the cost driver for it will involve material, component, equipment and tool. Considering the materials and component for practice are scrapped which are value-less, so these parts of costs can be ignored. So it only needs to calculate equipment cost and tool cost. Hence, the practice education and tool cost can be represented as Equation (4-10).

$$C_{eat} = C_{the} + C_{pra} \tag{4-8}$$

$$C_{the} = \sum_{i=1}^{m} S_{teai} \times T_{thei} + \sum_{j=1}^{n} S_{stuj} \times T_{thej} \tag{4-9}$$

Where:

$\boldsymbol{m}$ = Number of teachers in theory education and training;

$\boldsymbol{n}$ = Number of students in theory education and training;

S_{teai} = Unit Salary of teacher $\boldsymbol{i}$;

T_{thei} = Training time of teacher $\boldsymbol{i}$;

S_{stuj} = Unit Salary of student $\boldsymbol{j}$;

T_{thej} = Training time of student $\boldsymbol{j}$.

$$C_{pra} = \sum_{i=1}^{m} D_{pra\_equi} \times T_{pra\_equi} + \sum_{j=1}^{n} D_{pra\_tooj} \times T_{pra\_tooj} \tag{4-10}$$

Where:

$\boldsymbol{m}$ = Number of equipment used in practice education and training;

$\boldsymbol{n}$ = Number of tools used in practice education and training;

D_{pra_equi} = Deprecation cost of the equipment $\boldsymbol{i}$;

T_{pra_equi} = Working time of equipment $\boldsymbol{i}$;

D_{pra_tooj} = Deprecation cost of the tool $\boldsymbol{j}$;

T_{pra_tooj} = Working time of tool $\boldsymbol{j}$.

Equipment and Tool Update Cost can be categorized into three groups, new equipment and tool purchasing cost (C_{nep}), Hardware updating cost (C_{hau}) and Software updating cost (C_{sou}) as shown by Equation (4-11).

$$C_{etu} = C_{nep} + C_{hau} + C_{sou} \tag{4-11}$$

The main cost driver of new equipment and tool purchasing is the price of equipment and tool, though purchasing planning, supplier selection, investigation and invitation for bids will also result in cost, these costs are far less than the selling price of equipment and tool, and this kind of work is not a general work which happens frequently, so these parts of costs are ignored. So new equipment and tool purchasing cost can be represented by Equation (4-12)

$$C_{nep} = \sum_{i=1}^{m} P_{nep\_equi} \times N_{nep\_equi} + \sum_{j=1}^{n} P_{nep\_tooj} \times N_{nep\_tooj} \tag{4-12}$$

Where:

$\boldsymbol{m}$ = Categories of purchased new equipment;

$\boldsymbol{n}$ = Categories of purchased new tools;

P_{nep_equi} = Unit price of equipment $\boldsymbol{i}$;

N_{nep_equi} = Number of equipment $\boldsymbol{i}$;

P_{nep_tooj} = Unit price of tool $\boldsymbol{j}$;

N_{nep_tooj} = Number of tool $\boldsymbol{j}$.

The hardware updating cost is the cost spent on maintaining structure and appearance of equipment and tool. It generally includes component cost, tool cost and labor cost. Maintenance is a period work, and there are no error for equipment and tool at most of the time, so the component cost and tool cost are general far less than the labor cost, these parts of costs can be ignored. So the hardware cost can be represented by the maintenance labor cost which is shown as Equation (4-13). The software updating cost is the cost spend on updating edition of software and adjusting software function in equipment. It generally includes software purchasing cost and labor cost which shown as Equation (4-14).

$$C_{hau} = \sum_{i=1}^{n} S_{hau\_labi} \times T_{hau\_labi} \tag{4-13}$$

Where:

$\boldsymbol{n}$ = Number of update operators;

S_{hau_labi} = Unit salary of hardware updating operator $\boldsymbol{i}$;

T_{hau_labi} = Working time of hardware updating operator $\boldsymbol{i}$.

$$C_{sou} = \sum_{i=1}^{m} P_{sou\_sofi} \times N_{sou\_sofi} + \sum_{j=1}^{n} S_{sou\_labj} \times N_{sou\_labj} \tag{4-14}$$

Where:

$\boldsymbol{m}$ = Categories of software;

$\boldsymbol{n}$ = Number of software updating operators

P_{sou_sofi} = Price of software $\boldsymbol{i}$ purchased for updating;

N_{sou_sofi} = Number of software $\boldsymbol{i}$;

S_{sou_labj} = Salary of software updating operator $\boldsymbol{j}$;

T_{sou_labj} = Working time of software updating operator $\boldsymbol{j}$;

Appraisal Cost Calculation

According to the Equation (4-2), Appraisal costs are the sum of Inspection and Test Design and Management Cost (C_{itd}), Inspection and Test Operation Cost (C_{ito}), Evaluation Cost (C_{eva}).

As discussed before, the Inspection and Test Design and Management Cost in this model is equal to Quality Design and Management Cost.

Inspection and Test Operation Cost consists of Set up Cost (C_{itse}), Inspection and Test Equipment Cost (C_{iteq}), Inspection and Test Tool Cost (C_{itto}) and Inspection and Test Labor Cost (C_{itla}).

Set up Cost can be estimated by the ratio of set up cost to total process cost. The ratio is generally based on the industrial experience. Inspection and Test Equipment Cost is mainly equipment deprecation cost. The main driver of Inspection and Test Tool is tool deprecation. Inspection and Test Labor Cost can be calculated using unit cost of Inspector multiplies by working time. So the Inspection and Test Operation Cost can be represented by Equation (4-15).

$$C_{ito} = \sum_{i=1}^{m} \frac{\sum_{j=1}^{n} D_{iej} \times T_{iej} + \sum_{k=1}^{r} D_{itk} \times T_{itk} + \sum_{h=1}^{s} S_{ilh} \times T_{ilh}}{(1 - R_{ito\_seti})} \qquad \textbf{(4-15)}$$

Where:

$\boldsymbol{m}$ = Number of inspection and test;

$\boldsymbol{n}$ = Number of equipment used in inspection and test $\boldsymbol{i}$;

$\boldsymbol{r}$ = Number of tools used in inspection and test $\boldsymbol{i}$;

$\boldsymbol{s}$ = Number of labours in inspection and test $\boldsymbol{i}$;

R_{ito_seti} = Ratio of set up in inspection or test $\boldsymbol{i}$;

D_{iej} = Deprecation of equipment $\boldsymbol{j}$ in inspection and test $\boldsymbol{i}$;

T_{iej} = Working time of equipment $\boldsymbol{j}$ in inspection and test $\boldsymbol{i}$;

D_{itk} = Deprecation of tool $\boldsymbol{k}$ in inspection and test $\boldsymbol{i}$;

T_{itk} = Working time of tool $\boldsymbol{k}$ in inspection and test $\boldsymbol{i}$;

S_{ilh} = Unit salary of operator $\boldsymbol{h}$ in inspection and test $\boldsymbol{i}$;

T_{ilh} = Working time of operator $\boldsymbol{h}$ in inspection and test $\boldsymbol{i}$.

Evaluation Cost can be generally categorized into two major groups, Internal Evaluation Cost (C_{iev}) and External Evaluation Cost (C_{eev}). The main driver of Internal Evaluation Cost is labor, so Internal Evaluation Cost can be calculated using unit labor cost multiplies by working time. External Evaluation Cost generally comes from the third-party evaluation which to verify the Quality Management System in the company. It will be consist of supply fee, evaluation fee, meeting fee, report fee, etc. But all these fees are the expenditure to third-party evaluation organization. So the External Evaluation Cost can be represented by expenditure to third-party. So the Evaluation Cost can be represented by Equation (4-16).

$$C_{eva} = C_{iev} + C_{eev} = \sum_{i=1}^{m} S_{iei} \times T_{iei} + \sum_{j=1}^{n} E_{eej} \tag{4-16}$$

Where:

$\boldsymbol{m}$ = Number of internal evaluators;

$\boldsymbol{n}$ = Number of external evaluation;

S_{iei} = Unit salary of internal evaluator $\boldsymbol{i}$;

T_{iei} = Working time of internal evaluator $\boldsymbol{i}$;

E_{eej} = Expenditure of external evaluation $\boldsymbol{j}$;

Internal Failure Cost Calculation

Based on the Equation (4-3), internal failure costs are the sum of Scrap Cost (C_{scr}), Rework Cost (C_{rew}), Repair Cost (C_{rep}) and Delay Cost (C_{del}).

Scrap Cost is the cost spent on the component or material which need to be scrapped due to quality issues. It is the cost of the resource which had been used in the scrapped component or material. So scrap cost consists of the material cost (C_{scr_mat}), component cost (C_{scr_com}) and activities cost (S_{scr_act}) which includes processes, inspection and test used. It can be represented by Equation (4-17). And the way to calculate these three kinds of cost are illustrated in Equation (4-18) to (4-20).

$$Cscr = C_{scr\_mat} + C_{scr\_com} + C_{scr\_act} \tag{4-17}$$

$$C_{scr\_mat} = \sum_{i=1}^{n} P_{scr\_mati} \times Q_{scr\_mati} \tag{4-18}$$

Where:

$\boldsymbol{n}$ = Categories of material used;

P_{scr_mati} = Price of material $\boldsymbol{i}$;

Q_{scr_mati} = Used quantity of material $\boldsymbol{i}$.

$$C_{scr\_com} = \sum_{i=1}^{n} P_{scr\_comi} \times Q_{scr\_comi} \tag{4-19}$$

Where:

$\boldsymbol{n}$ = Categories of component used;

P_{scr_comi} = Price of component $\boldsymbol{i}$;

Q_{scr_comi} = Used quantity of component $\boldsymbol{i}$.

$$C_{scr\_act} = \sum_{i=1}^{m} \frac{\sum_{j=1}^{n} D_{saej} \times T_{saej} + \sum_{k=1}^{r} D_{satk} \times T_{satk} + \sum_{h=1}^{s} S_{salh} \times T_{salh}}{(1 - R_{scr\_acti})} \quad \textbf{(4-20)}$$

Where:

$\boldsymbol{m}$ = Number of activities (process, inspection, test);

$\boldsymbol{n}$ = Number of equipment used in activity $\boldsymbol{i}$;

$\boldsymbol{r}$ = Number of tools used in activity $\boldsymbol{i}$;

$\boldsymbol{s}$ = Number of labours in activity $\boldsymbol{i}$;

R_{scr_acti} = Ratio of set up in activity $\boldsymbol{i}$;

D_{saej} = Deprecation of equipment $\boldsymbol{j}$ in inspection and test $\boldsymbol{i}$;

T_{saej} = Working time of equipment $\boldsymbol{j}$ in inspection and test $\boldsymbol{i}$;

D_{satk} = Deprecation of tool $\boldsymbol{k}$ in inspection and test $\boldsymbol{i}$;

T_{satk} = Working time of tool $\boldsymbol{k}$ in inspection and test $\boldsymbol{i}$;

S_{alh} = Unit salary of operator $\boldsymbol{h}$ in inspection and test $\boldsymbol{i}$;

T_{alh} = Working time of operator $\boldsymbol{h}$ in inspection and test $\boldsymbol{i}$.

The calculation methods of rework cost and repair cost are the same as used in calculating scrap cost. So Equation (4-17) to (4-20) can be used directly for the rework or repair cost estimation.

Delay Cost is the additional cost resulted from schedule delay. The main reason for schedule delay is the occurrence of quality issues. Generally when quality issues happen, the procedure with quality issue will lead to schedule delay, and the latter step will be postponed at the same time. However, it is difficult to judge which time quantum belong to waiting time in normal working hours, so there will be a hypothesis when estimate the schedule delay cost. The hypothesis is “there will be no schedule delay in normal assembly condition, and all the delay will be handled in overworking time”. It means that overtime working is the only thing to be considered when estimated the schedule delay cost. The schedule delay costs are not the total overtime working, because the main cost of waiting is labor cost, material, part, equipment and tool are not used during this time. Hence, the schedule delay cost can be represented by overtime labor working cost. So the Delay Cost can be expressed by Equation (4-21).

$$C_{del} = \sum_{i=1}^{n} S_{del\_acti} \times T_{del\_acti} \tag{4-21}$$

Where:

$\boldsymbol{n}$ = Number of overtime working labour (operator, inspectors and testers);

S_{del_acti} = Unit salary of overtime working labour $\boldsymbol{i}$;

T_{del_acti} = Working time of overtime working operator $\boldsymbol{i}$;

External Failure Cost Calculation

Based on the Equation (4-4), the external failure costs are the sum of FRR compensation (C_{frr}) and delivery delay compensation (C_{ddc}). These two kinds of cost are not related to production factors such as material, component and activities. They are only associated with the value and quantity of the compensation. So the External Failure Cost can be represented by Equation (4-22).

$$C_{exf} = \sum_{i=1}^{m} C_{frci} + \sum_{j=1}^{n} C_{ddcj} \quad \textbf{(4-22)}$$

Where:

$\boldsymbol{m}$ = Number of FRR compensation;

$\boldsymbol{n}$ = Number of delivery delay compensation;

C_{frci} = Unit cost of FRR compensation $\boldsymbol{i}$;

C_{ddcj} = Unit cost of delivery delay compensation $\boldsymbol{j}$;

Total, Unit and Proportion of CoQ Calculation

Based on the definition, CoQ consists of four main parts, prevention cost, appraisal cost, internal failure cost and external failure cost. Hence, the total CoQ can be shown as Equation (4-23). Unit CoQ is the average CoQ in each product, so it can be calculated through Equation (4-24). The proportion of CoQ in total sales is generally used to reflect the influence of CoQ the condition of quality management. And it can be calculated by the ratio of unit CoQ to the average price of unit product in this model, as shown in Equation (4-25).

$$C_{coq} = C_{pre} + C_{app} + C_{inf} + C_{exf} \quad \textbf{(4-23)}$$

$$C_{ucoq} = \frac{C_{coq}}{N} \quad \textbf{(4-24)}$$

$$P_{coq} = \frac{C_{ucoq}}{P_{aup}} \quad \textbf{(4-25)}$$

Where:

C_{coq} = Total CoQ in estimation period;

C_{ucoq} = Unit CoQ for each product in estimation period;

N = Yield of product in estimation period.

P_{coq} = Proportion of CoQ in sales;

P_{aup} = Average price of unit product.

4.5.3 CBA Module

CBA is generally used as a decision-making process for comparing costs and benefits of activities. The objective of CBA is to make decision-making more reasonable and the distribution of resources more efficient. Most of CBA are used in evaluating whether a project is worth doing. However, in this model, CBA is used to support quality management.

Quantitative analysis is very important and useful for quality management. However, due to the lack of effective method to analyse and calculate the quality related data, quantitative analysis is generally hardly in use. Hence, most of investments on quality are based on experience, which may be blind sometimes due to the lack of the support of data. Therefore CBA may be a good selection for solving this problem as it can support necessary data for decision-making. Moreover, the support from CoQES may improve the limitation of CBA in cost and benefit estimation.

The steps of CBA have been introduced in Chapter 2. And it can be simplified into three main steps: cost identification and calculation, benefit identification and calculation and comparative analysis. In this module, CBA focuses on evaluating the investment on solving quality issues as reducing the number and cost of quality issues is the main method of quality improvement. So the cost and benefit involved are all related to quality issues.

4.5.3.1 Cost Elements Identification

The cost in CBA means the investment which can bring benefit for the activity or project. It is normally considered that prevention and appraisal cost are value-added which can reduce the unnecessary cost. Meanwhile, internal failure and external failure cost are non-value-added which only increase the total CoQ (Özkan & Karaibrahimoğlu, 2013). The cost benefit analysis is used to represent the relationship between the cost and the benefit which is brought through the cost, and those non-valued-added cost can hardly to find out the relationship as it is difficult to estimate the benefit. Hence, prevention and appraisal cost are the cost which considered and discussed in CBA.

However, In order to convenient to analyse the relationship between cost and benefit, some special limits are necessary in cost and benefit identification. Firstly, the cost can be assigned a financial value as it is impossible to apply CBA with a non-quantified parameter. Moreover, there is a relatively clear relationship between the cost and the benefit which can ensure the benefit can be identified precisely. Based on these limits, the education and training cost, and equipment and tool update cost will be the main objectives focused on in this module.

4.5.3.2 Benefit Elements Identification

The benefit in CBA means the profit which is resulting from the investment. It can be divided into two parts: profit improvement and cost saving. Profit improvement is the difference between current profit and former profit which mainly came from the improvement of sales. Cost saving is the difference between current cost and former cost which mainly came from the reduction of unnecessary cost. In aircraft manufacturing industry, the sales volume of product relies on the orders which are placed by the customers a long period before manufacturing, and the sales volume of every year had been planned. So it is impossible to improve the sales volume directly due to investment on quality. Otherwise, the prices of the product are generally constant except for special requirements from customers. So it is impossible to increase the profit by improving the sale price of product. Hence, it will be very difficult to represent benefit by profit improvement. Therefore, cost saving the most suitable and only way to represent benefit.

Cost saving generally means the reduction of the unnecessary cost in the manufacturing process. And failure costs which sometimes are generally thought as the unnecessary cost. As the aim of most of investment on quality is reducing failure cost. So reduced failure cost will be considered the benefit in this model. Additionally, according to the industry survey, some ideas to represent the benefit, such as quality problem reduced and customer satisfaction improvement, are collected. However, these parameters are hardly to quantify or compare with cost, so they will not be considered in this model.

Based on the literature and industry survey, the action time of investment are not same. Some investments may reflect the benefit immediately or in a short period, while others may need a long time to reflect the total benefit. So benefits are generally divided into short-term benefit and long-term benefit. Based on industry survey, the period for short-term benefit reflection is thought to be half or one year, while the period for long-term benefit is more than three years. So it is important to determine the category of the benefit before CBA for it may affect the parameter selection.

4.5.3.3 Cost Benefit Analysis

There are various methods can be used in CBA, including Net-Present Value (NPV), Internal Rate of Return (FIRR) and Benefit- Cost Ratios (B/C). (B/C) is the most intuitive and simply one in all these methods (Stenstrom, et al., 2015). It can be used to analyse the benefit of the investment which have been carried out, while it can also be used to simulate the prospective (B/C) before investment, either. In this model, it can be represented by Equation (4-26). In order to describe simply, β is defined to denote (B/C).

$$\beta = \frac{B}{C} = \frac{\sum_{i=1}^{n}(\Delta C_{infi} + \Delta C_{exfi})}{\sum_{i=1}^{n}(\Delta C_{eati} + \Delta C_{etui})} \tag{4-26}$$

Where:

$\boldsymbol{n}$ = Prospective benefit reflection period;

ΔC_{infi} = Reduced internal failure cost due to the cost in year $\boldsymbol{i}$;

ΔC_{exfi} = Reduced external failure cost due to the cost in year $\boldsymbol{i}$;

ΔC_{eati} = Additional education and training cost in year $\boldsymbol{i}$;

ΔC_{etui} = Additional equipment and tool updating cost in year $\boldsymbol{i}$.

If β >1, it means that the investment on quality is (will be) profitable in n years; if β =1, it means there is (will be) no loss of the investment in n years; if β <1, it means there is (will be) loss of the investment in n years.

There is an important hypothesis in CBA in this model. It is that the influence of all the production factors is constant to the manufacturing system. For example, if the investments on quality are the same in two years, then the whole condition of the manufacturing system in the two years are same. That means that if this year do not add investment on quality, the category and number of quality issues, the failure cost which caused by quality issue are same. The hypothesis is to simplify the calculation and analysis used in CBA.

The flow chart of CBA on quality management is illustrated in Figure 4-22. Firstly, quality issues are analysed using Pareto Analysis both in number and cost to determine the main quality issues which will be the main targets of quality improvement. And the data for Pareto Analysis will be obtained from CoQES and Quality Issues Analysis module. Secondly, the method to solving quality issue will be determined and the prospective target and period need to be set. Thirdly, the cost of the solution in the period will be calculated in CoQES. Fourthly, the CBA is applied to analyse the same investment before based on the history data in CoQES. And the maximum β in one year, the minimum β in one year and the average β in one year will be estimated. Then the maximum benefit, the minimum benefit and the predicted benefit will be simulated according to Equation (4-26). Then the benefit will be compared with the excepted target. If the results meet the requirement, the investment will be carried out. Otherwise, method and period will be adjusted.

4.6 Summary

In this chapter, the developing process of the CoQ estimation system and CBA model are illustrated. The industry survey results supplied data and ideas for the development of the model. The CoQ in tailplane assembly are identified and defined based on the P-A-F classification, then the cost drivers of the activities used in tailplane assembly are identified and analysed. The main cost drivers in tailplane assembly are component and labours. Furthermore, CoQ estimation system development is based on MS Excel. The GUIs are designed by using VBA. The databases and equations are built in the worksheets. Otherwise, a CBA module are developed which can analyse the benefit of the cost on quality relying on the calculation result in CoQES.

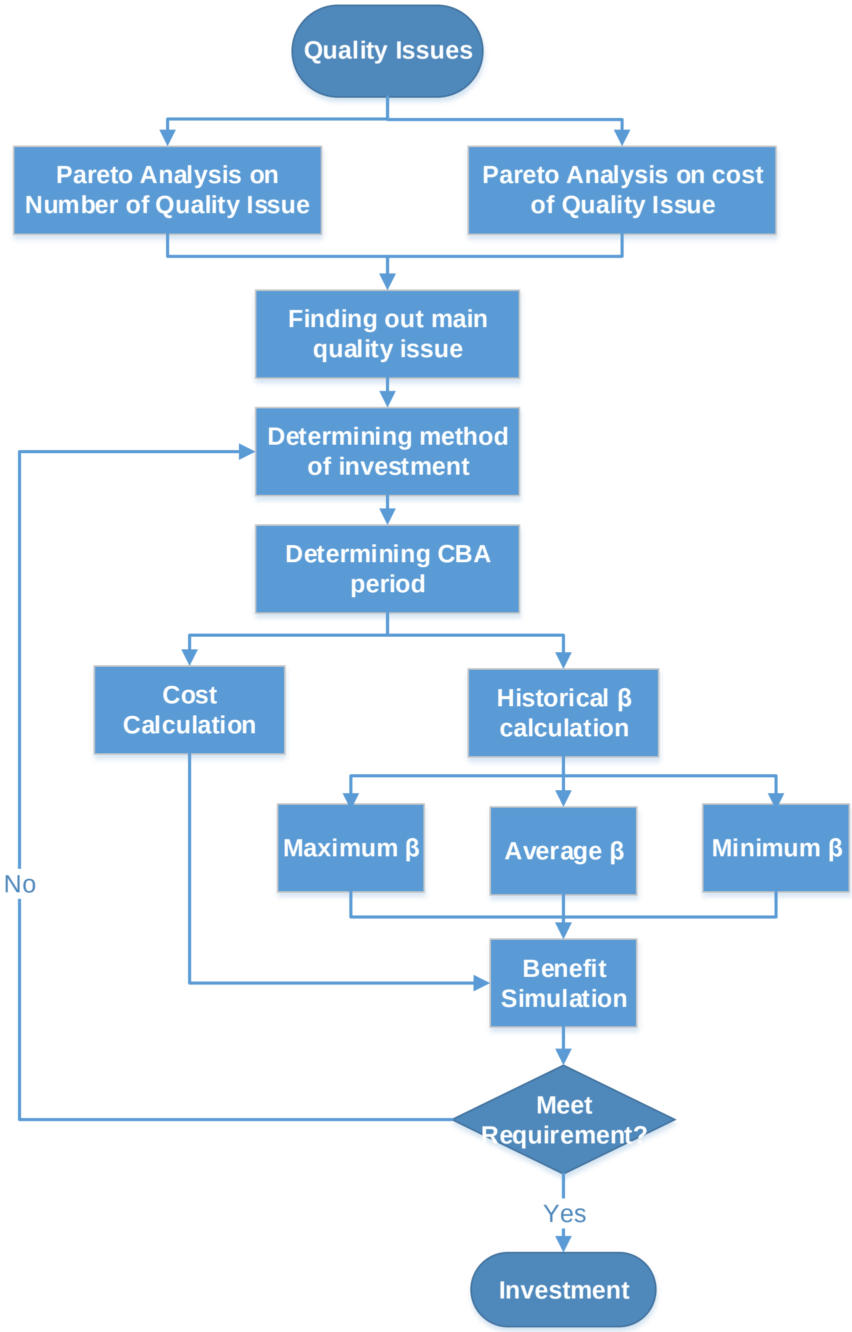


Figure 4-22 Flow Chart of CBA Module on Quality Management

5 VALIDATION OF THE COQ MODEL

5.1 Introduction

This chapter presents the validation process of the developed CoQ model. Case studies and expert judgements are used for the validation. As the tailplane assembly process is too complex to collect enough data for all the production factors, two small cases studies are used. One of the cases is used to discuss the CoQES based on the Final Assembly Phase in tailplane assembly. The other one is to illustrate the application of CBA on quality management. Otherwise, some experts with engineering experiences of quality management in aircraft manufacturing industry are invited to evaluate and grade the CoQ model. Based on the results of case studies and experts' suggestions, the advantage and disadvantage of CoQ model were discussed.

5.2 Case Study for CoQES Validation

5.2.1 Introduction

The CoQES is designed to be an effective tool to analyse and estimate the CoQ in assembly process, and a support tool for quality manager to manage and improve the quality based on the quantitative data. Based on the quality-related information which is input and stored in the system, the user can obtain the CoQ information in different years. The estimation result can reflect the CoQ value, the ratio of different kinds of CoQ in total CoQ and the proportion of CoQ in sales, all of which will be very useful in planning quality improvement.

The case for CoQES validation is based on the final assembly phase in tailplane assembly. The flow map of this phase is illustrated in Figure 5-1. All the data in this case are from the actual production record. As it is difficult to collect and calculate too much data in such a short period, only one year data is used in this case. Additionally, the activities involved in this case are those activities which affect the CoQ most significantly based on the findings of industry survey. Furthermore, only the labours which are related to these activities closely will be focused on, such as operator and inspector. Thus, the production factors used in this case are summarized in Table 5-1.

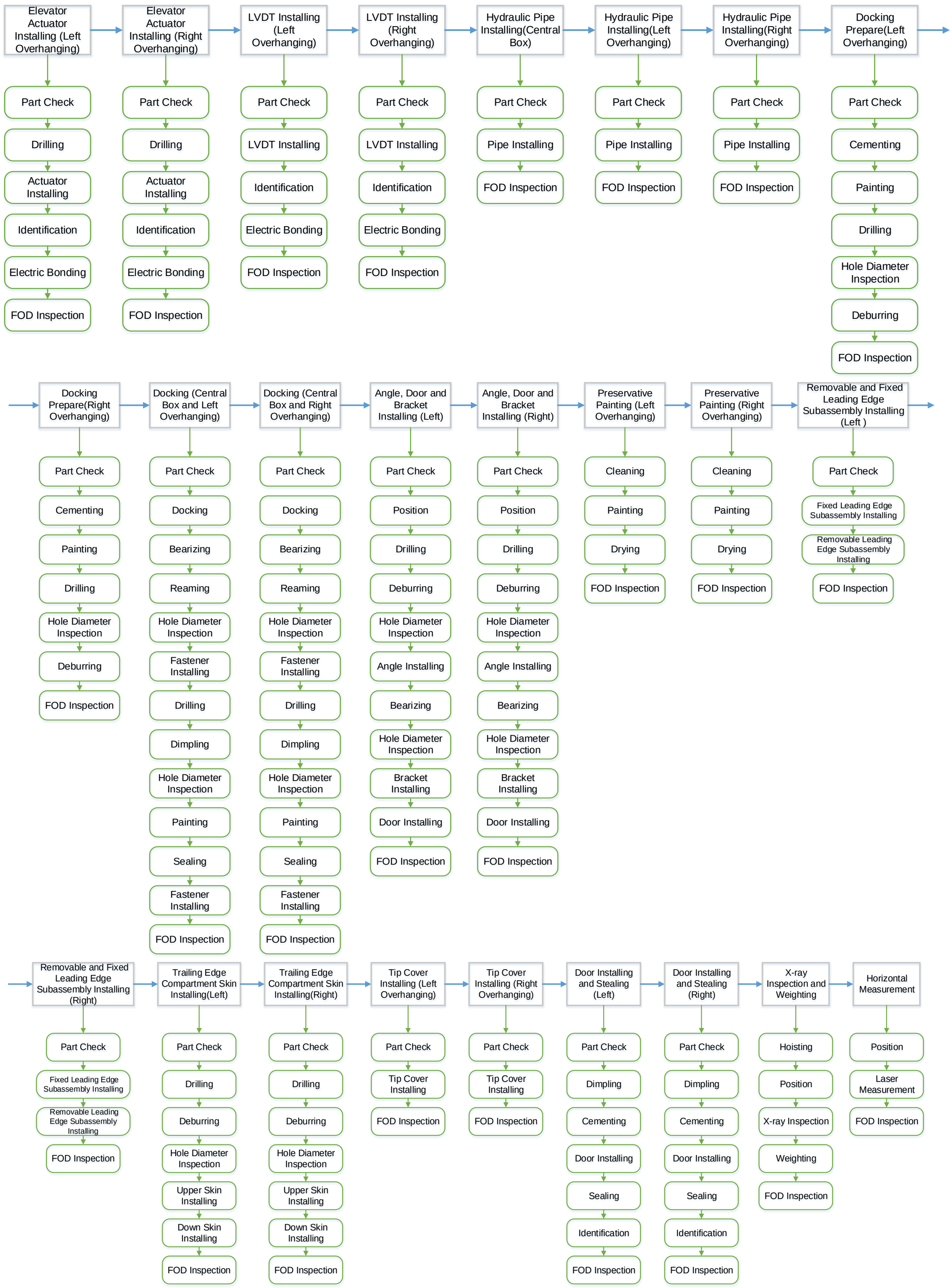


Figure 5-1 Flow Map of Final Assembly Phase in Tailplane Assembly

Table 5-1 Main Production Factors Used in Case 1

Production Factor	Detail
Material	Primer, Preservative, Sealant, Coolant, Lubricant
Component	Removable Leading Edge Subassembly, Fixed Leading Edge Subassembly, Tip Cover Assembly, Central Section, Elevator, Overhanging Section, Elevator Actuator, Surface Position LVDT, Angle Stock, Pipe, Joint, Bolt, Nail, Washer, Screw, Nut, Rivet, Skin, Fuse
Process	Riveting, Drilling, Position, Dimpling, Sealing, Reaming.
Inspection and Test	Part Check, FOD Inspection, X-ray Inspection, Laser Measurement
Equipment	Self-Feeding Drill, Riveter, Laser Measuring Device, X-ray Detector
Tool	Gauge, Drill, Countersink, Reamer, Docking Pin, Lift Car, Sling, Docking Car
Labour	Operator, Inspector, Quality Manager, Process Designer, Manufacturing Manager.

5.2.2 Result Analysis

As a consequence, the CoQ estimation results of Case 1 are summarized in Figure 5-2. From the result, it can be seen that "Internal Failure Cost" is the main cost in the final assembly phase in tailplane assembly, which accords for approximately 37.1% in total CoQ. "Appraisal Cost" and "Prevention Cost" follows with the proportion of 29.2% and 28.3%, respectively. "External Failure Cost" is the lowest one which is only about 5.4% in proportion. Moreover, the top three kinds of CoQ are very close that nearly each of them accords for one third of total CoQ. Furthermore, the sum of the prevention cost and appraisal cost are close to 60% of the total CoQ, which are far more than the failure cost.

According to the result, the quality condition in this case can be analysed. Firstly, high internal failure cost means that the quality issues in this process are still serious and the influence of quality issues to the product cost is remarkable. Moreover, the appraisal cost takes a great proportion in the total CoQ. From Figure 5-3, it is clear to see that the inspection and test operation is main one in appraisal cost. In aircraft manufacturing industry, due to the strict requirement on quality, most of the work has to be 100% inspected. Almost all the processes need to be inspected when they are finished by the operators. And as mentioned before, aircraft assembly is a complex progress, which involves tens of thousands of components and hundreds of processes. 100% inspection used in such a complex process result in the significant increase of the appraisal cost. Furthermore, the sum of prevention and appraisal cost exceed the sum of failure cost means that many investments on quality had been spent in tailplane assembly to ensure the quality. However, more investments on quality are still needed to reduce the failure cost, as those costs which cannot add value for the assembly process are hoped to be as low as possible.

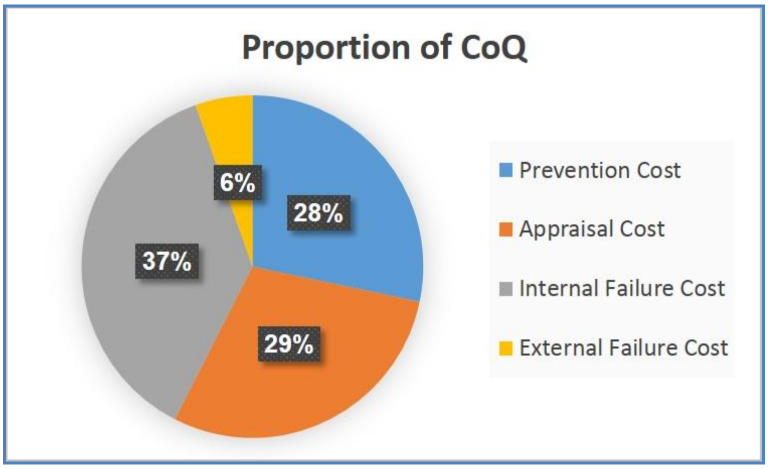


Figure 5-2 Proportion of Different Kind of CoQ in Total CoQ

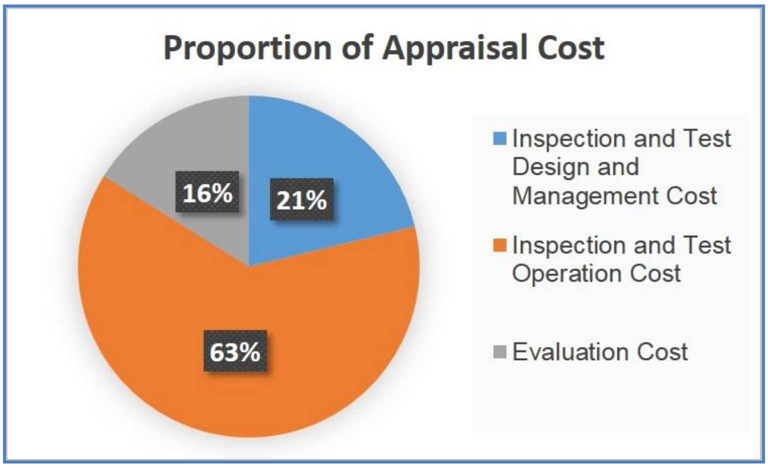


Figure 5-3 Proportion of Different Kind of CoQ in Appraisal Cost

The proportion of CoQ in sales is generally used to reflect the influence of CoQ to product (Giakatis et al., 2001). As mentioned before, the proportion can be calculated using the ratio of unit CoQ to price of unit product. However, as the data used in this case is not the integrated data in the assembly process, the ratio may be lower than the actual value. Hence, some amendments are needed to the CoQ value before calculating the proportion.

In order to evaluate the influence of the missing data, a hypothesis is set to amend the value of CoQ. The hypothesis is: “Cost of the activities which are not considered in the calculation own the liner relationship with the cost of activities used in the calculation”. For example, there may be fifteen processes used in tailplane assembly, but only six of them are considered in the calculation. The cost of other nine processes can be estimated using the product of the proportionality coefficient and cost of the six used processes. According to industry survey, the activities used in the estimation process are 10 activities with most significant influence on cost. The proportionality coefficients for these activities are less than 1 base on the experience of a quality engineer with more than 10 years working experience. Hence, the coefficient is set to be 1 which means that the costs of missing activities are equal to the used activities. Additionally, the estimation is based on the final assembly phase, and the CoQ in other phases are not considered. More amendment is needed to the CoQ value. An experience rate was obtained from a quality engineer with more than 10 years working experience. He thought the CoQ in final assembly phase is approximately 30% of the total CoQ. So the CoQ values are amended based on the hypothesis and the experience rate. Figure 5-4 shows the comparison of the ratio using original CoQ value and amended value. It can be seen that the proportion CoQ in sales using amended CoQ value is approximately 17.5%. It is close to the theory value: 21% to 30%, which is the result of industry survey.

Though the amended CoQ which based on hypothesis and experience rate cannot represent the actual value, it still prove that the CoQES can be used to estimate the CoQ in tailplane assembly with an acceptable tolerance if there is enough necessary data. However, verification process and improvement are still necessary before the CoQES is used to actual manufacturing condition.

Figure 5-4 Proportion of CoQ in Sales

5.3 Case Study for Application of CBA

5.3.1 Introduction

In this case, a simplified process is selected to validate the application of CBA in order to make the results simply to analyse and discuss. The flow map of the process is illustrated in Figure 5-5.

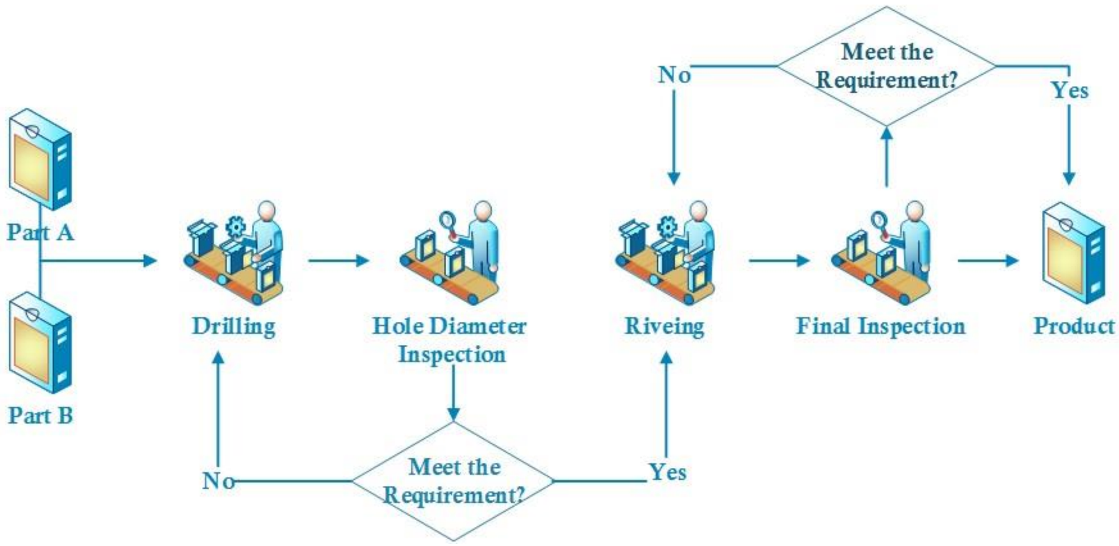


Figure 5-5 Flow Map of Case 2

According to the flow chart shown in Figure 4-9, the quality issues are analysed to determine the investment object and method. Figure 5-6 and 5-7 shows the results of Pareto Analysis on quality issues. It can been seen that the Hole problems which are caused by equipment failure are the main quality issue both in the number and the cost. So CBA is used to evaluate the investment on the solution of hole problem caused by equipment failure. The excepted target is that failure costs caused by this kind of quality issue are reduced 30% in three years and the investment can be one of the solution is to add 50% maintenance time every year, the other solution is to purchase 5 new equipment. Both of solutions are applied CBA and the results are analysed and compared as follow.

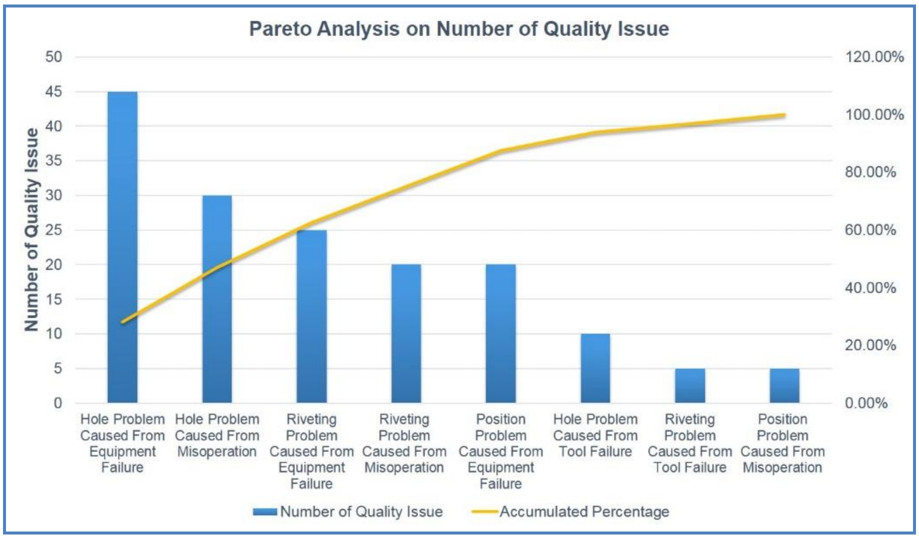


Figure 5-6 Pareto Analysis on Quality Issue Number

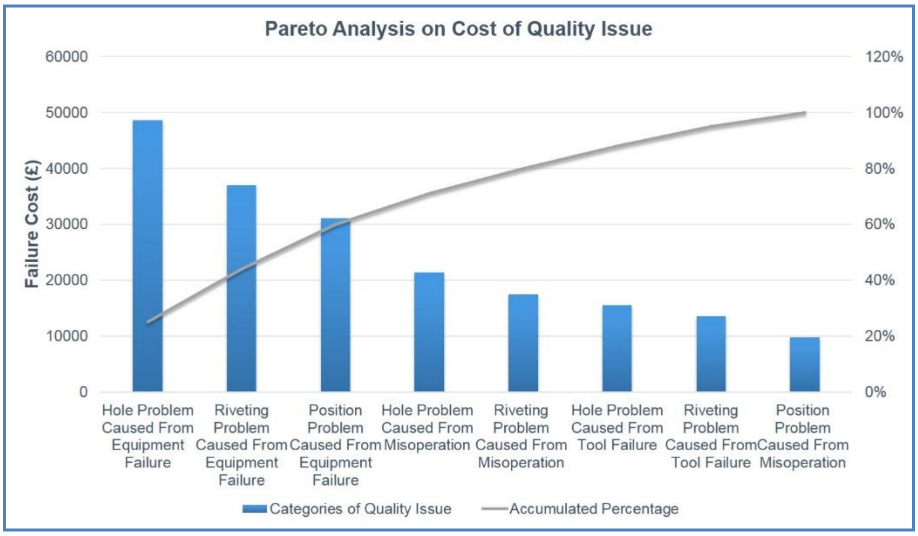


Figure 5-7 Pareto Analysis on Cost of Quality Issue

5.3.2 Result Analysis

Figure 5-8 illustrates the CBA result of solution 1. The maximum β in one year for equipment maintenance in history data is 0.35, the minimum β in one year is

0.24, and the average β in one year is 0.3. Hence, in three years, the maximum benefit can be 1.05 times of the cost on equipment maintenance in the first year, the minimum benefit can be 72% of the cost, and the predicted benefit is 90% of the cost. Additionally, according to the cost on additional equipment maintenance and the predicted β, the predicted benefit in the three years was estimated, and it was only 12% of the current failure costs which were caused by equipment failure. So based on the result, the solution 1 can almost meet the excepted target about the return of investment, but cannot meet the excepted target about the benefit value.

Figure 5-9 shows the CBA result of solution 2. The maximum β in one year for new drilling equipment in history data is 0.21, the minimum β in one year is 0.15, and the average β in one year is 0.18. So in three years, the maximum benefit can be 63% of the cost of purchasing new equipment in the first year, the minimum benefit can be 45% of the cost, and the predicted benefit is 54% of the cost. Additionally, according to the cost on new equipment and the predicted β, the predicted benefit in the three years was estimated, and it was 33% of the current failure costs which were caused by equipment failure. So based on the result, the solution 2 can meet the excepted target about the benefit value but cannot meet the excepted target about the return of investment.

Comparing the two results, it can be found that both of the solutions cannot meet all the excepted targets. So some new method may be analysed if the excepted targets are not changed. However, focusing on one target may be a good way. If the return of investment is thought to be more important, solution 1 is the better choice. In contrast, solution 2 should be selected.

From the results, it is clear that the CBA module can supply useful reference information for the user in decision-making on quality investment. And it is simply to obtain more feasibility analysis results through changing the parameters used in solutions which can help the user to analyse the solution systematically. However, due to the simulated value relying on the history data significantly, there may be limitations when apply this method in a process with no enough history data. Moreover, the average β may be suit for the long-term benefit simulation as it can reduce the influence of fluctuation in single year, but it may be not suit for the simulation in short period.

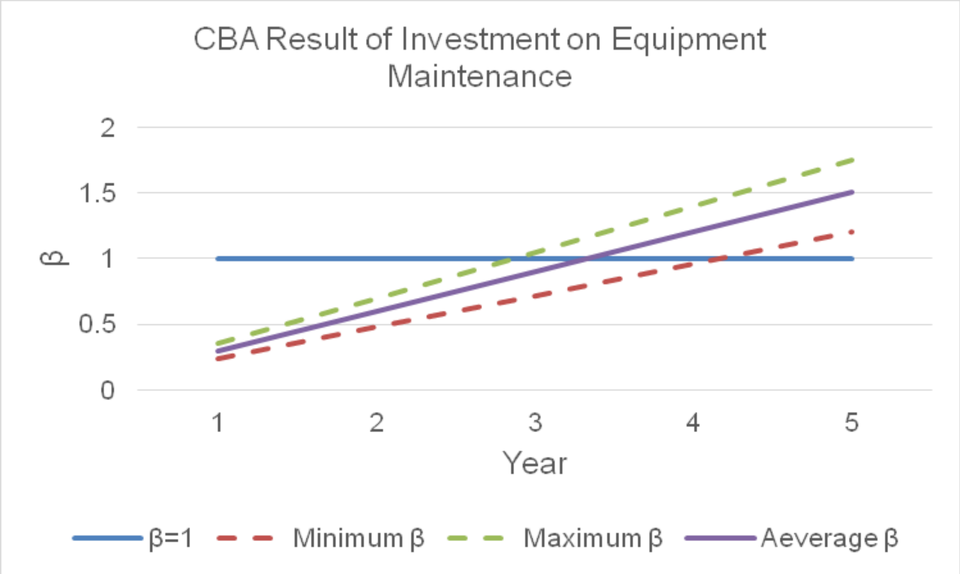


Figure 5-8 CBA Result of Investment on Equipment Maintenance

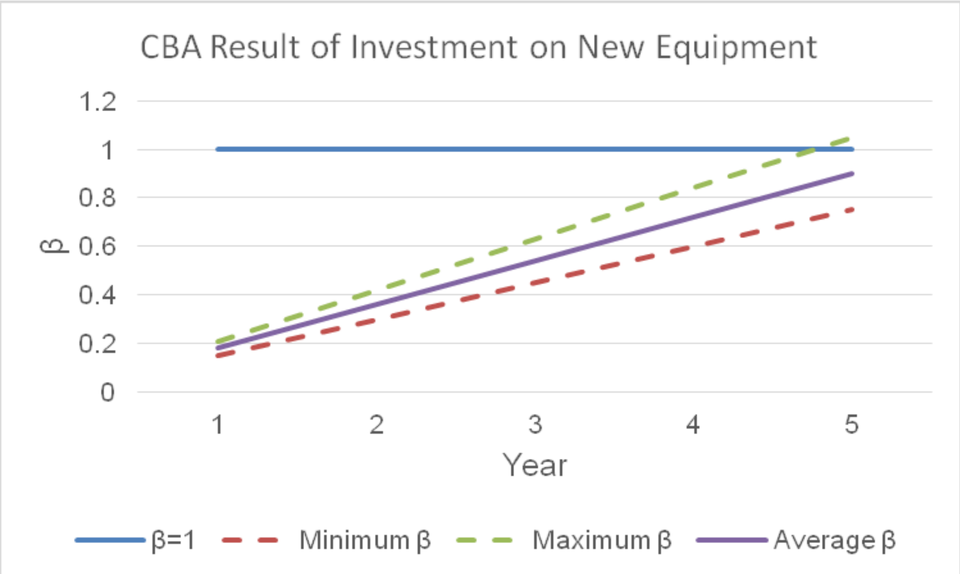


Figure 5-9 CBA Result of Investment on New Equipment

5.4 Expert Judgment

As experts can supply more professional suggestions and guidance based on the professional knowledge and experience, expert judgement was used to validate the developed CoQ model in this section. The expert judgment is used to validate the whole performance of the CoQ model. It is a qualitative analysis result based on the working experience of these experts. The main aim of the expert judgment is to validate whether this model is suit for the aircraft manufacturing industry. In order to collect opinions widely, six experts from three different companies in aircraft manufacturing industry in China were invited for evaluation. The general information of these experts was illustrated in Table 5-2. In accordance with the requirements of experts, the names of their companies are not mentioned in the thesis.

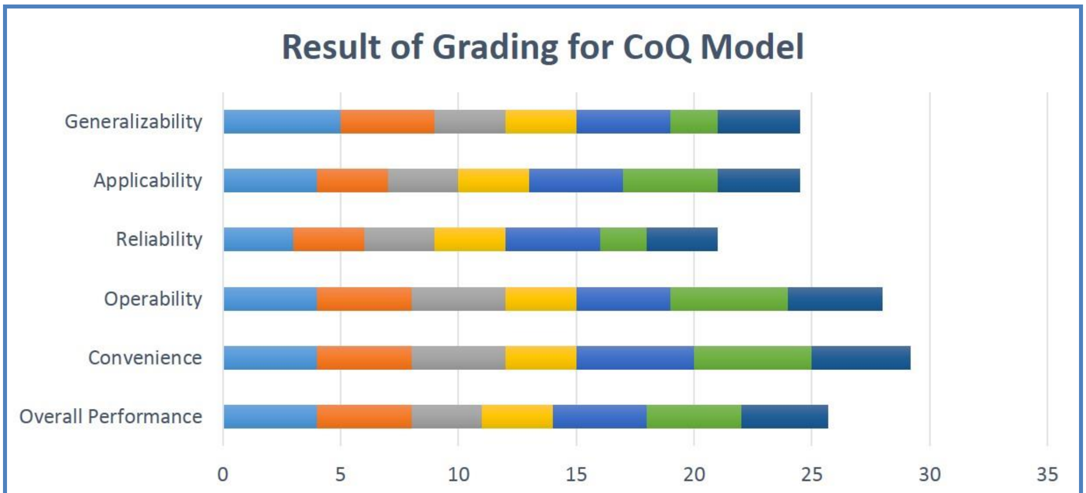
Table 5-2 General Information of Experts

Expert	Company Type	Responsibility	Working Experience
A	Aircraft Design	Overall Design Senior Engineer	8 years
B	Aircraft Design	Project Management Engineer	6 years
C	Aircraft Manufacturing	Quality Management Senior Engineer	12 years
D	Aircraft Manufacturing	Project Management Engineer	7 years
E	Aircraft Manufacturing	Quality Management Engineer	8 years
F	Aircraft Manufacturing	Process Design Engineer	10 years

As all the experts are abroad, it is impossible to arrange a face to face validation session. Hence, the CoQ model is sent to these experts through E-mail, and the results of case studies are submitted to them at the same time. In order to ensure the experts can use the CoQES conveniently, an instruction was attached to the model together.

Otherwise, a grading form (see Appendix B) is designed to collect the suggestions and comments from the experts. The form includes two parts content. One part is the grading for the CoQ model. The experts who attend this validation will grade the CoQ model based on their own application results and the case studies results which supplied them before. Five scores are designed to represent different level of the CoQ model: score 1 means very bad; score 2 means bad; score 3 means not bad; score 4 means good and score 5 means very good. The average value of the six scores from experts will be used to represent the level of performance of CoQ model in different aspects. The experts will grade the CoQ model from six aspects, which are overall performance, convenience, operability, reliability, applicability and generalizability, respectively. The result of grade will be collected to analyse the level of the CoQ model. The other part is opinions and suggestions collection. The experts will give theirs opinions on the advantage and limitation of the CoQ model, and make suggestions for the improvement in the form. The information is very important and useful for the improvement of model and the determination of the future work.

The results of the grading for CoQ model are illustrated in Figure 5-10. It can be found from the result that the CoQ model had been approved by the experts as all the average score value are not lower than 3 which means that all the aspects of the CoQ model are not bad in experts mind. In all these characteristics, convenience and operability are thought as good. It may be due to the application of the GUI which can supply user-friendly interface to the users. The performance of applicability and generalizability are regarded between not bad and good. It may be due to the combination of theory practice. The identification and definition of CoQ are based on the actual manufacturing progress, so the parameters and calculation methods may be suit for the aircraft industry. Moreover, many aircraft manufacturing company are lack of the systematic CoQ management methods, so this CoQ model can be a template for these companies. That may be why the experts considered it is worth to promotion. The score of reliability is the lowest. Though score 3 means not bad, as a core index, it is still not meet the anticipated effect. The reason for this may be the over simplification of the actual manufacturing process and the overlook of some kinds of CoQ which are hidden or difficult to quantify in the phase of identification and definition. One of the experts gave explanation for the issue in his feedback. He said that it needs too much data to validate the reliability for this model, and it is impossible to collect enough data in a short period by one person. So most of the judgements on this characteristic are based on the case results supplied to him. As it is not his own practice result, so he could only give a relatively conservative result to avoid supplying wrong information. Data is still a problem in all the process of model development. Though the explain shows some reason of the low score of this characteristic, it still means that the CoQ model need more improvement before it can be used in actual manufacturing.



	Overall Performance	Convenience	Operability	Reliability	Applicability	Generalizability
Expert A	4	4	4	3	4	5
Expert B	4	4	4	3	3	4
Expert C	3	4	4	3	3	3
Expert D	3	3	3	3	3	3
Expert E	4	5	4	4	4	4
Expert F	4	5	5	2	4	2
Average Value	3.7	4.2	4	3	3.5	3.5

Expert A Expert B Expert C Expert D Expert E Expert F Average Value

Figure 5-10 Result of the Grading for the CoQ Model

Table 5-3 summarized the experts' opinions for the CoQ model about advantage, limitation and suggestions. In general, the CoQ model are considered to be a good tool for quality manager to estimate and analyse the CoQ. And it is worth to promotion in aircraft industry in China. However, there are still some limitations in this model, especially selected parameters in CoQ calculation and benefit simulation and the reliability of the model need be evaluated based on more actual data. Therefore, the model needs more improvement before it can be used in actual production. Additionally, some useful suggestions on improving the model are given, and some of them, such as production factors selection have been considered in the improved model. For example, more than twenty kinds of processes and inspections are analysed and the involved parameters such as materials, equipment, tools have been put into the basic database in the model. It can make the model to estimate the CoQ of more activities in the tailplane assembly.

Table 5-3 Expert Opinion for CoQ Model

CoQ Model	CoQES	CBA Module
Advantage	➢ A good tool for quality manager to collect and analysis CoQ ➢ Very convenient to operate ➢ A tool suit for the actual condition of aircraft manufacturing industry ➢ Can be used as a sample and tool to promote and popularize the cost of quality in whole company	➢ A good idea and method which can supply necessary reference data for quality managers and help them to make better decision ➢ Supply a new procedure for quality management ➢ Fill in a gap in quantitative management and assurance
Limitation	➢ The database is too small, it need to update frequently when calculating complex progress ➢ The categories of CoQ are not integrated, more kinds of CoQ need to be identified and defined ➢ The limitation of Excel will influence the application of the estimation system. When calculating complex progress the system may crash ➢ The calculation methods used is a little simple, the interactions between different activities are not considered.	➢ The parameter which used to represent the benefit is too simply and single which can hardly reflect the actual benefit accurately ➢ The hypothesis about the influence of cost is not reasonable as the influence is generally complex ➢ Using existing data to simulate future benefit is a good idea, but the simulation method should be more mathematic and rigorous
Suggestion	➢ Improve the database and put more necessary data into it before the CoQES be used in actual manufacturing ➢ Identify more kinds of CoQ as some of them are hidden or difficult to quantify ➢ More production factors should be considered, and some parameters such as scrap rate and error rate	➢ Identify more parameters to represent the benefit, especially the benefit which is difficult to quantify ➢ Use more reasonable method to estimate the influence of the cost or investment ➢ Find out more optimized method to simulate the benefit of cost on quality

	can be used in calculation ➢ Advanced software may to select if the CoQES is planned to calculate more complex progress such as aircraft general assembly	

5.5 Summary

In this Chapter, case studies and experts judgements are used to validate the developed CoQ model. The result of Case 1 which is used to analyse the capacity and reliability of the CoQES showed that the CoQES can be used to estimate the CoQ in the aircraft manufacturing industry, but the reliability need to be validated through more verification process based on integrated data. Case 2 demonstrated the application of the CBA on investment analysis and quality management. Finally, some experts from aircraft industry graded for the CoQ model, the result of which showed that the CoQ model is not bad in all aspects, and good in convenience and operability. And future work need to done to improve the model before it was used in actual production.

6 DISCUSSION AND CONCLUSIONS

6.1 Introduction

A CoQ model for tailpane assembly which consists of CoQES and CBA module was developed in Chpter 4, and case studies and expert judgements were used to validate the overall performance of the CoQ model from different aspects in Chapter 5. In this chapter, the fulfillment of the aim and objectives of this research will be discussed. Moreover, the main findings will be summarized and conclusions will be stated. Furthermore, achievement and limitation of the research will be presented, and future work will be proposed.

6.2 Discussion

At the beginning of the research, the aim had been represent to develop a CoQ model which can be used to analyse and estimate the CoQ in tailplane assembly. In order to achieve the target, several objectives were set in Chapter 1. Based on the finished work, the fulfilment of each objective will be discussed in this section.

6.2.1 Fulfilment of the Objectives

The first three objectives are the identification and definition of the necessary parameters which applied in the CoQ model, including: CoQ in tailplane assembly, cost drivers and benefit. They were the preparation of the CoQ model development, and were mainly achieved through literature review, actual operation analysis and industry survey. The theory definition and categories of the CoQ, cost drivers and benefit were mainly be found through the literature, includes thesis, books, papers and reports which are related to the topic. The actual data were collected through the analysis of the operation report and quality report in an aircraft company in China and the industry survey in the aircraft manufacturing industry in China. As stated in Chapter 4, the CoQ in tailplane assembly can be divided into prevention cost, appraisal cost, internal failure cost and external failure cost according to the classical P-A-F model.

The production factors and activities for the CoQ were identified and defined based on the ABC approach. The cost drivers for the CoQ in tailplane assembly can be divided into five groups, materials, component, equipment, tool and labour, and component and labour are the two main cost drivers. Benefit in tailplane is difficult to identify and represent quantitatively. Based on literature and industry survey, the cost saving is the best way to reflect the benefit of cost on quality, and time will be an important factor which effect the value of benefit.

The fourth and fifth objectives are CoQ model development. The CoQ model developed in this research consists of two main parts: CoQES and CBA modul. Based on the identification and definition of CoQ elements, the equations for calculating every element were designed and developed. Then the framework of the CoQES was set up. In order to make the estimation system more convenient to use for the user, GUI was developed with VBA in the MS Excel based on the framework. The GUI consists of Login interface, Main Menu, Quality Information Input Interface, Cost Information Input Interface, Estimation Interface and Report Interface. These interfaces are used to collect, store, calculate and output the CoQ. It can make the CoQES simple to operate for different users, and it make the CoQES to be a real tool for the user. Database is a very important part for the system. Some basic database is built according to the data supplied by an aircraft manufacturing company and collected through industry survey. Based on the data in the database and inputted by the user, the CoQ can be calculated through the equations designed before in the system. Finally, the calculation result will be summarized in a CoQ estimation report and spread to the user for analysis.

CBA application in the CoQ model is an attempt as it is scarcely used in quality improvement. In order to analyse the cost and benefit quantitatively, the cost and benefit used in the CBA are redefined. And a classical method for CBA is used to analyse the relationship between cost and benefit. Two main possible application of the CBA module were introduced.

The final objective is to validate the CoQ model. A case study based on the final assembly phase in tailplane assembly is used to validate the performance of the

CoQES. Moreover, another case study based on simple assembly process are used to demonstrate the application of the CBA module. Finally, expert judgements is used to validate the integrated model. The experts graded the CoQ model and gave suggestions for the future improvement.

6.2.2 Application of the CoQ Model

It has been proposed that the aim of the research is to develop a CoQ model which can be used to analyse and estimate the CoQ in tailplane assembly. The CoQ model was developed and validated through the work illustrated in Chapter 4 and Chapter 5. This section will focus on the characteristic of the CoQ model and the application of the CoQ model.

Firstly, according to the identification and definition of the CoQ, the categories of CoQ in this model are based on traditional P-A-F classification which is accepted widely in many fields. So the model will be suit for the company which used P-A-F classification in quality cost management. Moreover, the cost elements selected in the model were the analysis results through comparing the theory categories and actual operation of tailplane assembly. Some of the cost elements may be the characteristics of the aircraft industry, such as FRR compensation. So the CoQ model will be suit for the aircraft manufacturing industry, especially for the tailplane assembly. Furthermore, ABC is used for the estimation of CoQ of this model, so the parameters and calculation methods are based on the ABC methods, it means that the CoQ model will be suit for the company which adopts the ABC in costing management. Finally, the CoQ model only focus on the manufacturing phase of the production, other phases such as design and sell are not considered. So it may be only can be used in the manufacturing phase. In conclusion, the CoQ model is best for estimating the CoQ in manufacturing in the tailplane assembly company which uses P-A-F classification in quality management and uses ABC in costing management. However, it is only the most suitable application environment. Actually, the influence of the methods used in quality and cost management on the CoQ model is not remarkable, some modification on the original methods may solve the issue. And for some company which is lack of the systematic management on CoQ, the CoQ model can be applied directly, it can be seen as the basic of the new CoQ management. So the CoQ model may be widely used in aircraft manufacturing industry.

Otherwise, the purpose of the CoQ model is to analyse and estimate the CoQ. As the duty on CoQ management mainly belong to quality manager in many manufacturing industries. So quality manager may be the main user of the model. The quality information collected and stored in the system and the estimation result may help the quality manager to decide the direction of quality improvement and the result of CBA may supply necessary data for the decision-making of the detail method to solve quality issue. Moreover, as quality manager is not the only person when handle quality issue, the participants with other responsibility, such as process design and structure design, may be the user of the CoQ model.

6.3 Conclusions

In conclusion, the process for developing and validating a CoQ model which is suit for the CoQ analysis and estimation in tailplane assembly are stated in this thesis. The CoQ model enables the user to estimate and analyse the CoQ in the manufacturing progress, and it also own the capacity to analyse the relationship between the cost spend on quality and the benefit it brings. It may help quality manager to make better decision on handling quality issues and perfecting quality management system.

The research results could be summarized as follows:

- Component and Labour are the two main influence factors in the CoQ estimation process in tailplane assembly.
- The estimation results of CoQ in tailplane assembly are different from many other industries. Though Internal Failure Cost is still the main cost, the Appraisal Cost is very high which is close to the Internal Failure Cost. And the sum of Prevention Cost and Appraisal Cost are far more than Failure Cost in tailplane assembly.

- Cost Benefit Analysis may be an efficient method to help the quality manager to make better decision on quality improvement.
- The overall performance of the developed CoQ model is approved by the experts in aircraft industry. The model is suit for aircraft manufacturing industry and worth popularizing in this field.

6.4 Research Contributions

To sum up, amounts of work have been done in this research, and the contributions of these works can be summarized as follow:

Firstly, the research illustrates an integrated process of CoQ modelling based on an actual application background. From the requirement analysis to the data collection, from the framework developing to the model validating, all the ideas and approaches of developing the CoQ model can be seen as a sample to develop CoQ model in other fields.

Moreover, it supplies a method to analyse and handle quality issues quantitatively. CoQES can be used to estimate the CoQ which result from quality issue, and CBA module can be applied in the analysis the benefit of the cost on quality, all these information may help the quality manager to make the right decision in quality issue handling and quality improvement.

Furthermore, the CoQ model can be popularized readily as a quality management tool in the aircraft manufacturing industry due to its good performance and high operability. It can be used as the basic of CoQ management in the companies which is lack of systematic method in CoQ management.

6.5 Research Limitations

Though the CoQ model can be used in CoQ analysis and estimation in tailplane assembly, there are still some limitations for the model which may affect the application of the model.

Firstly, the application scope of the CoQ model is limited. Based on the analysis above, the CoQ model was developed based on the actual manufacturing background, and the CoQ definition and equations are suit for the tailplane assembly. Though some small modification can make it suit for other aircraft manufacturing phase, it is difficult to be applied in other manufacturing field, such as textile.

Secondly, the basic database in the CoQES is too simple which may affect the application of the model, and the parameters selected in calculation equations are based on the activities with most significant influence on cost, they may be not enough to some complex activities. So the improvement of CoQES is necessary.

Thirdly, the validation for the CoQ model is not enough. According to the result in Chapter 5, there is only one year data used in Case 1, and the data may be not integrated in such short period, so the result may be not reflect the actual condition of CoQ in tailplane assembly. And as mentioned in the expert judgement, amount of data is necessary to evaluate the reliability of the CoQ model which need to be collected in a long time, so more validation for the CoQ model is necessary.

Finally, the method used in CBA is the simplest one, and some financial relationship could not be reflected and considered in this method. It may affect the result simulation result. Otherwise, the method to simulate the future benefit is a little simple as it is impossible to vary by the same proportion in different year. So more coefficients which are used to represent the trend of change need to be considered.

6.6 Future Work

As presented previously, there are still some limitations for the developed CoQ model, so future work need to done for the improvement of the CoQ model. And the recommended future work can be summarized as follows:

Firstly, CoQES needs to be improved. More basic data which belongs to the activities which not considered in the system need to be put into the system.

And the calculation method of complex activities will be analysed and more parameters will be introduced into the calculation system. Based on the improvement work, the CoQES is planned to be used in CoQ estimation in whole airplane assembly.

Moreover, more validation will be designed and tried. More estimation results of CoQ in different years will be collected and analysed together. The composition of CoQ and the proportion of CoQ in total cost will be discussed again based on the results.

Furthermore, other methods of CBA will be considered to be used in CBA module, such as NPV and FIRR. More parameters will be introduced into the benefit simulation, and actual data will be collected to analyse the influence of the cost to benefit. And the application based on actual process and data will be summarized and discussed.

6.7 Summary

In this chapter, the achievement of the objectives was discussed firstly, and all the objectives were fulfilled in the process of developing CoQ model. Then the application of the CoQ model was discussed, and the CoQ model may be popularized in aircraft manufacturing industry and quality managers may be the main user of the model. Moreover, the conclusions for the research were summarized. Furthermore, the contributions and limitations of the research were discussed. Finally, future work for the improvement of the CoQ model was proposed.

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APPENDICES

Appendix A Questionnaire

QUESTIONNAIRE

Analysis and modelling of the quality cost in aircraft tailplane assembly

This questionnaire aims to gather the quality problem and process data of tailplane assembly which will be the resource of the database for the researcher's quality cost model. The model can help quality managers and designers with quality cost estimating, statistics and analysis.

Thanks for take part in the research. The analysis results of quality problem and process data of tailplane assembly will benefit you and your company. The result can be sent to you if required.

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

Contact E-mail: d.xu@cranfield.ac.uk

Section 1: General Information

Q1. What is the type of your company?

A) Aircraft Design

B) Aircraft Manufacturing

C) Aircraft Design & Manufacturing

D) Others

Q2. What is your department in your company?

e.g. 'Structure Design'; 'Process Design'; 'Quality Management'

Q3. What is your responsibility in your department?

e.g. 'Process Supervisor'; 'Quality Inspector'; Design Department Director'.

Q4. How many years are you working in your current field?

A) No more than 3 years

B) 3 - 5 years

C) 6 - 10 years

D) More than

Section 2: Quality Problems

Q5. For tailplane assembly, in which phase the quality problems occur most frequently?

A) Overhanging Section Assembly Phase
B) Central Box Section Assembly Phase
C) Elevator Assembly Phase
D) Tailplane Final Assembly Phase

Q6. What kind of quality problems occur most frequently in the phase (choose in Q5)? (Multiple-choice, No more than 3)

A) Hole Problems
B) Riveting Problems
C) Sealing Problems
D) Cementing Problems
E) Position Problems
F) Roughness Problems
G) Painting Problems
H) Others

Q7. From your experience, what percentage of the most general quality problems (choose in Q6) account for, respectively, in all quality problems in the phase (choose in Q5)? (Please ensure the sequence of the answers is in keeping with Q6)

	0 - 10%	11% - 20%	21% - 30%	31% - 40%	41% - 50%	Above50%
Quality Problem 1	○	○	○	○	○	○
Quality Problem 2	○	○	○	○	○	○
Quality Problem 3	○	○	○	○	○	○

Q8. What is the main immediate causes for these most general quality problems (choose in Q6)? (Multiple-choice, No more than 3)

A) Defective Design
B) Non-Conforming Materials
C) Non-Conforming Parts
D) Defective Equipment
E) Defective Tools
F) Misoperation
G) Unsuitable Environment
H) Others

Q9. From your experience, what percentage of the main immediate causes (choose in Q8) account for, respectively, in all immediate causes for the most general quality problems(choose in Q6)? (Please ensure the sequence of the answers is the same as Q8)

	0 - 10%	11% - 20%	21% - 30%	31% - 40%	41% - 50%	Above50%
Immediate Cause 1	○	○	○	○	○	○
Immediate Cause 2	○	○	○	○	○	○
Immediate Cause 3	○	○	○	○	○	○

Q10. What is the main root causes for these most general quality problem in the phase (choose in Q6？ (Multiple-choice, No more than 3)

A) Lack of Professional Skill
B) Materials Inspection Failure
C) Parts Inspection Failure
D) Equipment Periodical Inspection Failure
E) Tools Periodical Inspection Failure
F) Environment Management Failure

G) Others

Q11. From your experience, what percentage of the main root causes (choose in Q10) account for, respectively, in all root causes for the most general quality problems (choose in Q6)? (Please ensure the sequence of the answers is the same as Q8)

	0 - 10%	11% - 20%	21% - 30%	31% - 40%	41% - 50%	Above50%
Root Cause 1	○	○	○	○	○	○
Root Cause 2	○	○	○	○	○	○
Root Cause 3	○	○	○	○	○	○

Section 3: Cost Estimation

Q12. For tailplane assembly, in all the processes, which 6 are the highest cost? ('Equipment Price', 'Tool Price' are not included in the cost; 'Energy Consumption', 'Depreciation', 'Labour' are included in the cost)

A) Drilling
B) Dimpling
C) Bearizing
D) Boring
E) Riveting
F) Installing
G) Burring
H) Cementing
I) Cleaning
J) Sealing
K) Fixing
L) Hoisting

M) Trimming
N) Reaming
O) Weighting
P) Milling
Q) Others

Q13. From your experience, in all processes, which 6 are most frequently used?

A) Drilling
B) Dimpling
C) Bearizing
D) Boring
E) Riveting
F) Installing
G) Burring
H) Cementing
I) Cleaning
J) Sealing
K) Fixing
L) Hoisting
M) Trimming
N) Reaming
O) Weighting
P) Milling
Q) Others

Q14. For tailplane assembly, in all the inspections and tests, which 4 are the highest cost? ('Equipment Price', 'Tool Price' are not included in the cost; 'Energy Consumption', 'Depreciation', 'Labour' are included in the cost)

A) Part Inspection
B) Hole Diameter Inspection
C) Position Inspection

D) FOD Inspection
E) Roughness Inspection
F) X-ray Inspection
G) Laser Measurement
H) Axial Force tests
I) Push-out tests
J) Pipe Pressure tests
K) Others

Q15. From your experience, in all inspections and tests, which 4 are most frequently used?

A) Part Inspection
B) Hole Diameter Inspection
C) Position Inspection
D) FOD Inspection
E) Roughness Inspection
F) X-ray Inspection
G) Laser Measurement
H) Axial Force tests
I) Push-out tests
J) Pipe Pressure tests
K) Others

Q16. For tailplane assembly, in all the processes, inspections and tests, which factors have the most significant influence on the cost? (Multiple-choice, No more than 3)

A) Labour
B) Equipment Depreciation
C) Tools Depreciation
D) Energy Consumption
E) Others

Q17. From your experience, what percentage of the factors (choose in Q16) account for, respectively, in total factors which influence the cost of processes, inspections and tests? (Please ensure the sequence of the answers is the same as Q16)

	0 - 10%	11% - 20%	21% - 30%	31% - 40%	41% - 50%	Above50%
Factor 1	○	○	○	○	○	○
Factor 2	○	○	○	○	○	○
Factor 3	○	○	○	○	○	○

Q18. From your experience, what percentage of the cost of quality cost (prevention cost, appraisal cost, failure cost, etc.) account for in total cost of the tailplane assembly?

A) 0 - 10%
B) 11% - 20%
C) 21% - 30%
D) 31% - 40%
E) 41% - 50%
F) Above 50%

Section4: Benefit Simulation

Q19. From your experience, what can significant reflect the benefit of the cost on quality (e.g. Using machine with higher accuracy, planning more training) in short-term? (Multiple-choice, no more than 3)

A) Number of Quality Problems Reduced
B) Qualification Ratio under First Acceptance Improved
C) Scrap Rate Reduced
D) Less Program Delay
E) Others

Q20. From your experience, what can significant reflect the benefit of the cost on quality (e.g. Using machine with higher accuracy, planning more training) in long-term? (Multiple-choice, no more than 3)

A) Total Cost Reduced
B) Customer Satisfaction Improved
C) Production Capacity Improved
D) Profit Improved
E) Others

Q21. From your experience, how long will the benefit reflect in short-term after the investment on quality?

A) 3 - 6 Months
B) 7 - 12 Months
C) 13 - 18 Months
D) 19 - 24 Months
E) Others

Q22. From your experience, how long will the benefit reflect in long-term after the investment on quality?

A) 1 - 2 Years
B) 3 - 4 Years
C) 5 - 6 Years
D) 7 - 8 Years
E) Others

Appendix B Grading Form for CoQ Model

Performance of CoQ Model	Grade				
	1	2	3	4	5
Overall Performance	○	○	○	○	○
Convenience	○	○	○	○	○
Operability	○	○	○	○	○
Reliability	○	○	○	○	○
Applicability	○	○	○	○	○
Generalizability	○	○	○	○	○
Advantage					
Limitation					
Suggestion					