UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

School of Engineering Sciences

Life Cycle Cost Modelling as an Aircraft Design Decision Support Tool

by

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Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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This report summarizes the work that has been carried out as part of the FLAVIIR project, a 5 year research program looking at technologies for future unmanned air vehicles. A novel classification of aircraft product definition is utilised and a framework to estimate the life cycle cost of aircraft using the product definition is presented. The architecture to estimate the life cycle cost and the associated models are described. The acquisition costs are estimated using a hierarchical structure and a discrete simulation model is used to estimate the maintenance and operation costs.

The acquisition cost model uses an object oriented approach with libraries of materials and processes integrated into the cost model. Risk analysis is performed to identify the important design parameters and uncertainty in the model. The acquisition cost model developed has the capability to estimate the costs of aircraft structures manufactured using metal-based materials as well as non-metal-based materials.

The discrete event simulation model estimates the operation and maintenance costs of a fleet of aircraft using the mission characteristics, aircraft

performance and the logistics data as input. The aircraft performance parameters are calculated by using aerodynamic analysis along with performance analysis models and the simulation model utilises a novel methodology to link aircraft performance with survivability analysis for estimating the maintenance costs.

A framework is presented in which the cost models developed can be integrated into the conceptual design process to facilitate the comparison between different configurations. The usage of the life cycle cost framework as a decision support tool is outlined and three case studies are presented which include composites vs metals trade-off analysis, optimisation studies and web deployment for real time cost estimation. The novel contributions of this research are outlined and interesting avenues for future research that can be pursued are identified.

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Declaration of authorship

I, Praveen Thokala, declare that the thesis entitled ”Life cycle cost modelling as an aircraft design support tool” and the work presented in it are my own and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this report has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this report is entirely my own work;
- I have acknowledged all main sources of help;
- Where this report is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published and some articles are under review as:

1. **Journal articles**

   - Thokala, P., Scanlan, J.P. and Chipperfield, A. "Life Cycle Cost Modelling as an Aircraft Design Support Tool", *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* (accepted)
   - Thokala, P., Scanlan, J.P. and Chipperfield, A. "Simulation based Life Cycle Cost Optimization of Unmanned Air Vehicles", *AIAA Journal* (submitted)

2. **Conference publications**

   - P. Thokala, J. Scanlan and A. Chipperfield, "Simulation-Based Life Cycle Cost Modelling as a Decision Support Tool", *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, Belfast, 18 - 20 Sep 2007
   - P. Thokala, J. Scanlan and A. Chipperfield, "Life Cycle Cost Modelling of Unmanned Air Vehicles", *4th International Conference on Digital Enterprise Technology,* 19-21 September 2007
   - P. Thokala, "Life Cycle Cost Modelling of Unmanned Air Vehicles", *Proceedings of the IIIrd postgraduate research Showcase*, 2008, University of Southampton.

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Nomenclature

ABC	Activity Based Costing
AD	Air Defence
AGILE	Analytic Gaussian Intersection for Lethality Engagement
AS	Air Superiority
ATL	Automated Tape Laying
BWB	Blended Wing Body
CAD	Computer Aided Design
CAS	Close Air Support
CBR	Case Based Reasoning
CCA	Critical Component Analysis
CER	Cost Estimate Relationships
CFD	Computational Fluid Dynamics
DOD	Department of Defence
DoE	Design of Experiments
ESDU	Engineering Sciences Data Unit
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FLAVIIR	Flapless Aerial Vehicle Integrated Interdisciplinary Research Programme
FP	Full Potential
GA	Genetic Algorithm
GPSS	General Purpose Simulation System

HALE	High Altitude Long Endurance
HSCT	High Speed Civil Transport
ID	Interdiction
IDE	Integrated Desktop Environment
IDS	Interdiction/Strike
ISS	International Space Station
KBS	Knowledge-Based System
LCC	Life Cycle Cost
MDO	Multi-Disciplinary Design Optimisation
MOP	Measures of Performance
MRET	Maintenance Resources Evaluation Technique
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
NASA	National Aeronautics and Space Administration
OV	Overhaul
RAGE	Rapid Geometry Engine
RAM	Rapid Aircraft Modeler
RAND	Research and Development
RSM	Response Surface Model
SCEA	Society of Cost Estimating and Analysis
TBO	Time Between Overhauls
UML	Unified Modelling Language
WBS	Work Breakdown Structure
WWW	World-Wide Web

List of Symbols

Ω	Friction stir welding cost
l	length of the part
ω'	friction stir weld rate
κ	hourly friction stir welding rate
n	Number of Monte Carlo Observations
C_L	Lift coefficient
C_D	Drag coefficient
P_K	Probability of aircraft kill
P_H	Probability of hit on the aircraft
$P_{K\|H}$	Probability of aircraft kill given a hit on the aircraft
$P_{k\|Hi}$	Probability of ith system kill given a hit on the aircraft
$P_{h\|H_i}$	Probability of hit on ith system given a hit on the aircraft
$P_{k\|h_i}$	Probability of ith system kill given a hit on that system
$R(t)$	Reliability function
$F(t)$	Probability that a system will fail by time t
$f(t)$	Failure probability density function
$E(t)$	Expected life

Chapter 1

Introduction

1.1 Context

The UK aerospace industry is one of the most successful manufacturing sectors with a world market share of 13% and has a turnover of around £20 billion [1]. Although in the past technology has been the dominant driver in the aircraft design process, there has been a demand for cost reduction in the commercial aircraft industry to satisfy the customers needs. There has been a realisation by the aircraft producers that cost reduction needs to be tackled at the conceptual design phase as it is widely believed that typically 70% of the total avoidable cost is controllable at the design stage [1]. There is a strong need to understand the cost associated with different competing concepts and this could be assisted by incorporating cost estimation in the conceptual design process. This approach can contribute in indicating how cost varies with changes to the design. Section 1.2 describes the importance of knowledge of how cost varies with changes to the concept design parameters, such as geometry and material choice during the conceptual design process.

1.2 Cost and conceptual aircraft design

Most aerospace companies now follow a standardised product development process with clearly identified review procedures and decision points as illustrated in Figure 1.1. This process seeks to understand and implement a logical and consistent progression through the product's design life cycle. This is performed by systematically identifying and minimising uncertainties with respect to both technical maturity and commercial risk [2]. The

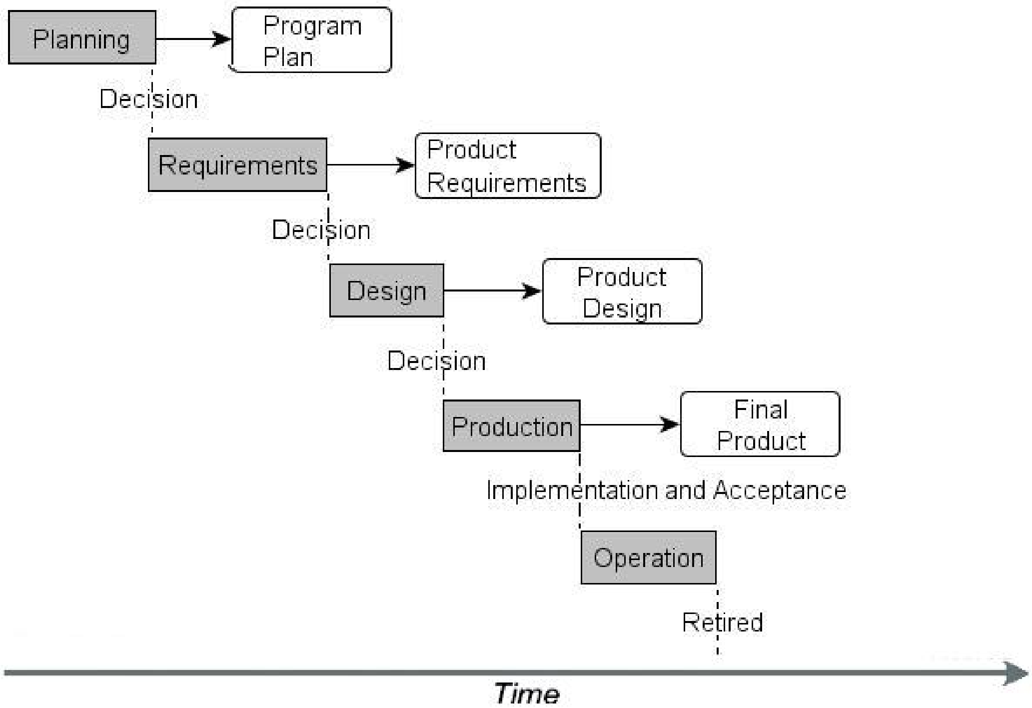


Figure 1.1: Product development process [1]

earlier stages of aircraft conceptual design generally has limited technical depth and available data, hence broad studies are performed to identify the required aircraft. This is achieved by identifying the basic aircraft product definition from the uncertain requirements. The design space in which a satisfactory solution is likely to be found is identified by making assumptions are made about aircraft shape, size and configuration. The validity of these assumptions is evaluated by performing different analysis during the design life cycle to generate data that enable the understanding required to support decision making and answer the critical issues that emerge at that specific stage. Initial analysis is generally aircraft sizing with the aim of achieving the producer's requirements. However, as product definition details become available more focussed assessments are performed. Aerospace companies are developing increasingly sophisticated analysis tools to predict the performance of their products with considerable accuracy [3], [4]. These analysis involve specialist engineers in many relevant disciplines, particularly where more substantial types of analysis such as detailed Computer Aided Design (CAD), Finite Element Modelling (FEM), and Computational fluid dynamics (CFD) study is required. However, very little consideration has been given to the cost associated with one concept compared with another, based on an understanding of the product's design and developement.

Cost predictions are rarely as accurate at the early design stage and have, until recently, depended upon simplistic parametric estimates. Also, the cost incurred due to design changes in the concept has not been historically evaluated as an integral part of the multidisciplinary conceptual design process. This is a major source of risk within the product development process. It is hoped that the focus of study in this thesis on improving the knowledge of the causes of cost during conceptual design, their relative contribution and sensitivity to the design parameters will contribute towards achieving an useful solution to this problem.

1.3 Research objectives and purpose

1.3.1 Motivation

It is important for a company to understand the cost associated with competing options, as it is a vital part of understanding its commitments if the concept development matures into a fully launched progam. This requires knowledge of the aircraft architecture, its components and the cost changes associated with particular design, structural, manufacturing and operational concepts. This cost knowledge should help to ensure the aircraft company that the business makes sense, i.e. cost of the aircraft does not exceed the market entry price. Also, identifying and quantifying major contributors of cost can be useful in component and sub-component selection studies. These selection decisions can be improved by quantifying the link between the product design parameters such as geometry, shape, material form and type, other characteristics such as manufacturing processes, mission parameters, operating conditions and the costs associated with them. Any approach that performs this assessment should be structured, easily accessible, visible and understandable if it is to be used by different teams of engineers. This is particularly relevant in big aircraft companies which have distributed sets of designers, stress engineers and fluid dynamicists. The need for cost evaluation as an integral part of conceptual design has been identified, but an acceptable solution has yet to emerge. It is intended that the framework developed in this thesis may indicate how this can be achieved.

1.3.2 Research hypothesis

The hypothesis for this research can be stated as :

"An elegant, flexible and extensible framework can be constructed to estimate the life cycle cost (LCC) for a fleet of aircraft. This framework can be integrated with engineering design tools to perform concept design".

This research investigates whether this framework can be constructed in the manner envisaged, and what benefits will be achieved by the proposed design decision support system. This hypothesis can be more formally stated as the research question, research purpose, and research objectives:

1. **Research Question** : How can cost be modeled using the aircraft product definition to allow integration with conceptual design?

2. **Research Purpose** : The purpose of this research is to provide information to product designers (or managers) that will enable them to make informed design choices.

3. **Research Objective** : The desired result of this study is a framework for life cycle cost estimation, which could be used to perform trade-off studies and multi-disciplinary analysis. Sub-objectives were:

    - Validation of the cost models

- To assess the needs of aircraft designers by analyzing typical trade studies used during the conceptual design phase
- To provide a development framework for design decision support system

1.3.3 Measures of success

The LCC framework aims to satisfy each of the sub-objectives listed in the research objective (sub-section 1.3.2). It is difficult however, to quantify the level of satisfaction. To adequately measure success, multiple attributes should be considered. Other qualities that are desired of the research are:

- Validation : the framework should be validated against historical data
- Elegance: the methodology should be easily explained and understood by potential users of the system.
- Flexibility: the framework should allow for a flexible approach to configure it for different manufacturing and operating systems, and to allow for subsequent modifications to the system.
- Extensibility: the framework should be extensible to perform more detailed/in-depth studies when data becomes available.
- Cost: the potential benefit of the system should significantly outweigh the cost to implement it.
- Portability: it should be possible to adapt the methodology for use on different software platforms.

1.4 FLAVIIR

This thesis summarizes the work that has been carried out as part of the FLAVIIR project, a 5 year research program looking at technologies for future unmanned air vehicles. This is a UK Engineering and Physical Sciences Research Council funded project sponsored by BAE Systems. The project is managed from Cranfield University and includes 9 other University partners, the programme covers all the key aspects of the next generation UAV from an aeronautical point of view. The focus for the research is the Grand Challenge laid down by BAE Systems:

"To develop technologies for a maintenance free, low cost UAV without conventional control surfaces and without performance penalty over conventional craft"

The technical research is split into 7 themed areas; Aerodynamics, Control systems, Electromagnetics, Manufacturing, Materials/Structures, Numerical simulation and Integration. The University of Southampton was entrusted with numerical simulation which involved developing a framework to integrate cost modelling within a concept design tool. Alongside the research into individual technologies themselves, the FLAVIIR project also delivered a flying demonstrator vehicle for these new advances, thus applying the research methodology to the integration phase and providing direct experience and evidence of real performance benefit.

Cost modelling research was undertaken not only to obtain the cost of parts but also to capture and evaluate the potential of FLAVIIR research knowledge output. The research helped to understand the overall/relative "goodness" of the novel technologies and whether they can "buy" their way on to the vehicle. The geometry based designs are linked to a concept design tool to allow "what-if" studies to be undertaken and integrated with an optimiser to perform cost-based optimisation. A schematic flow sketch describing the LCC framework is shown in Figure 1.2.

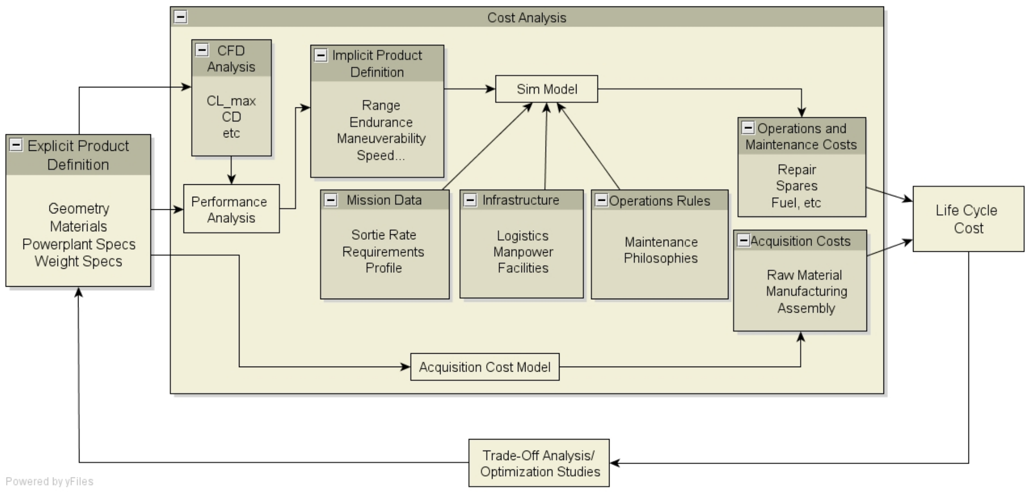


Figure 1.2: LCC framework

1.5 Layout of the thesis

The remainder of the thesis has the following structure. In the literature review (Chapter 2), the various topics relevant to this work are reviewed. In each topic, the specific factors that are used in the theoretical development of the LCC framework are emphasized.

In Chapter 3, the LCC framework is presented along with an overview of the models involved. The LCC framework developed here has the capability to estimate the costs of aircraft by having product definition as input to cost models, so that any change in the design is reflected in the calculated cost. The aircraft product definition is classified in a novel manner into explicit and implicit product definition. The implicit product definition parameters are estimated from explicit product definition using physics-based models and thus, explicit product definition alone is required to estimate the LCC of an aircraft. The LCC of an aircraft includes the material and the manufacturing costs along with the costs necessary for operation, maintenance and repair of a fleet of aircraft. The raw material and manufacturing costs are estimated by using the acquisition cost model while the discrete event simulation model gives an estimate of the cost of maintenance and operations.

In Chapter 4, the acquisition cost model is presented with emphasis on the object oriented approach used in the model. Sample objects are described and results of the acquisition cost model are presented. The acquisition cost model uses explicit product definition as input so that any changes to the design are reflected in the cost model. Explicit product definition includes the design parameters whose effects on the cost are easily recognisable and includes the geometry parameters (i.e. dimensions of the design), material type and power plant specifications. A parametric representation of aircraft geometry is developed based on the explicit product definition and a tool is built in Matlab to provide the three dimensional visualisation of aircraft using its parametric geometry representation, which acts as a sanity check to verify whether the aircraft is realistic before proceeding with the cost estimation. The acquisition cost model has a hierarchical structure that reflects the actual physical structure of the aircraft to allow easy and intuitive navigation. Libraries of materials and processes have been created for integration into the cost model and sensitivity analysis is also performed to identify the important design parameters. The acquisition cost model developed has the capability to estimate the costs of aircraft structures manufactured using metal-based materials as well as non-metal-based materials.

In Chapter 5, a simulation model which estimates the operation and maintenance costs of a fleet of aircraft using the mission characteristics, implicit product definition and the logistics data as input is presented. Implicit product definition includes design parameters whose affects on the cost are not easily identifiable such as aircraft performance and signature data. The aircraft performance parameters are calculated by using aerodynamic analysis and performance analysis models. The simulation model utilises a novel methodology to link aircraft performance with survivability analysis for estimating the maintenance costs. The aircraft performance along with mission data affects the mission efficiency and the aircraft then need repair based on the level of damage sustained. The maintenance performed on the aircraft is dependent upon the level of repair and the simulation model estimates the fuel, repair and maintenance cost for each aircraft. The modular approach of the simulation model is described and results are presented.

In Chapter 6, the usage of LCC framework as a decision support tool is outlined and three case studies are presented. They include composites vs metals trade-off analysis, optimisation studies and web deployment for real time cost estimation.

Finally, chapter 7 investigates possible avenues for further research and opportunities to use this methodology for other applications.

Chapter 2

Literature Review

The breadth and extent of cost modelling is seen not only in engineering applications but also in economics, business, management science, medicine, and public administration where models have been constructed to estimate the relevant costs. Its continued use in such diverse fields marks it out as an important tool for research and decision support. This section presents a review of the current state of cost modelling applicable to engineering design.

Boothroyd et al [5] present a comparison of cost committed to different elements of manufacturing, and the corresponding influence of each part on the total cost of the product. They also state that whilst conceptual design constitutes between 1% and 10% of the total product realisation cost, it commits the manufacturer to between 70% and 85% of the subsequent cost of bringing that product to fruition. The selected design concept determines the cost associated with the manufacturing the product but also influences the operating costs. Horder indicates that 55% of the total airline costs are influenced directly by the type of aircraft operated, based on 2001 ICAO data [6]. This 55% comprises of depreciation, rental and training, navigation fees, landing fees, insurance, fuel and oil, maintenance, flight crew salary and expenses. Seo et al [7] and Gu et al [8] also state that over 70% of the total life cycle cost of a product is committed at an early design stage.

An integral aspect of product design is how to make trade-offs (e.g. among cost, performance, reliability, between making or buying a component, between long term operating costs and initial costs, and so on). Product cost estimation at an early stage is important for decision-makers to assess the impact of the design choices they have to make. Designers would benefit greatly from tools that help them evaluate these trade-offs in a rigorous and systematic manner. This provides the stimulus for this work. The life cycle cost framework is intended to be one of the tools to satisfy this need, by enabling designers to evaluate the cost implications of their design decisions early in the design process. They will be able to evaluate cost and function trade-offs between different concept designs, manufacturing methods, and between different materials for the designed components. The methodology also seeks to avoid some of the inaccuracies of traditional cost models.

In this chapter, first the various cost definitions relevant to aerospace design are explained. A literature review of the state-of-the-art in cost estimation is then presented. For the sake of completeness, the literature review begins with an overview of different cost estimating methodolgies in the context of aerospace engineering applications. A critical description of the existing cost models in the literature is then provided. Then, the existing design decision support models/frameworks are reviewed focusing on concurrent engineering and multidisciplinary studies. Section 2.3 describes the different kinds of cost models in the literature while section 2.4 describes the use of cost models as decision support tools. The implications of the literature review on the research are presented and the motivation for present work is outlined.

2.1 Cost definitions

This section includes a brief description of various costs that are relevant to the aircraft industry. The following categorisations are well documented in the literature [9] and are included for completeness.

A product's cost can be arranged into a cost breakdown structure, which is driven by the design of the product and includes all the costs only once [1]. The classifications that fall into this category are (a) Direct or indirect costs, (b) Non-recurring or recurring costs and (c) Variable or fixed costs.

2.1.1 Direct and indirect costs

A direct cost is an expenditure which can be identified and specifically allocated to a product or service. Indirect costs are the opposite of the direct costs; while direct costs can be allocated directly for a certain objective the indirect costs costs cannot be identified with a specific objective [10]. This means that direct costs can be allocated directly as the allocation base is known, whereas the allocation base for the indirect costs has to be defined. This makes identification and the association of the indirect costs with a specific objective difficult in the first instance. However, indirect costs are a necessary for undertaking an activity and are labelled as overheads or burdens and examples of this are costs of electrical power, etc.

2.1.2 Fixed and variable costs

Fixed costs are costs of production that do not change when the rate of output is altered. They are treated as general production costs required to keep the company operational. Typical examples include costs of telecommunication, executive salaries, and leasing. On the other hand, variable costs vary in proportion to the volume of production, e.g. increasing the volume of production will increase the variable cost [1]. Typical examples include costs such as labour and material costs.

2.1.3 Non-recurring and recurring costs

A non-recurring cost is typically a capital expenditure which occurs prior to the production. The cost of initial design process, tooling acquisition, system testing and manufacturing planning are the typical examples of the non-recurring costs. Non-recurring cost is an element of development and investment costs that generally occurs only once in the life cycle of a work output [10]. Conversely, costs of raw materials, supplies, parts and other expenditure which are utilised to produce a unit of output are designated as recurring costs. These are similar to variable costs as they vary with production quantity. Recurring costs are required to maintain the set-up through the whole life cycle and includes costs such as material procurement costs, consumables, labour and personnel costs.

2.1.4 Life cycle cost

LCC quantifies the overall cost of a product from its birth up to, and including its disposal. LCC includes all costs incurred during the projected life of a system and can be defined in many different ways but all classifications tend to start with either product development or acquisition, and continue through to product disposal or retirement. Asiedu and Gu [8] divided the life cycle cost into into several cost categories:

- Research and development costs;
- Production and construction costs;
- Operations and maintenance costs; and
- Retirement and disposal costs.

This breakdown is shown in Figure 2.1.

LCC is of interest when making decisions or to assess the competitiveness of a products design. LCC is useful when an estimate is to be used in a performance trade-off study of a process or activity. NASA selected the international space station (ISS) systems primarily on technical excellence and crew safety with emphasis on near-term schedules rather than the total program costs, which has resulted in significant cost overruns for the space station [11]. They have concluded that life-cycle cost models are needed to address whether the system requirements can be met within budget constraints.

The research interest of this thesis lies in evaluating the life cycle cost of a fleet of aircraft.

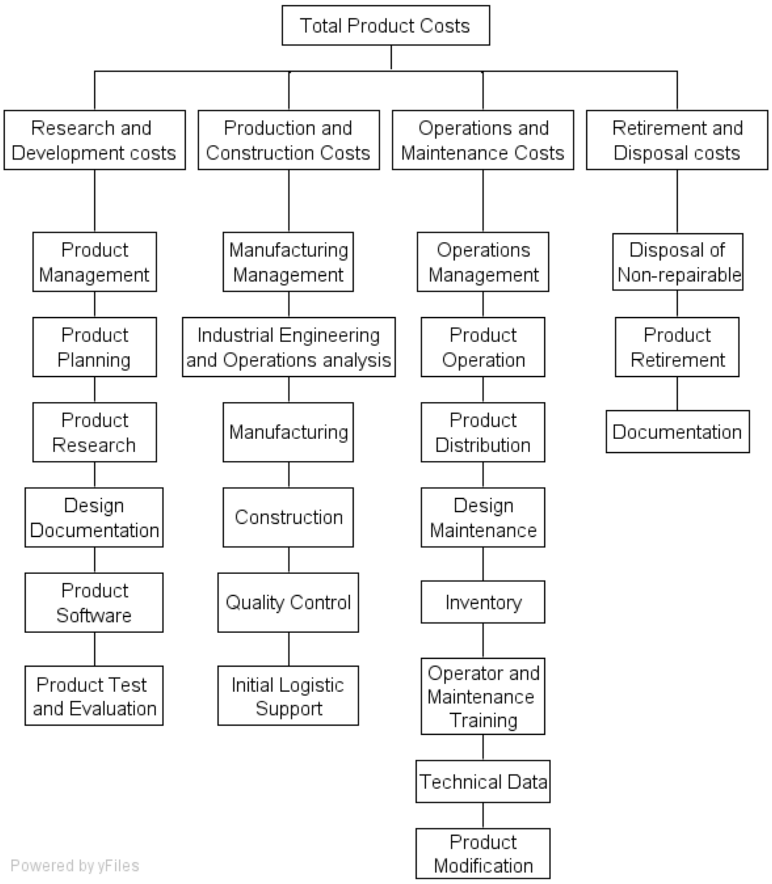


Figure 2.1: Cost breakdown structure [8]

2.2 Cost estimation techniques

Cost estimation is defined as the process of prediciting the cost of a product before all the stages of the product development have been executed in the Federal Aviation Administration (FAA) life cycle cost estimation handbook [12]. There are quite a few well-recognized costing techniques that are currently employed in evaluating cost in aerospace engineering, as described by Asiedu and Gu [8] and Scanlan et al [13].

These cost estimation techniques can be classified in many different ways.

For example, Roy *et al.* [14] classified the cost estimation techniques into qualitative and quantitative methods. According to Curran *et al.* [1] the techniques can be classified into classic estimation techniques and advanced estimation techniques. Classic estimation techniques include analagous, parametric and bottom-up methods while feature-based costing, neural networks and fuzzy logic are included in the advanced estimation techniques. Niazi *et al.* [15] combined these two classification methods into an elegant hierarchical classification as shown in Figure 2.2.

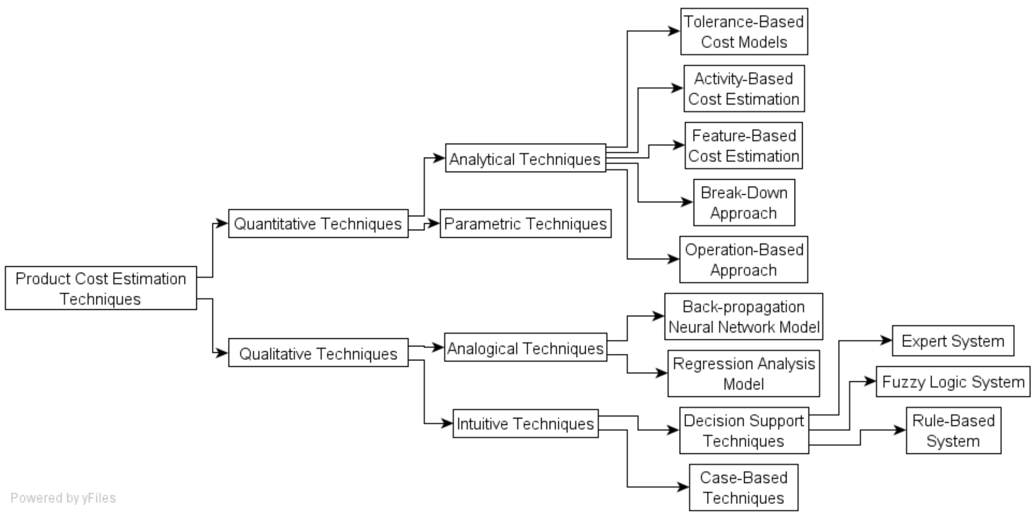


Figure 2.2: Classification of the cost estimation techniques [15]

The classic estimation techniques are summarised in the following subsections along with strengths and weaknesses associated with each category. Analogous methods comprise of cost models which are based on analogy i.e. comparative costing based on the similarity and differentiation of like products. The family of costing methods associated with the use of probabilistic relations between appropriate product features and cost (the CERs) are known as top-down or parametric methods. The family of cost estimation methods that are built up from detail are known as detailed or bottom-up methods. These methods are typically physics based and require knowledge of the manufacturing process and material type. An overview of the advanced cost estimating techniques is also presented.

2.2.1 Analogous costing

Analogous costing is a traditional costing technique that uses the cost of a similar product to gain an initial baseline estimate [16]. The analogous costing methodology is characterised by selecting a product that is similar to or related to the product undergoing the cost analysis and making adjustments relative to the differences between the two products. The effectiveness of this method depends heavily upon the ability to identify correctly the differences between the two cases, i.e., a high degree of expert judgment is required [8]. Thus, this method is suited for use in estimating the design effort and hence it is very popular in the software industry. Hughes provides an explanation of the use of expert judgement as an estimation method for software development [17]. A state-of-the art review of expert estimation of software development effort is provided by Jorgensen [18]. This method is also widely used within aerospace costing and there is a similarly wide range of implementation techniques, ranging from subjective expert opinion to objective use of calculated differentials. The FAA life cycle cost estimating handbook [12] recommends use of analogous costing for estimating the cost of a new product or system for which recent and complete historical cost data is available. The product or system can be a combination of existing sub-systems, equipment or components. Bashir and Thompson predict the design effort of new projects using a manual comparison approach [19]. However, it is a reasonable approach for estimating the unit cost of a new product that does not incorporate very different design features or utilise new manufacturing processes.

2.2.2 Parametric costing

A parametric cost estimate is one that uses Cost Estimate Relationships (CERs) and associated mathematical algorithms (or logic) to establish cost estimates, according to the Parametric Cost Estimating Handbook of the Department of Defence(DOD) [20]. This approach makes use of statistical methods to identify high-level relationships between product design parameters and cost, making use of historical data [21]. These relationships are typically determined utilising regression analysis [22], which is a commonly used technique within aerospace industry [1]. This method is suited for overall product cost estimation; however estimation of the component costs has to be achieved by using additional CERs [10]. Parametric estimating can involve collection and revision of significant volume of historical data in order to identify the relevant parametric relationships. But once the data is available, estimates can be produced rapidly. The detailed design information for the various system components and accounting information for all material, equipment, and labour is used estimate the parametric costs by the RAND (Research & Development) Corporation [23]. RAND Corporation is credited with the development of CERs for different classes of aircraft and various operational parameters, developed to help the DOD estimate the cost of new military aircraft [20], [23]. CERs based on speed, range, altitude, and complexity were developed for estimating the cost of intercontinental ballistic missiles, jet and cargo aircraft. However, parametric estimating is not suitable for estimating the cost of products that utilize new technologies [13]. Also, parametric costing is not intuitive as the cost drivers can not be easily identified.

2.2.3 Detailed costing

Detailed costing methodology involves identifying the individual parts of a product before sizing the component parts and tasks to estimate the individual costs. These individual costs are aggregated in order to produce the overall estimate, making use of detailed engineering analysis and calculation. Since this method utilises detailed knowledge of product and processes, an accurate detailed estimate and a breakdown of costs can be achieved, even though it is expensive and time consuming. The activity based costing (ABC) method is the most common method of detailed costing and it estimates the cost of a product by decomposing the work required into elementary tasks, operations or activities with known (or easily calculable) costs [24]. The ABC method identifies the activities that consume resources and estimates the costs. These costs are assigned to the product to help designers understand the impact of product's design on individual processes costs and assembly costs [25]. Instances of this method can be found in various fields of study; a survey of the usage of this method in UK's largest companies is performed by Innes and Mitchell [26]. Narayanan *et al.* [27] measured the impact of activity based costing on managerial decisions while Tornberg *et al.* [28] used the activity based costing capability to provide useful information to the designers. This method is especially suitable for accurate estimation of the production or manufacturing costs [29], [30], [31]. Spedding and Sun used discrete-event simulation to estimate manufacturing and machining cost through an activity-based approach [32]. The aim of this work is to link the design of an aircraft to its life cycle cost to identify the cost drivers. This is difficult to achieve by utilising statistical techniques (parametric costing) or analogous costing which estimate the costs using historical data. ABC allows detailed tracking of costs and provides cost information to aid decision making as it relies on the way an activity is undertaken, however, must be re-modelled if there is any change in the process activity. This is not a major disadvantage and the positives easily outweigh the negatives; thus the cost models in the LCC framework are built using the ABC methodology.

2.2.4 Advanced estimating techniques

The cost estimating techniques described here fall under either parametric or detailed cost estimating methodologies, but, they utilise more sophisticated methods for cost estimating. Generative costing falls under detailed or bottom-up methods while the neural network method falls under top-down or parametric costing methods.

According to Scanlan et al [13], the generative approach uses the emerging product definition to infer a manufacturing sequence and to estimate individual process times. The generative approach is classified into feature-based and feature-recognition methods. The feature-recognition approach is based on identifying groups of features that can be associated with typical manufacturing processes and uses this knowledge to estimate the cost of the component. As more detailed production information becomes available, the complexity of the cost estimation can be increased as necessary relative to accuracy. An alternative is to use a feature based design approach which requires the design and manufacturing communities to agree a common feature library. The manufacturing feature-based approach is based on the requirement that the product definition is to be constructed using a pre-defined set of features, which are directly linked to different manufacturing processes. The feature-based approach does not need the feature-recognition algorithms, but compromises the flexibility of the design process as the database of features currently available is limited.

The neural network method is based on the concept of a system that learns to predict the effect on cost when presented with a range of product-related attributes [7]. The method learns which product attributes most influence cost and use that information to approximate the functional relationship between the cost and attributes. The prediction accuracy is dependent the quality, quantity and relevancy of the input learning data [33], [34]. They require a large historic data bank in order to be robust and also, neural networks are not applicable to novel or innovative product developments.

Cost estimation sometimes requires combinations of different cost estimation methodologies. Roy et al describe the development of a cost-estimating methodology for predicting the cost of engineering design effort [14]. It estimates the qualitative costs through questionnaires and the expert knowledge necessary to design the cost estimating relationships (CERs), which integrate both quantitative and qualitative design activities. The methodology looks at the quantitative and qualitative issues in isolation before adding them to produce the final CER. However, this method was still unable to remove all the subjective issues involved with estimating the design effort.

2.3 Cost models

The Society of Cost Estimating and Analysis (SCEA) define a cost model as: "a compilation of cost estimating logic that aggregates cost estimating details into a total cost estimate... an ordered arrangement of data, assumptions, and equations that permits translation of physical resources or characteristics into costs" [35]. In general, a cost model can be said to consist of a set of equations, logic, programs and input formats that specify the problem. It is necessary to apply a combination of logic, common sense, experience, and judgement in order to generate a relevant and meaningful final estimate [36]. The cost estimation methods can be classfied into parametric and generative models, as shown in Figure 2.3, based on the costing tools employed [37].

This section provides a description of the existing cost models in the literature. The review of the cost models is split into manufacturing cost models, maintenance cost models and finally, the life cycle cost models.

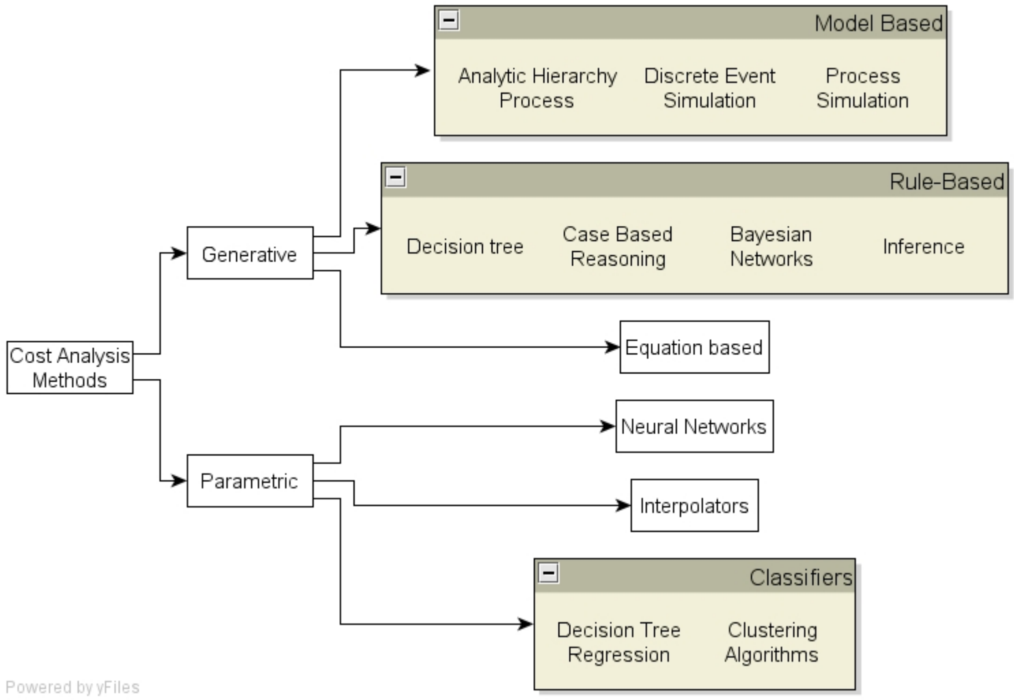


Figure 2.3: Cost analysis method classification [37]

2.3.1 Manufacturing cost models

Rehman describes a method for modelling costs throughout the design phase of a product's life-cycle, from conceptual to detail design [16]. This is automated by linking design knowledge to production knowledge using a framework which incorporates both case-based and rule-based reasoning. Since cost estimation in conceptual design involves recalling past designs, case-based reasoning (CBR) is incorporated at this stage. The objective of the case-based design facility is to consider the incomplete description of the new design problem, retrieve a similar past design from the case base, and adapt the retrieved design to satisfy the new problem description. Ping et al proposed an approach which uses multi-agent system for cost estimation [38].

In this work, a distributed multi-agent system is described, which is architecture of a multi agent system with each agent representing one kind of cost estimation method.

Watson et al present a generic, hierarchical and multifidelity unit cost of acquisition estimating methodology for machined parts from outside production [39]. The method is capable of generating multilevel and multifidelity cost relations for large volumes of parts with analogous classification, parametric trending and ratio estimating. It makes use of the process, supply chain costing data and part design information at various levels of the design process. Hicks et al. define different classes of engineering components and proposes methods of cost forecasting for each class [40]. These components include (a) standard selected components, which are selected from a range of components sizes from a third-party supplier, (b) standard design components which are fully specified through established design procedures, and (c) bespoke elements which are one-off elements tailored to meet specific requirements. A generic procedure to develop the cost relationships by making use of the component attributes is used to develop the component-based cost models.

The applicability of neural networks for design concurrent calculation is described in Bode et al [33], [34]. The product characteristics that impact on the costs are the input variables of the neural network. Between the input and output neurones, there are internal neurones with numerous layers of internal neurones possible. An internal neurone weighs the information and transfers it to the neurones of the following layer. The neurone of the output layer provides the information requested. The number of cost-driving parameters must be low, and they have to be known. Moreover, when parametric functions are employed, neural networks do not transparently show how costs are derived. Thus, neural networks are not applicable for generative design, since innovative manufacturing technology, for example new machine tools and machining tools, cannot be taken into account.

The cost models detailed so far use the historical costs to derive a relationship using data regression analysis. These relationships are fitted to the product data to extrapolate the costs for new configuration. The main drawback to using this is that the CERs are based on the cost experience in the past. It would be unrealistic to extrapolate the specific cost figures for new parts, given the rapid advances in manufacturing techniques, changes in procurement and organisational structure. Thus, these cost models can be reasonably expected to suffer from the drawbacks discussed in Section 2.2. Specifically, these models could not be applied to calculate the cost of any given aircraft component, as is the intended purpose of the current research study.

Activity based manufacturing cost models

Manufacturing process cost models are based on analysing cost drivers in the manufacturing processes to capture all the costs associated with a given process, including materials, labour costs, recurring and non-recurring costs for production. These models use activity based costing to provide accurate cost estimates but require detailed knowledge of processes.

Using the example of machined parts, Ben-Arieh estimates the cost for machined parts focusing on the costs for set-up, machining and raw material costs [41]. These explicit cost calculations are based on the part geometry, cutting tools available and the machined parts retrieved. A system is presented which calculates the time that a part is needed to stay on the machine and this time, which includes processing set-up as well as tool changes, is used to find the machining cost. Similarly, Stockton elaborates the development of time estimating models for advanced composite manufacturing processes [42]. Process time estimating models were developed for each of the main manufacturing processes considered for part manufacture and assembly and the outputs from these models are used to form the basic data from which the process costs are estimated. This approach to model development is implemented on the automated tape laying (ATL) process and the process time estimating methods for the ATL process are developed.

A framework for estimating manufacturing cost from geometric design data is outlined by Wei [43]. The developed cost estimation system chooses the best process sequence from among all feasible alternative sequences and the selection is based on the minimization of the total manufacturing cost. Feng et al estimate the manufacturing cost of a design according to the shapes and precision of its features i.e. feature based design [44]. The machining cost of a part depends upon the type of form features and the relationship between them. The cost is calculated for different machining techniques and the manufacturing cost is formulated as the shortest path problem to determine the minimum cost design alternative. A model designed to estimate process cost directly from the design specifications was developed by Kulkarni et al [45]. The model was implemented using a simple worksheet, database and CAD software. The model is used to study the effect of design specifications on manufacturing cost but it is not automated. Also, the model is limited to milling operations. A production cost estimation framework to support product family design is presented by Park et al [46]. The framework can assist the designers in choosing the components which are best for the family and the product family design which corresponds to the least cost. The model is demonstrated on a family of screwdrivers that share a number of components.

Ben-Arieh et al [47] present a system that uses the internet to link design stations and manufacturing shops in order to provide fast and accurate cost estimation. By utilizing Web technologies, the designers submit the design to a central server that links to the various manufacturing shops and help them generate accurate cost estimation. The system is a Web-enabled integrated environment that provides process-planning capabilities, machining time and cost estimation, and supplier selection. The central server provides the designer with the best cost option, without compromising the manufacturers sensitive cost data. Also, a study which interfaces CAD and Manufacturing cost estimation software using COM/OLE technology is detailed by Liu et al [48]. They used COM/OLE technology to develop a link between AutoCAD and an in-house cost estimator to assist the designers for quick and easy relation of the geometric entities to the manufacturing features.

A major problem with the existing manufacturing process cost models is that the programs are self owned, and the cost database contains proprietary information which the owners do not wish to share with the public. Most of the manufacturing process models are part or process specific, the method can only be applied to a specific part of the aircraft or a specific process.

2.3.2 Maintenance cost models

In the military aerospace industry, maintenance is an essential function for making aircraft ready for flights and minimizing mission delays, essentially providing quality service that includes reliable aircraft. Effective and planned maintenance contributes to a safer and more reliable and airline industry.

The aircraft maintenance work load is generated through a continuous airworthiness maintenance program [49], [50]. These programs include : (1) aircraft inspections which deal with routine inspection, minor services and tests performed on the aircraft at prescribed intervals; (2) scheduled maintenance that includes replacement of life-limited items, periodic overhauls and special inspection; and (3) unscheduled maintenance which is usually generated by inspections, pilot reports and failure analysis. The different types of maintenance are carried out in facilities of variable capabilities and resources. In order to perform the maintenance work, production maintenance is organized into different levels. The first level is the first line which deals with inspection, testing and minor maintenance tasks. The second line maintains major tasks, e.g. overhaul and replacements of limited-life equipment. The third line or depot maintenance is used for major jobs which cannot be handled by the first and second lines. All repair stations must be established in accordance with standard operation methods prescribed by the organization or adopted from international standards [51], [52].

Maintenance costs can be broadly classified into three categories:

- Variable Costs : Variable costs vary as a function of utilization and they include fuel costs, labour costs, and spares costs

- Fixed Costs : Fixed costs include those costs that must be borne by the flight department irrespective of the level of aircraft utilization. These include Hangar lease expense, salaries, and software services.

- Periodic Costs : Periodic costs include those overhaul, refurbishment and modernization items, which occur infrequently.

In this research, only variable costs are of interest as the aim is to compare different aircraft rather than estimating the exact maintenance costs. Maintenance cost estimation models can be classified into either analytical models or simulation based models. Analytical models predict the maintenance costs based on pre-defined probability distributions while simulation based models make use of simulation to estimate the maintenance costs.

Analytical models

Edwards et al present a methodology for predicting life cycle maintenance expenditure over the useful life of tracked hydraulic excavators [53]. A time series analysis (using a moving centred average) is used to capture the trend in maintenance cost expenditure. It is based on comparison of actual to predicted cost expenditure by providing an essential financial datum for determining maintenance cost performance.

An evaluation of forecasting methods for intermittent parts demand in the field of aviation is presented by Ghobbar et al [54]. The paper deals with techniques applicable to predicting spare parts demand for airline fleets. The experimental results of 13 forecasting methods, including those used by aviation companies, are examined and clarified through statistical analysis. A new approach to forecasting evaluation, a predictive error-forecasting model which compares and evaluates forecasting methods based on their factor levels when faced with intermittent demand is also presented.

Kong et al propose a methodology for the evaluation of expected life-cycle maintenance cost of deteriorating structures by considering uncertainties associated with the application of cyclic maintenance actions [55]. The methodology is used to determine the expected number of maintenance interventions on a deteriorating structure, or a group of deteriorating structures, during a specified time horizon and the associated expected maintenance costs. Frangopol et al use a multiple-objective approach to evaluate a large pool of alternative maintenance and management solutions, helping active decision-making by choosing a solution by balancing structure performance and life-cycle cost [56].

Guarnieri et al introduce a method used for the Argentine air force to estimate the mean number of aircraft that can be restored in a given time between consecutive sorties, given specified maintenance resources and base physical geometry [57]. A spreadsheet-based program makes use of an analytical approach, Maintenance Resources Evaluation Technique (MRET), to estimate the mean and variance of aircraft unscheduled downtime. These parameters are then used in a stochastic analysis of scheduled and unscheduled maintenance tasks necessary to prepare aircraft for the next sortie.

In the military aircraft industry it is essential to treat maintenance and operations as one system, due to the high degree of dependency between them [58]. However, this need increases the complexity of the system. Studying and analysing such systems necessitates the use of simulation as it is quite difficult to represent the system using analytical techniques. Several researchers have realized this dependency and have developed simulation models to investigate the impact of maintenance on operation.

Simulation based models

Simulation is the process of representing a system on the computer, and based on well designed experiments the system performance can be evaluated [59]. It is one of the most desirable approaches for modeling maintenance, due to the following characteristics of maintenance functions, according to Duffuaa and Andijani [49], [50]

- Complex interactions of maintenance functions with other technical and engineering functions.
- High dependence of maintenance factors on each other.
- Uncertainty in maintenance functions. This includes uncertainty in demand for maintenance, time of arrival of job requests, job content, time to complete a job, and equipment and spare parts availability.

Simulation has been applied in different areas of the airline industry. Hill et al at the Air Force Institute of Technology discuss the use of computer simulation in support equipment reduction, army recruiting and modeling strategic effects [60]. Simulation has also been used for modelling maintenance operations. Keeney at Boeing developed a simulation model, using General Purpose Simulation System (GPSS), with operational and logistics simulation capability that could be adapted to varied aircraft systems with minimum programming revision [61].

Richard Cobb describes how a GPSS/H simulation model can be used as a tool useful to managers when evaluating either current maintenance system performance or the potential effects of ad hoc operating decisions on maintenance turntimes [62]. This paper shows that by using simulation modeling effectively appropriate changes can be made in maintenance process to help reduce the turntime. Cook et al developed a computer model GPSS computer code to simulate helicopter maintenance operations in combat [63]. It mathematically models a fleet of helicopters performing combat missions. Scheduled inspections, system maintenance, and repair of battle damage are performed in the course of the simulation. The model helped in reducing the maintenance workload and increasing the mission capability of Army helicopters in combat.

Matilla et al present a discrete-event simulation model for maintenance operations of a fleet of fighter aircraft in crisis situations, where the fleet operations are affected by a threat of an enemy's actions [64]. The model is used to evaluate different maintenance strategies in the elevated states of readiness and in the presence of hostile activities. It is stated that the model offers a valuable educational aid in training maintenance personnel by demonstrating the implications of airbase maintenance and logistics activities to fleet performance. Similarly, Upadhya et al have addressed the availability of weapon systems during battles through different models [65], [66], [67]. The models include Monte Carlo methods applying different probability distributions for failure times due to battle damage and system unreliability, and for repair times. Probabilistic distributions are also used for logistics delay time and for logistics factors, spares, crew and equipment. The models are used to plan combat missions and to design an improved system which focuses on the factors affecting the availability as brought out in this simulation. Adamides et al describe a modular system dynamics model which is used for analysing the dynamics and for assessing the long-term performance of military aircraft engine maintenance systems [68]. The model is used to investigate the drivers of good and poor maintenance and operational performance and to determine the systemic interventions necessary for achieving a required performance profile.

Most existing maintenance cost models in the literature deal with a specific activity of maintenance. A need exists to integrate all aspects of maintenance and combine them with operations goals and objectives. There is also a need to link aircraft design information with maintenance costs to compare different design concepts.

2.3.3 Life cycle cost Models

The life cycle cost of a given system can be modelled using a work breakdown structure (WBS), as described by Gu [8]. The life cycle cost captures all of the cost elements of the system, from conceptual design phase, through detailed design and planning phases, to manufacturing, distribution, operation of the system, logistic support and maintenance of the system, and finally disposal or retirement.

Diraby presents a web-based semantic system for managing products life cycle costs using a a hierarchy of cost elements as the basic architecture of the proposed system [69]. Sandberg et al present a model for life-cycle cost (LCC) prediction in the conceptual development of a jet engine [70]. The model incorporates all activities that occur after the product has left the factory, which enables consideration of important scenario issues as design engineers can directly assess LCC during detail design. The model also helps design-review activities by giving fast LCC feedback on proposed design changes between teams working with interfacing components. Marx et al developed a hierarchical cost model structure which is used to determine life cycle effects of design and manufacturing alternatives for the major structural components of the wing of a High Speed Civil Transport aircraft concept [71], [72], [73]. The models make use of the bottom-up cost estimates for definitively calculating the cost differences associated with various material, fabrication, and assembly procedures. The benefits incurred as a result of technology improvements are directly assessed and the magnitude of their effects are compared to the effects on economic factors.

2.4 Cost engineering

Cost engineering can be described as the application of scientific and engineering principles and techniques to problems of cost estimation and can be decomposed into cost estimation, cost calculation and evaluation, and cost modelling. The cost estimation function generates cost estimates and the actual costs are compared with these cost estimates and their underlying assumptions, which then become the basis of the cost modelling. The role of cost control is the detection of cost values and the causes of those costs in order to identify opportunities for cost reduction or to keep cost within a limit [22]. Also, cost control must be able to compare and contrast cost estimates with actual values in order to feed findings back into the process and improve understanding and predictions. The modelling of cost as a means of enhancing cost control was developed by the Rand Corporation. Cost is an important factor in the engineering design process and it should have a more directly influential role, for example cost should be a part of an integrated design process that is embedded within multidisciplinary systems modelling architecture [1].

2.4.1 Concurrent engineering

Concurrent engineering is a philosophy for product design that relies on the design being simultaneously evaluated by the design engineers, manufacturing engineers and the marketing experts, in order to achieve the greatest level of customer satisfaction [74]. Consideration is given to design for manufacturability, design for assembly, and design for reliability and maintainability. Due to the highly specialised nature of the manufacturing industry, the cost based design tools are application specific and highly customised.

An analysis of cost estimating processes used within a concurrent engineering environment during the whole product life cycle is presented by Rush et al [75]. The paper analyses parametric estimation, feature based costing, artificial intelligence and cost management techniques and it outlines their advantages and limitations in a concurrent engineering environment. Park et al incorporated life-cycle cost into early product development by making use of approximations to estimate the maintenance cost [76]. Brinke et al [77] developed a cost estimation architecture using information management for cost control.

An approach to integrated product and process design is given by Kusiak et al using a modularity perspective [78]. An integrated design and manufacturing methodology is described by Marx et al using a Knowledge-Based System (KBS) [71]. The methodology assesses the aircraft producibility using a KBS which addresses both procedural and heuristic aspects of integrating design and manufacturing using the example of a High Speed Civil Transport (HSCT) wing. A generic framework for cost estimation and control in product design is described by Weustink et al [79]. This framework has the capability to identify the origin of product costs and consequently, most cost driving elements and the causes of costs can be identified. The authors claim that design alternatives can be easily compared and the most cost effective alternative can be selected. Chan et al have developed an automated cost estimation tool which can be linked to a CAD package in order to provide the estimated cost of machined parts from a particular material [80]. Their tool enables product designers to incorporate manufacturability and cost criteria into their decision making.

An activity based approach to evaluate the cost for machined parts and to perform cost management during the design and development stage is used by Ben-Arieh et al [24]. This methodology is demonstrated on a sample part produced in a controlled manufacturing facility. Chogule et al describe the implementation of a casting cost estimation model in an integrated product and process design environment [81]. The cost estimation is based on a hybrid model which combines analytical and parametric approaches and is linked to a web based collaborative engineering system enabling design modifications to achieve the targeted cost. Barlow et al detail the development of a methodology for determining the optimum manufacturing method for a component design [82].

2.4.2 Trade studies and optimisation

This subsection provides an overview of design optimization and trade studies that evaluate aircraft designs. Optimisation studies configure the aircraft to achieve the best objective while trade studies are used to observe how the objective is affected by the design parameters.

An aspect of cost-integrated design is assessing the trade-off between technologies or materials. Hackney et al describe a life cycle model for performing comparisons of emissions, costs and energy efficiency trade-offs for alternative fuel vehicles [83]. They use a spreadsheet based approach to model the full life cycle of the fuels and vehicles. Similarly, using a life cycle approach, Babikan et al show that despite their low fuel efficiency, i.e., higher fuel costs, regional aircraft have similar operating costs comparable to turboprop aircraft when flown over comparable lengths [84].

The influence of manufacturing tolerance on aircraft cost is examined by Curran et al [85], [86]. The cost-tolerance modelling was performed using statistical analysis, making use of manufacturing tolerance data from Bombardier Aerospace. The study showed that production costs can be reduced by relaxing the tolerances in fabrication and assembly.

Bruening et al conducted a study to define payoffs in terms of mission capability and system level life cycle costs associated with implementing three different propulsion system development approaches into an unmanned combat air vehicle [87]. An advanced technology engine, an existing (off-the-shelf) engine and a derivative of an existing engine were considered and a study was performed to assess whether the additional costs associated with the development of a new advanced engine is worth the investment. Metschan et al performed cost assessment for different design configurations and manufacturing method combinations and the attributes of various cost analysis models were evaluated [88]. Vermuelen et al present a design study of a pressurised fuselage section in aluminium and carbon fibre reinforced plastics. It focuses on comparing the performance of each material taking the damage tolerance characteristics into account [89].

Bao et al demonstrate the use of process-based manufacturing and assembly cost models in a traditional performance focused multidisciplinary design and optimization process [90]. They perform cost comparisons for different concepts and cost optimization on a generic wing which is made of two spars, five ribs and skin with a total of 45 design variables, making use of commercial software. This type of approach is similar to much of the classic research within the aerospace industry in parametric optimisation: key design parameters that drive performance are optimised in order to maximise performance. Gantois et al also present a multilevel (multidisciplinary design optimisation) MDO process implemented through a hierarchical system with cost at the top level and apply the method to a civil aircraft wing to achieve a minimum cost design [91]. The multi-disciplinary design of the wing is performed by taking only the manufacturing costs into account.

A heuristic-model for optimizing performance based on reliability and life-cycle costs along with other measurements is given by Prasad et al [92]. Marx et al linked MDO to life cycle analysis by defining high level objective functions that encompass the life cycle needs of aircraft [72]. They use the case study of a HSCT to investigate the best structural layout for the wing in terms of life cycle requirements.

Scanlan et al have identified the need for detailed and reliable cost information for the optimization of a product design [13]. The merits of various cost estimation approaches are outlined based on the cost modelling work performed on Airbus A380 aircraft. They outline the limitations of the existing cost modelling tools, particularly their incapability to model uncertainty and multiple levels of abstraction associated with emerging design and propose an object-oriented data structure which has these capabilities.

2.5 Limitations

The review of existing literature is intended as background to the current research. It serves to illustrate some of the desirable features in these systems, and also to point out limitations and disadvantages of the models. Here, the focus is to look at the limitations of the existing cost models and the observations made here are in the context of the aerospace engineering design process. After looking at the current state of the art in cost modelling, a number of limitations are apparent.

- Most cost models are based on statistical techniques or analogous costing which utilise historical data to estimate costs. This makes it difficult to understand the relationship between the product design and its effect on costs.

- Most cost models are concerned with a particular element of cost instead of looking at the holistic cost architecture. Similarly, modelling is directed towards a particular stage of the life cycle instead of the whole LCC. This leads to highly product specific cost models rather than generic models.

- Most cost models give a single number as the cost estimate and cannot identify which are the cost driving elements in the product description. It is realistic to have a range of cost estimates rather than a discrete value.

- Most cost models are not easily auditable and not transparent. Cost models should show variables and parameters which have the most impact on the design so that comparisons between alternate products can be permitted.

- The integration of cost models in the design process for concurrent design is not solved satisfactorily. Most cost models are used for estimating the costs rather than updating the product design for cost reduction. In addition, automation needs to be considered if multidisciplinary analysis or trade-off studies need to be performed.

2.6 Implications for the research

The review of cost estimation techniques and aircraft design decision support tools provided a platform on how the cost model framework needs to be developed. The existing literature reinforces the argument that significant portions of the life cycle cost are committed early in the design process, and well before the production phase. Most existing cost models look at a specific manufacturing process or a particular aspect of maintenance and hence, can not provide the complete picture. Thus, this research uses life cycle cost as the measure of cost-effectiveness.

The LCC framework includes acquisition cost model and a simulation model, which estimate the manufacturing/raw material costs and operational costs respectively. Both models use activity based costing to estimate the resources consumed and calculate the corresponding costs. This methodology allows the breakdown of costs and identification of cost drivers. Cost of design effort is not included due to the subjective nature of the required effort, i.e., it depends on the complexity of the aircraft, designers experience and novelty of the aircraft/systems.

Also, there is a developing need to provide more accurate models of the complex relationships between the life cycle cost and the main design variables, which is the motivation for this research. The life cycle cost framework is intended to provide early indication of the cost of the aircraft to allow the consideration of alternatives during the conceptual design stage. This is significant for this research, as the cost-effectiveness and affordability of future aircraft can be estimated using a comprehensive life cycle cost model.

2.7 Summary

An introduction to the different types of costs, costing methodologies and cost engineering has been presented. An overview of the state of the art in cost estimation and cost-based design has also been given. The limitations of existing cost models are outlined and their implications for the research are presented.

This research is based on some of the key principles in the engineering cost estimation domain. The life cycle cost framework is intended to give designers the information they need to improve product design. Chapter 3 describes the life cycle cost framework architecture and the different software used in the framework.

Chapter 3

Life Cycle Cost Framework

3.1 Overview

This research concerns the conceptual design of an unmanned air vehicle along with cost considerations. The overriding reason for this research is to provide decision making information to product designers (or managers) that will enable them to make informed design choices. Life cycle cost is the primary figure of merit for the aircraft, and the balance of performance variable versus cost usually guides designers final choices. The aim of this research is to develop a life cycle cost (LCC) model which allows to estimate the cost of an aircraft given its specifications.

3.2 Improving cost estimation

Cost estimation has been used extensively for many years in the aircraft industry but there is a need for further research. Figure 3.1 shows cost estimation in the past and present and a potential structure for future cost estimation. Cost models should be complete and generic, i.e. they should give the whole picture and should be applicable for a range of cases. They should be transparent, i.e. costs should be traced back to the driving elements in the product description. In order for the cost model to be relevant, it should be integrated with design tools so that design decision support tool can be achieved. Also, the cost model needs to be linked to product definition so that any change in product details is reflected in the cost model. A good database for storing all the information and data mining techniques to extract the relevant parameters are important for an efficient cost model. Statistical analysis can be combined with cost estimation in order to predict the cost estimation uncertainty and where it is attributed.

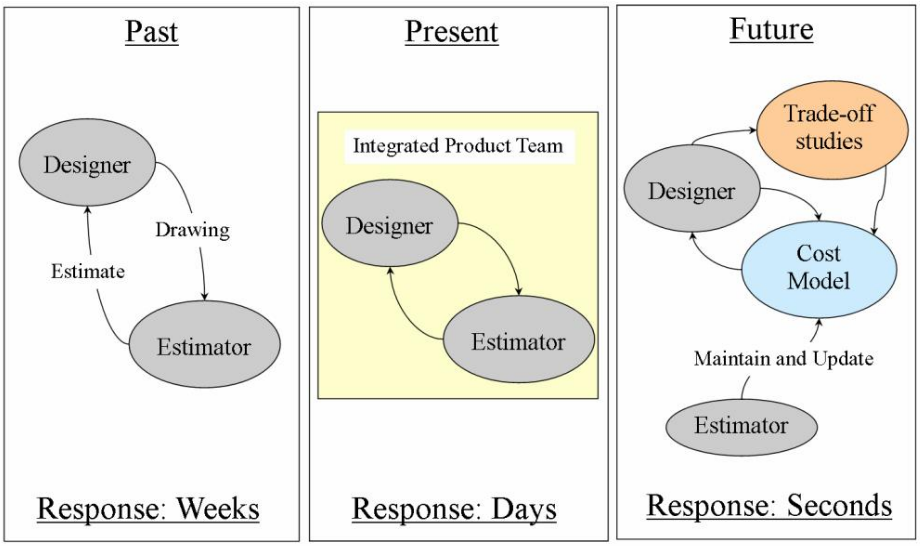


Figure 3.1: Cost estimation

The visualisation of cost information is an important aspect which has been often overlooked. If the cost information is delivered in a sub-optimal format, it makes cost analysis prone to misinterpretation. Although considerable efforts remain invested in enhancing cost estimation accuracy, if the raw data is provided without a way to analyse it thoroughly, then the usefulness of the data generation process is questionable. Therefore, cost models must be built which facilitate adequate visualization tools. Also, cost models are not very useful if the access to the models is reserved for the people building them. They have to be made available to wide range of people. This assists designers in making modifications to the design for cost reduction in early stages. The Internet is an obvious option since it is readily available, not limited to the local network, and cheap. It is the most convenient way to release existing knowledge locked in proprietary formats.

3.3 Cost in conceptual aircraft design

Cost modelling should be integrated into the design process along with other analysis in order achieve efficient aircraft [93]. There have been studies that included life cycle cost in early stages of design to evaluate the effectiveness of aircraft using different methodologies [94], [95]. However, these previous published works do not take all the design aspects into account. This research aims to include the design aspects to estimate the life cycle cost for integration into the early design process.

In aircraft design, there are different methodologies for designing the aircraft. The design methodology commonly used for aircraft design, which uses different levels of detail and defines the aircraft as an "object", is known as conventional aircraft design methodology [96]. This methodology includes three stages/levels of design detail; conceptual design, preliminary design, and detail design. Conceptual design usually begins with a conceptual sketch of the entire aircraft and predictions of aircraft performance based on a specific set of user/design requirements. This is an iterative process as the performance capabilities need to be compared against the requirements. Preliminary design stage starts once the conceptual design is finalised and the aircraft configuration is frozen. In this stage, the aircraft is analysed in different disciplines such as aerodynamics, structures, dynamics and control. to verify if the aircraft is ready for the detail design stage. The detail design stage includes rigorous testing and analysis of all aircraft components including flight simulation and control.

The estimation of effectiveness of an aircraft during mission can not be performed until the detailed design stage in the conventional aircraft design methodolgy. An alternative design methodology which integrates survivability (and its effect on life cycle cost) into aircraft design process by utilising "system of systems" approach [97], [98]. In this method, an aircraft is treated as a sub-system of the overall system (which represents an operation or campaign) and aircraft Measures of Performance (MOPs) were the metrics used to assess the goodness. A similar design methodology, which integrates operation simulation, survivability assessment, reliability & maintainability assessment and life cycle cost estimation into conceptual and preliminary design stages has also been studied and presented by Nilubol [99], [100]. This methodology is used measure aircraft operational and operational cost effectiveness as a function of aircraft MOPs in several design aspects, such as survivability, reliability, and operational cost and to facilitate tradeoffs between aircraft MOPs. This methodology can also be used to enhance the combat survivability of aircraft, resulting in operational and monetary efficiency [101].

A combination of both these conceptual aircraft design methodologies, which links all possible design aspects to cost, is used in the development of this framework to estimate the life cycle cost.

3.4 Framework requirements

This chapter details the framework to estimate the life cycle cost (LCC) of aircraft. The total life cycle cost of an aircraft includes the cost of building the aircraft, which includes the material costs and the manufacturing costs as well as the cost necessary for operation, maintenance and repair of a fleet of aircraft. The aim of this research is to develop a generic life cycle cost model which can be integrated into a multidisciplinary design framework. Particularly, the cost models must

- Enable cost control,
- Be modular, so that its possible to integrate with other software packages and for the possibility to extend the system,
- Be transparent, i.e., that it should be easy to use and understand, and
- Be highly automated, so that multidisciplinary analysis and trade-off studies can be easily performed.

The cost models must be developed to have the desirable characteristics mentioned above. Thus, cost models are developed using software which satisfy these requirements.

3.5 Generic aircraft product definition

The framework developed here has the capability to estimate the costs of any given aircraft. This is achieved by having product definition as an input to the cost model so that any change in the design is reflected in the estimated cost. After careful consideration, the product definition of an aircraft can be broadly classified into explicit and implicit product definition.

Explicit product definition includes the design parameters whose effects on the cost are easily recognisable, i.e. a straightforward relationship between cost and the design parameter can be easily identified. Explicit product definition includes the geometry parameters (i.e. dimensions of the design), material type, and power plant specifications. For example, a change of the design dimensions leads to a change in raw-material and manufacturing costs. It can be easily observed that there is an explicit relationship between cost and design dimensions, thus making these design parameters part of the explicit product definition. Implicit product definition on the other hand includes design parameters whose affects on the cost are not easily identifiable, i.e. a straightforward relationship between cost and the design parameter cannot be easily observed. For example, the affect of manoeuvrability of the aircraft on the cost is not easily apparent. However, the battle damage is dependent on the manoeuvrability of the aircraft; higher manoeuvrability means less chance of getting hit/shot which in turn means lower cost of repair.

Thus, the product definition of an aircraft can be broadly classified into:

(a) Explicit Product Definition

- Aircraft geometry
- Power plant and systems data
- Material type, and
- Aircraft weights.

(b) Implicit Product Definition

- Performance specifications (range, endurance, acceleration, turn radius, manoeuvrability, cruise and maximum speeds)
- Signature data (e.g. visibility, radar cross section etc)
- Critical component analysis (CCA) data

Implicit product definition design parameters are dependent on explicit product definition and the dependencies can be modelled using physics based models. A performance model has been developed to estimate aircraft performance from its explicit design parameters, making use of standard flight dynamics equations. Similarly, signature and CCA data can be estimated using simple signature analysis and reliability analysis models respectively. There is no need to specify the implicit product definition design parameters as inputs at the start of the LCC estimation process as they can be derived from explicit product definition of the aircraft. This is significant because the LCC of a given aircraft can be estimated by having only explicit product definition as input to the LCC framework.

3.6 Life cycle cost framework architecture

This section gives an overview of a proposed LCC estimation framework. The aim is the estimation of the life cycle cost of a generic unmanned air vehicle. This is be achieved by having explicit product definition as input and the structure of the LCC framework is shown in Figure 3.2. The LCC of an aircraft includes the material and the manufacturing costs along with the costs necessary for operation, maintenance and repair of a fleet of aircraft.

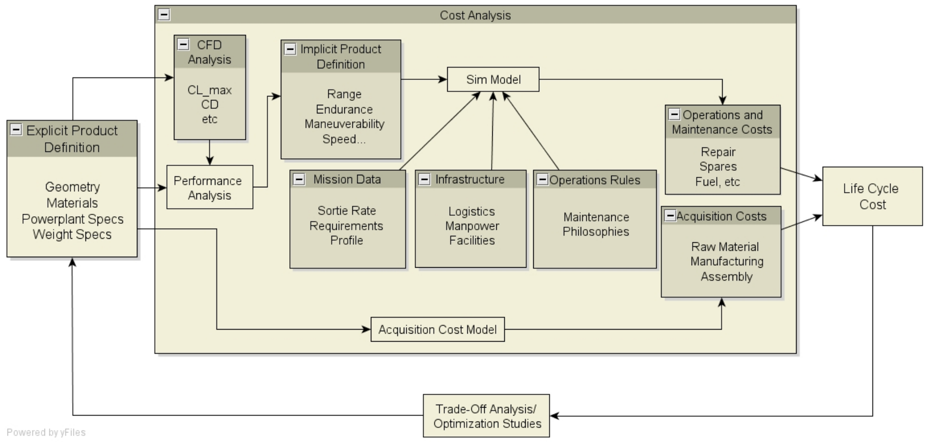


Figure 3.2: LCC framework architecture

From the aircraft geometry specifications and material type, the raw material and manufacturing costs are estimated by the acquisition cost model using an activity based costing approach. The simulation model gives an estimate of the cost of maintenance, operation, and repair making use of the aircrafts implicit product definition, mission details and logistics data as inputs. These costs, when combined, give the whole life cycle cost of the aircraft. The acquisition cost model is developed using DecisionPro™ [102], while the operation and maintenance costs are estimated with a discrete event simulation model developed using Extend™ [103]. Although each model is explained in more detail in subsequent chapters, an overview of different models used in the framework is provided here. The reasons for choosing the software are provided without going into detail on the model development aspects, which are elaborated in more detail in Chapters 4, 5.

3.6.1 Geometry model

The geometry of the aircraft is modelled in Matlab, utilising a parametric representation of the aircraft geometry which enables three-dimensional representation of the aircraft. The geometry model is versatile and can be used to represent conventional and blended-wing body (BWB) aircraft configurations as shown in Figure 3.3.

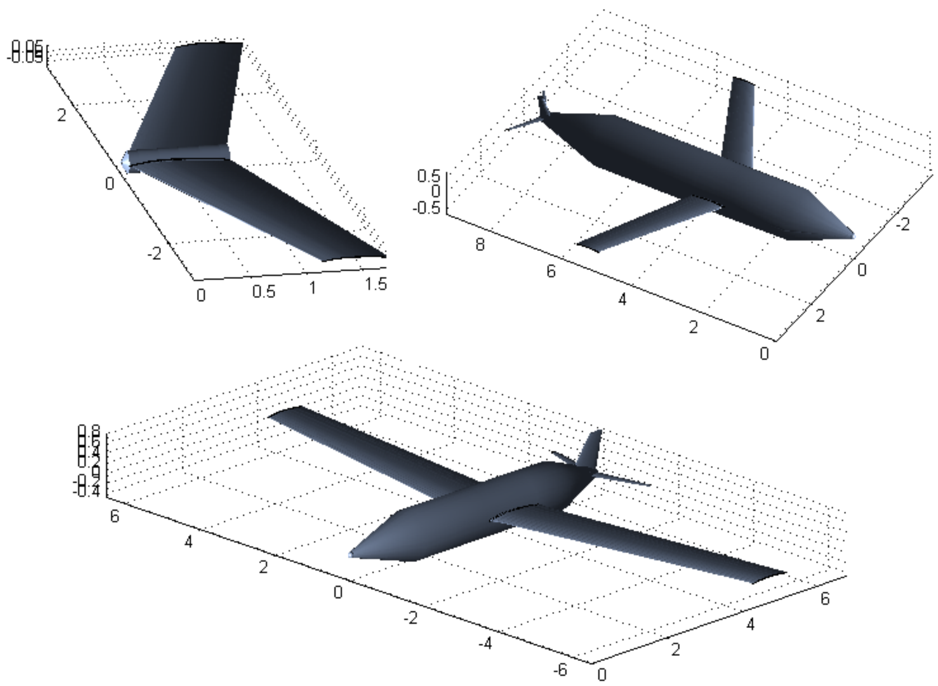


Figure 3.3: Selection of aircraft geometries generated by the geometry model

This parametric representation, which is a part of the explicit product definition, includes the shape and dimensions of wing, fuselage and empennage. The geometry model acts as a "sanity check" to verify whether the aircraft is realistic before proceeding with the cost estimation. The geometry model is explained in detail in section 4.2.

3.6.2 Acquisition cost model

The acquisition cost model developed using DecisionPro is shown in Figure 3.4. The model makes use of aircraft product definition and costing data to estimate the acquisition costs. The model has a hierarchical structure,

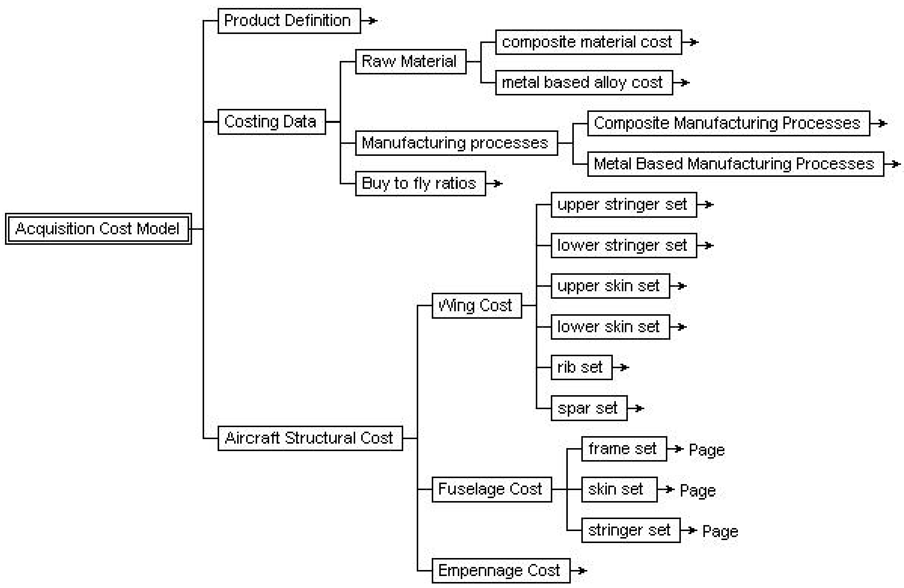


Figure 3.4: Acquisition cost model

i.e. the cost of the structure is split into wing, fuselage and empennage costs which are further divided into different categories. Both wing and fuselage costs are the sum of the costs of different structural sets, i.e. spar set, rib set, etc. Libraries of materials and processes have been created for integration into the cost model. This object oriented approach makes the cost model consistent, easy to maintain and permits reuse of components. The acquisition cost model has the capability to estimate the costs of aircraft structures manufactured using metal-based materials as well as non-metal-based materials.

3.6.3 Simulation model

A simulation model is developed using Extend™ to estimate the operating and maintenance costs for a fleet of aircraft, taking into account the mission characteristics, aircraft performance and the logistics data. Extend is used because of its good visualisation capability, ease of integration with other software and its effectiveness in modelling complex systems. Also, it has the capability to model both discrete and continuous simulations.

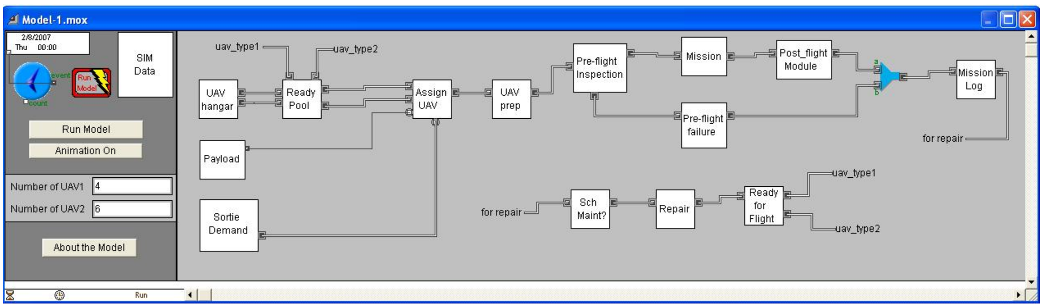


Figure 3.5: Simulation model

The simulation model is shown in Figure 3.5 for the purpose of illustration. Aircraft are drawn from a ready pool, inspected, and launched on the mission according to the flying schedule. In the course of the mission, system failures are experienced and the aircraft receive combat damage. Aircraft are lost and missions are aborted according to specified probability functions. When missions are completed, aircraft are recovered and serviced. Required scheduled and unscheduled maintenance tasks are performed to return the aircraft to a ready status. Statistics are generated at the end of a simulation to evaluate the combat effectiveness of the aircraft under various sets of conditions. The simulation model is also equipped with survivability and reliability analysis.

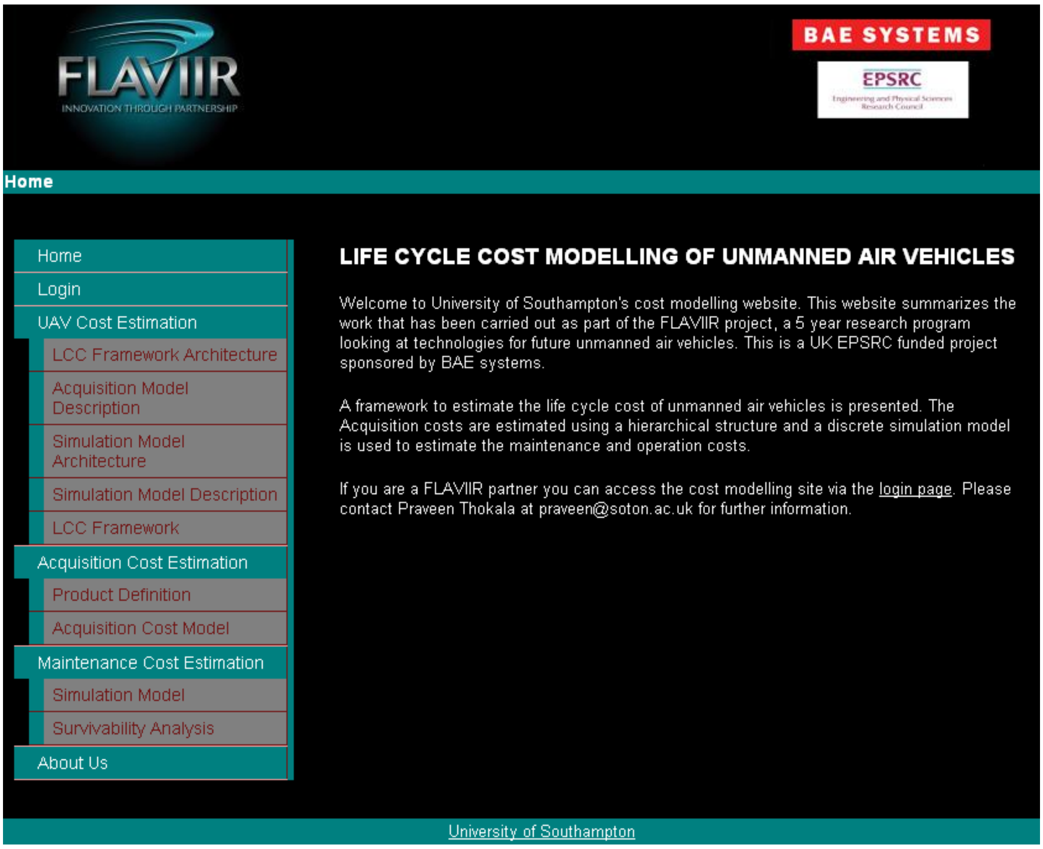


Figure 3.6: Cost estimation website

3.6.4 Web deployment

The models developed have been published on the local internet network for remote access; Figure 3.6 shows the website which allows the user to verify the aircraft geometry before estimating its acquisition costs. It is planned to deploy these cost models on a secure web server for public access. The LCC framework developed is integrated into the design process to facilitate the comparison between different configurations and can be used to evaluate the cost penalty of survivability enhancement concepts.

3.7 Summary

An overview of the framework and different software used in the architecture is provided in this chapter. The acquisition cost model developed using DecisionPro™ and the simulation model developed using Extend™ are explained in more detail in chapters 4 and 5, respectively.

Chapter 4

Acquisition Model

In this section, the DecisionPro™ cost model used to estimate the product acquisition costs is presented. The reasons for choosing this software are outlined before describing the developed model. The model shown here is capable of estimating the acquisition costs of an aircraft, given the aircraft product definition. A parametric geometry representation utilised as the explicit product definition is described along with a three dimensional geometry model of the aircraft. The acquisition cost model is detailed with emphasis on novel approaches such as manufacturing knowledge base utilisation, object oriented programming and risk analysis. A case study is then provided with example objects to illustrate the object oriented approach along with sensitivity and uncertainty analysis to estimate the involved risk. Finally, contribution to the body of knowledge is given along with a short summary of the chapter.

4.1 Software selection

The idea was to select a software environment that is as easy to use and as flexible as a spreadsheet but which avoids the downsides of spreadsheet based systems. DecisionPro™ was identified as a better candidate, in particular due to the following key characteristics:

- Storage of information in structured tree hierarchies and/or data tables,
- Ease of use,
- Powerful stochastic and analytical capabilities,
- Presence of a powerful scripting language called DScript,
- Possibility to declare data in a wide variety of formats (numerical, non numerical, and stochastic),
- Support of units of measure and automatic reduction, and
- Ease of deployment through standard web browsers.

The hierarchical structure of DecisionPro™ allows users to decompose a problem into a logical series of steps resulting in the model having a clear and easily comprehendible structure. This standardised structure adopted results in a uniform approach maintained throughout the model.

DecisionPro™ also includes other functionalities (for example, sensitivity analysis, Monte Carlo simulation, optimization, decision trees and forecasting) that are useful for performing multidisciplinary analysis, optimization and trade-off studies [104], [105], [106]. A programming language called

DScript based on Java is used for programming in DecisionPro™ . This is similar to other programming languages and has the capability of representing functions, arrays, and matrices.

4.2 Explicit product definition

The acquisition cost model uses the aircrafts explicit product definition to estimate the cost of aircraft structure. Explicit product definition parameters are design parameters whose effects on cost are easily recognisable and they include systems data, aircraft weights, geometry and material type. Since the emphasis is on material and manufacturing costs, the systems data is not included in our explicit product definition. Thus, explicit product definition essentially consists of geometry specifications and the material type. The geometry specifications in the explicit product definition should have enough detail to estimate the acquisition costs for any given aircraft, which is our aim as mentioned in Chapter 1.

Explicit product definition includes the dimensions and material type of the aircraft and these details can be easily extracted from a geometry model of the aircraft. Geometry tools can either be computer-aided design (CAD) software based or tools based on parametric geometry such as NASAs RAM (Rapid Aircraft Modeler) tool [107], Boeings proprietary tool (General Geometry Generator) [108], and Desktop Aero's rapid geometry engine (RAGE) [109]. CAD based approach can be time-consuming and labour-intensive, especially if the geometry is generated and linked to analysis tools manually. It is difficult to extract the relevant parameters from the

CAD models as they are based on splined surfaces rather than aircraft design parameters. Also, CAD geometry models are tedious to link to different analysis tools such as the cost models, aerodynamic analysis, etc.

Thus, a parametric representation of the aircraft design is chosen as the geometry description that is input into the cost model. This is because a parametric representation of the design geometry is intrinsically generic in nature i.e. any given aircraft can be represented in parametric form [110]. Furthermore, the parameters that represent the geometry can be used as design variables for multidisciplinary analysis and optimization studies. In order to achieve cost estimation for a generic aircraft, a parametric geometry representation is proposed.

4.2.1 Parametric geometry

A parametric representation of the aircraft geometry which enables three-dimensional representation of any given aircraft was developed, making use of previous parametric aircraft geometry representations [107], [108], [109]. This representation is based on conventional aircraft configuration which comprises of wing, fuselage and an empennage. Although this parametric representation does not consider rotorcrafts, biplanes or other unusual configurations, it is still flexible enough to represent canard and blended body wing (BWB) configurations as shown in Figure 3.3.

The proposed parametric representation is as shown in Figure 4.1. The parametric representation of the aircraft can be divided into wing, fuselage and empennage sections. The wing section geometry is specified using

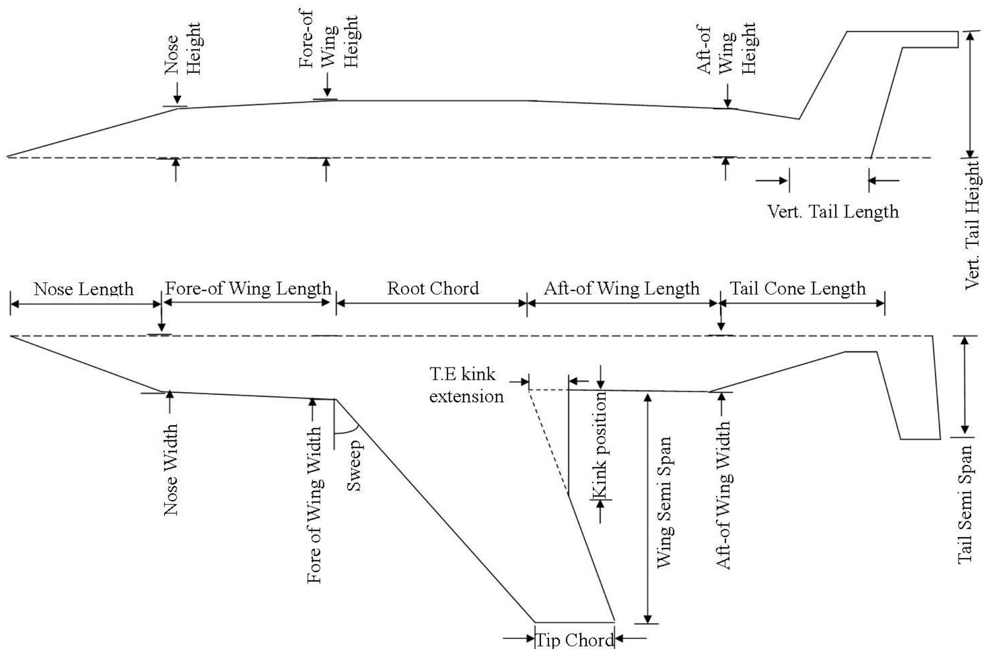


Figure 4.1: Parametric geometry representation

the wing design parameters: semi span, root chord, tip chord, sweep, and thickness-to-chord ratios. Twist is not included as it is outside the scope of this research. However, there is provision to specify kinks and airfoil data at root, tip and kink cross sections which results in a well defined wing. Similarly, the fuselage geometry is specified using cross sectional dimensions and shapes at different longitudinal positions. Smoothing is performed between different cross sections to achieve and represent realistic fuselage concepts. The fuselage is divided into five sections as shown in the figure whose detail is sufficient for the present work. Finally, a vertical tail is represented using its length, height and thickness while the horizontal tail is represented using just the tail semi span assuming the tail planform has the same shape as the wing. The parametric representation can be extended to include more parameters (such airfoil sections and lofts) due to its flexible and modular nature. For example, airfoil sections at root, kink and tip were included to estimate the lift and drag coefficients while performing aerodynamic analysis as described in subsection 5.3.1.

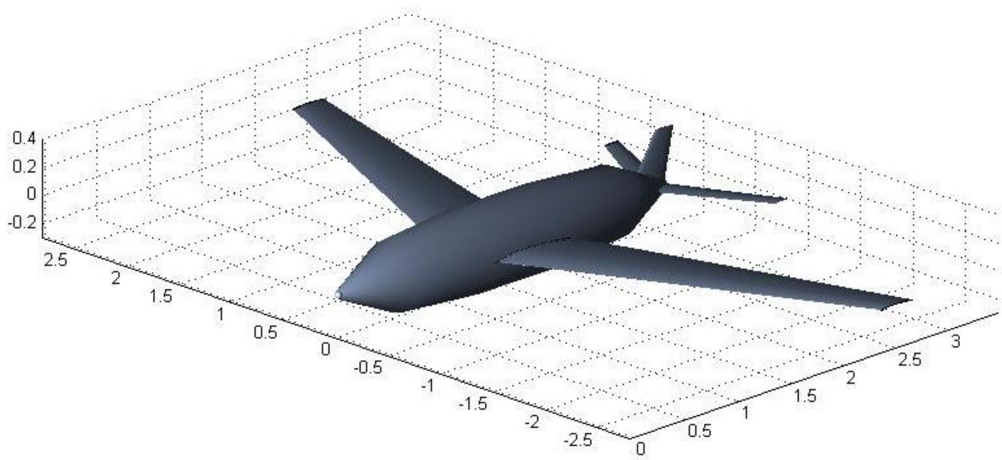


Figure 4.2: 3D aircraft geometry built using Matlab™

Developing parametrised CAD models can be a difficult challenge and would involve significant effort [111]. Thus, a tool is built in Matlab which can provide the three dimensional visualisation of any aircraft using its parametric geometry representation. This acts as a "sanity check" to make sure the aircraft design is realistic and one that is intended by the user before proceeding to the phase of cost estimation. The 3-D geometry of the aircraft for which the costs are estimated in section 4.4 is shown in Figure 4.2.

4.2.2 Internal structural representation

The internal structure shown in Figure 4.3 is similar to that found in most types of aircraft and is flexible to represent various aircraft configurations [112].

The wing essentially consists of framework chiefly of spars, ribs, and stringers. Spars run the length of the wing from the point nearest the fuselage out to the wing tip. The wings as a default have two spars, the front spar and the rear spar, but any number of spars can be specified by adjusting the spar pitch. The spar shapes and thicknesses can also be specified. The ribs cross the spars and extend between the leading and trailing edges of the wing. Again, any number of ribs can be specified for the wing by adjusting the rib pitch and their thicknesses can also be set. Similarly, any number of stringers can be specified depending on the need by adjusting the stringer pitch and they run the length of the wing. The type of stringers and their dimensions can be chosen dependent upon the need. Finally, this whole wing framework is covered by the wing skin whose thickness can be adjusted.

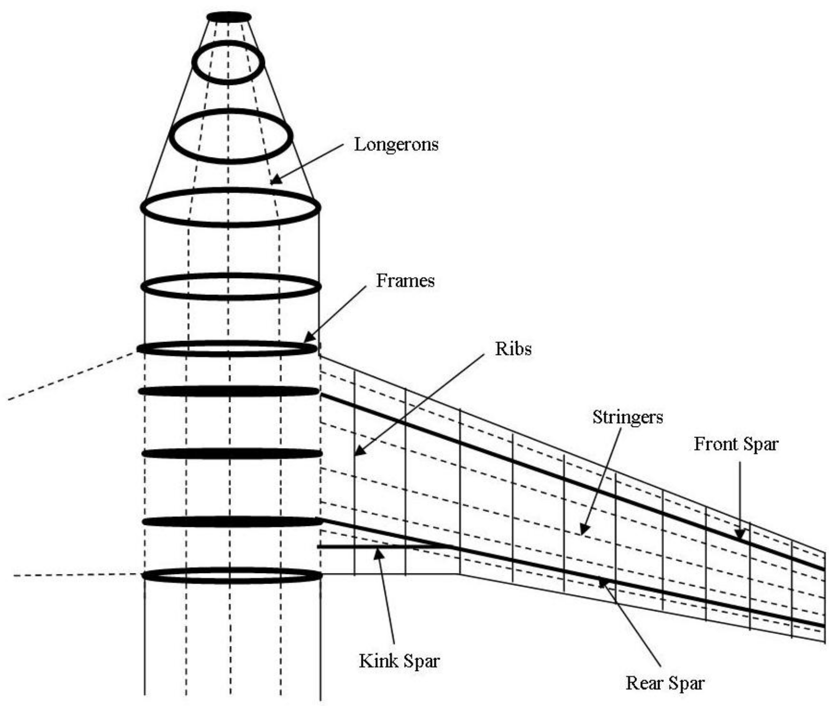


Figure 4.3: Internal aircraft structure

The type of fuselages that are considered in the study have the semi-monocoque structure which includes frames, stringers/longerons and skin. The frames run along the length of fuselage and the number of frames in each fuselage section can be specified along with their shapes and thicknesses. These frames are held together by a series of longitudinal elements called stringers or longerons. Again, the shape and dimensions of these elements can be specified as well as their number, which can be specified by adjusting their pitch. This whole internal fuselage structure is covered with skin, whose thickness can be adjusted. The empennage is assumed to have the same structure as the wing and it can be populated sparsely or densely depending upon the need of the aircraft. This flexibility in specifying the internal structure provides the capability to represent any given aircraft.

4.3 Acquisition cost model

The model is capable of estimating the acquisition costs of aircraft, given the explicit product definition so that any changes to the design are reflected in the cost model. The cost model uses the product definition and details of the internal structure to infer a manufacturing sequence and to estimate the process times and material costs.

4.3.1 Hierarchical approach

The model is capable of estimating the costs for composite materials as well as metal-based alloys and this capability assists in performing trade-off studies between traditional alloys and the composite materials. The overview of the acquisition cost model is presented in the context of structural cost as the model concentrates on estimating the manufacturing and material costs of the structure. DecisionPro has a hierarchical structure and taking advantage of this characteristic, the acquisition cost model is organized in a hierarchical tree structure that reflects the actual physical structure of the aircraft which allows easy and intuitive navigation.

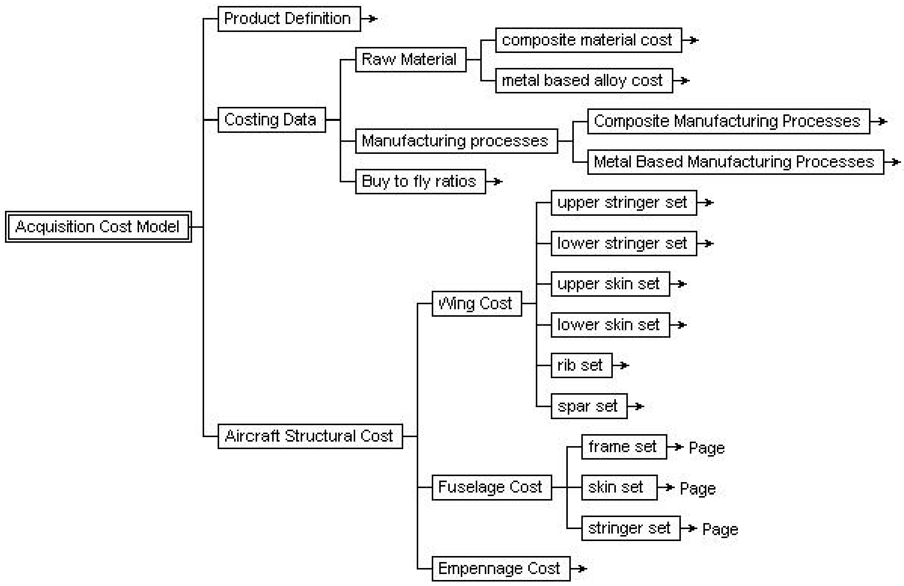


Figure 4.4: Estimating structural cost using hierarchical approach

The cost of the structure represented as Structural cost in Figure 4.4 is split into wing and fuselage costs which are further divided into different categories. Both wing and fuselage costs are the sum of the costs of different structural sets i.e. spar set, rib set, etc and the cost of each structural set is estimated by adding the cost of individual structural parts (i.e spars, ribs). The cost of each part is estimated using an activity based costing approach which calculates the raw material and manufacturing resources consumed for each part, making use of its dimensions. The dimensions of the individual structural parts are calculated from the explicit product definition of the aircraft (which includes high level dimensions such as wing span, sweep, chord length, fuselage length, width and height) and the internal structural data. The details of the parts of the aircraft structure include characteristics such as their serial number, length, area, volume, and their material type. This data is used to estimate the raw material and manufacturing costs for each part by using the relevant process/material data from the knowledge base existing in the cost model. The costs of individual parts are then added to estimate their respective set costs and the costs of all the structural sets are then added to achieve the overall acquisition cost of the aircraft.

4.3.2 Internal structural data

The aircraft structure considered here is fairly simple and generic. It is a conventional configuration with fuselage, wing and tail. The wing consists of stringers, spars, ribs and an outer skin. The number of stringers, spars or ribs is variable and can be modified and the acquisition cost model structure in itself is independent from this variation. The fuselage is assumed to have a semi-monocoque structure with frames, stringers and skin. Again, the number of frames and stringers can be varied. The numbers of these structural parts (i.e spars, ribs etc) are dependent upon the structural spacing. Internal structure data, shown in Figure 4.5, contains this structural spacing data such as stringer pitch, rib pitch, etc and the specifications of the parts such as rib thickness, stringer type etc. The dimensions of these individual parts are then calculated from the high level geometry. The raw materials and the manufacturing costs for each part are estimated from their dimensions and the costs of all these parts are then added to achieve the overall acquisition cost.

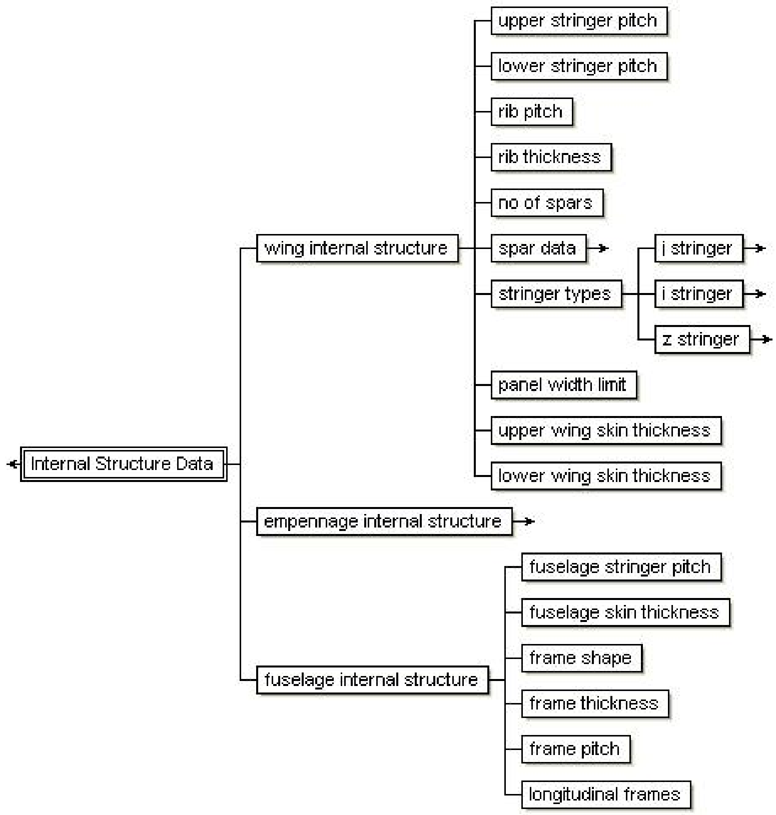


Figure 4.5: Internal structure data

4.3.3 Cost modelling approach

The cost model is equipped with metal-based and composites manufacturing knowledge which facilitates the capability to estimate the manufacturing costs for composite materials as well as metal based alloys. The cost of the structure is split into wing, fuselage and empennage costs which are further divided into different structural sets and the cost of each structural set is estimated by adding the cost of individual structural parts. Any finished individual part is achieved by the application of different manufacturing processes on the raw material. Thus, the cost of individual parts in the structural sets are calculated by inferring a manufacturing process sequence required for converting the raw material into the finished part and estimating the individual process times using the part data.

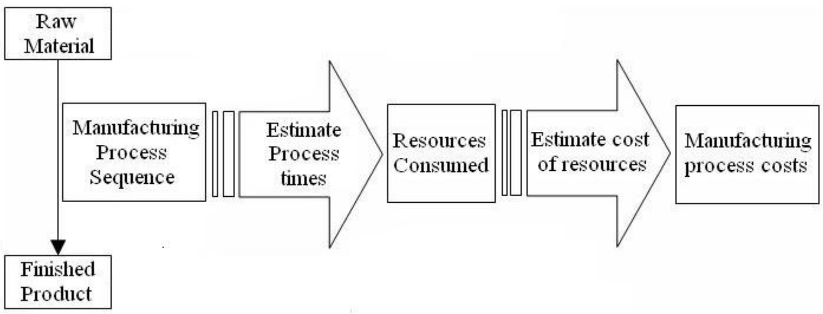


Figure 4.6: Manufacturing cost estimation

This research has cautiously implemented a cost estimation approach by identifying the processes required to manufacture the key structural parts (such as spars, stringers, and skin panels). The key structural parts are limited to those mentioned in the internal structural representation. A predefined manufacturing process sequence is specified for these key parts and the process times are estimated using the part dimensions, as shown in Figure 4.6. Since the manufacturing sequence is dependent upon the material of the part, different process sequences are specified for metal-based parts and composite parts. It should be noted that this approach is not conducive to estimating the cost of radically new designs and cost comparison between different manufacturing approaches.

4.3.4 Object oriented programming

The knowledge base in the cost model formalizes the manufacturing knowledge so that the information can be reused is an easy manner. The knowledge base contains libraries of processes and materials modelled as objects to enable a generic and hierarchical costing environment. The cost model makes use of different objects (called "components" in DecisionPro™) for estimating the material and manufacturing costs. The use of object oriented approach in our model makes use of the sophisticated library function which provides the capability to allow classes and instances to be defined. This approach makes the cost model consistent, easy to maintain and permits reuse of components as well as making it easier for testing and validation. For example, it is easier to analyse a particular manufacturing process than the complete cost model. Also, it allows for controlled access i.e. modification of individual components without disturbing the actual cost model. And, finally, it results in a consistent model structure and standards for the cost model.

Libraries of materials and processes have been created for integration into the cost model and the structural sets make use of the relevant objects for calculating the costs of the individual parts. An example of this is shown in Figure 4.7. The cost of the skin set is estimated by adding the cost of the skin panels and the cost of each panel is calculated by estimating its raw material and manufacturing costs. In this case, the raw material and

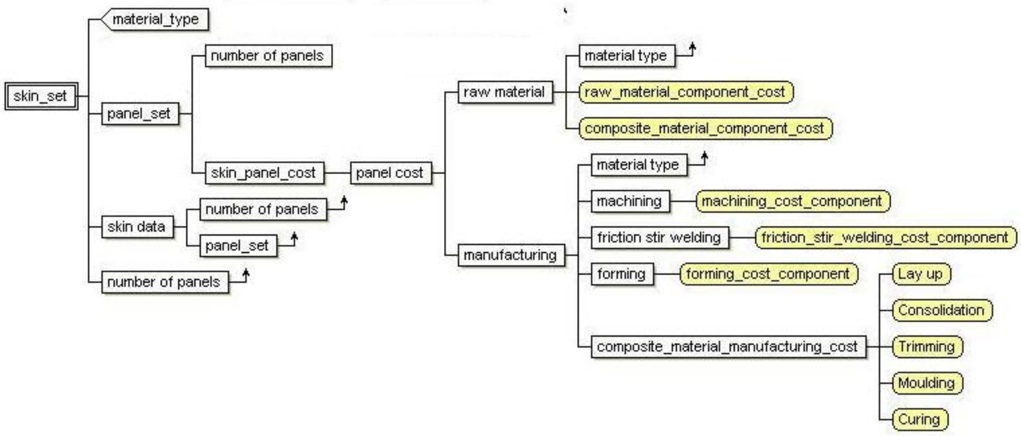


Figure 4.7: Component estimating the cost of a skin set

manufacturing costs of the skin panel are estimated by calling the machining, friction stir welding and forming objects which are in the process libraries. Similarly, other structural set costs can be estimated by making use of the relevant objects for different manufacturing processes and raw materials.

4.3.5 Manufacturing knowledge

The manufacturing knowledge base contains libraries of materials and processes, modelled as objects, for easy integration into the cost model. These objects are used as building blocks to estimate the cost of the structural parts and are stored in generic libraries and the structure of these libraries is as shown in Figure 4.8. The library functionality in the cost model provides easy access and re-use of the library objects.

The libraries include objects that represent both metal-based manufacturing as well as composites manufacturing knowledge. The metal-based manufacturing data is acquired from the literature and the composites knowledge is captured from Cranfield University under the auspices of the FLAVIIR

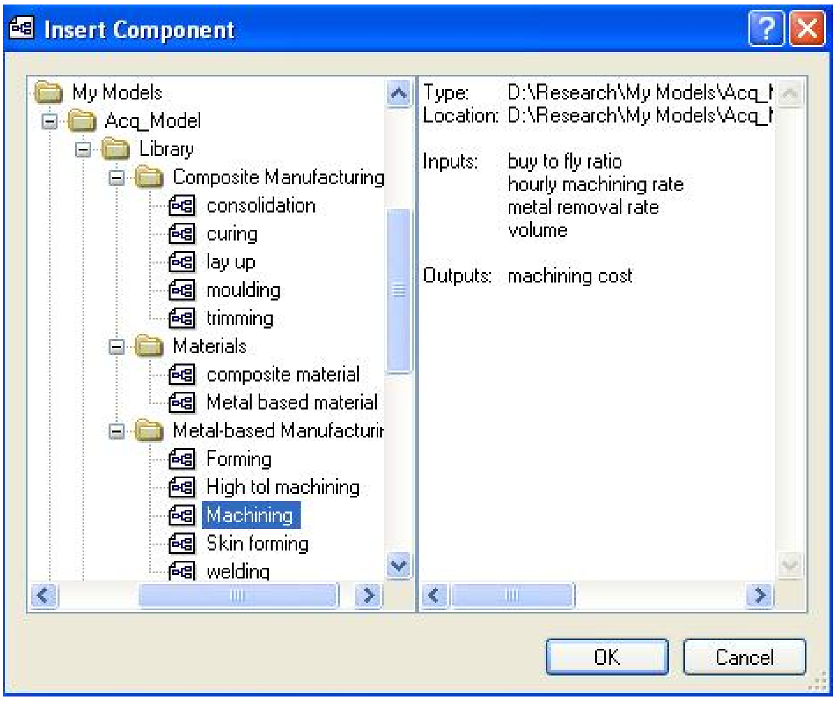


Figure 4.8: Libraries of materials and processes

project [113], [114]. The generic libraries in the manufacturing knowledge database provide an environment that integrates the design, manufacturing and costing disciplines facilitating concurrent engineering.

4.3.6 Risk analysis

It is more useful to have a range of cost estimates rather than a single value to capture the variation in cost and design information. Variation of the cost with variation in design parameters is known as cost sensitivity while the variation of cost with variation/errors in the sources (databases) for cost and manufacturing information when the design parameters are constant is known as cost information uncertainty. Sensitivity analysis and Monte Carlo simulation are incorporated into the acquisition cost model to do cost sensitivity analysis and cost uncertainty analysis, respectively.

Sensitivity analysis is important to isolate cost drivers and is performed by analysing the affect of design parameters on cost. Cost sensitivity can be measured using absolute and relative sensitivities and automatic differentiation method is used in the cost model to calculate these values. Absolute sensitivity is the absolute amount the output changes for a unit change in an input deisng parameter while relative sensitivity is the percentage change on the output that is caused by a 1% change in the input design parameter. The hierarchical structure of the cost model allows sensitivity analysis to be performed at different levels of abstraction which helps identification of the effect of design parameters on different costs across the acquisition cost model.

Cost uncertainty analysis is a process of quantifying the cost impacts of manufacturing information uncertainty and Monte Carlo simulation method is used for this prediction. Monte Carlo simulation is used to replace uncertain design parameters in the cost model with probabilistic distributions to identify the effect of uncertainty on the costs. A suitable distribution is chosen based on the information available and uncertainty involved with uniform, discrete, triangular, normal, lognormal, gamma, Weibull, beta, custom, Bernoulli, binomial and Poisson being the available distributions. Monte Carlo simulation performs deterministic computation using the different random sample inputs and the results of the individual computations are aggregated into probability density function graph (and cumulative probability function graph) to assess the cost uncertainty.

4.4 Case study

The aircraft in this example has a wing span of 6m, length of 3m, and height of 0.5m. The acquisition costs are estimated for the aircraft by calculating the dimensions of the individual parts from the high level dimensions such as wing span, sweep, chord length, fuselage length, width and height. The aircraft structure considered here is a conventional configuration with fuselage, wing and tail. The wing consists of stringers, spars, ribs and an outer skin and the fuselage is assumed to have a semi-monocoque structure with frames, stringers and skin. In this case study, the wing has 3 center spars, 6 stringers and 5 ribs while the fuselage has 8 frames and 9 stringers. The dimensions of these individual parts are calculated from the high level geometry and the raw materials and the manufacturing costs for each part are estimated from their dimensions. The costs of all the structural sets are then added to achieve the overall acquisition cost. The structure of the acquisition cost model is split into product definition, costing data and cost estimating objects as shown in Figure 4.9. The nodes within the model can be declared as either input or output nodes, which allows any of the variables that the designer may want to manipulate to be shown on the same sheet as the root node thus permitting easy navigation. The key output metrics can also be shown on the same sheet. It also facilitates in easy integration and automation.

Explicit product definition containing the material type and aircraft geometry parameters is used as input with the model outputting the aircraft structural costs. Internal structure data contains structural spacing data such as stringer pitch, rib pitch, etc and the specifications of the parts such

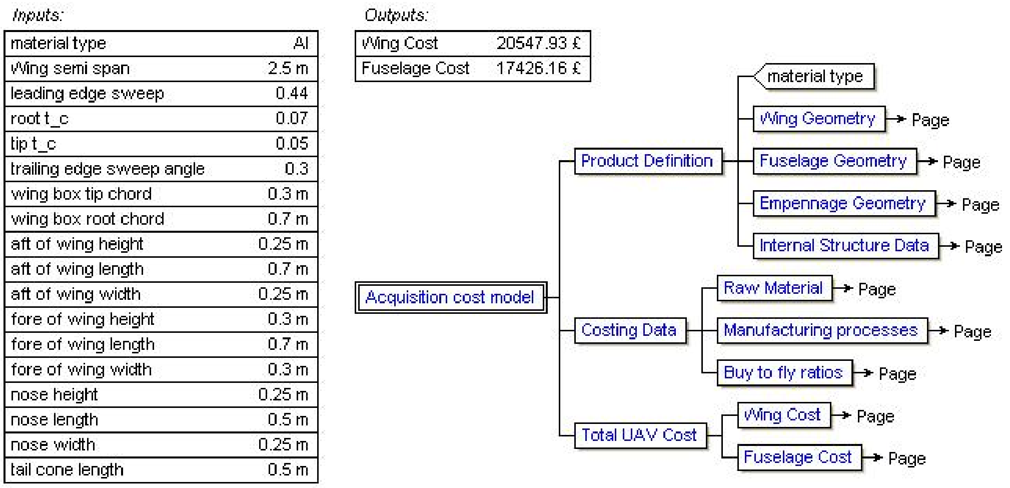


Figure 4.9: Acquisition cost model

as rib thickness, stringer type etc as shown in Figure 4.10. The costing data contains the libraries of different materials and processes as well as the buy-to-fly ratios (amount of the material wasted while manufacturing the structural part).

4.4.1 Description of the model

A couple of modules are selected from the acquisition cost model to demonstrate the hierarchical design. It is difficult to display the details of the whole model as the model is quite large; thus example objects of the structural component and the manufacturing processes are presented. A component which estimates the acquisition costs of a rib set, shown in Figure 4.11, is presented as an example here. This component extracts the dimensions of the rib set from the aircraft product definition. The details of the rib set can be output in the form of text files, spreadsheets or even dynamic linkage. The rib set

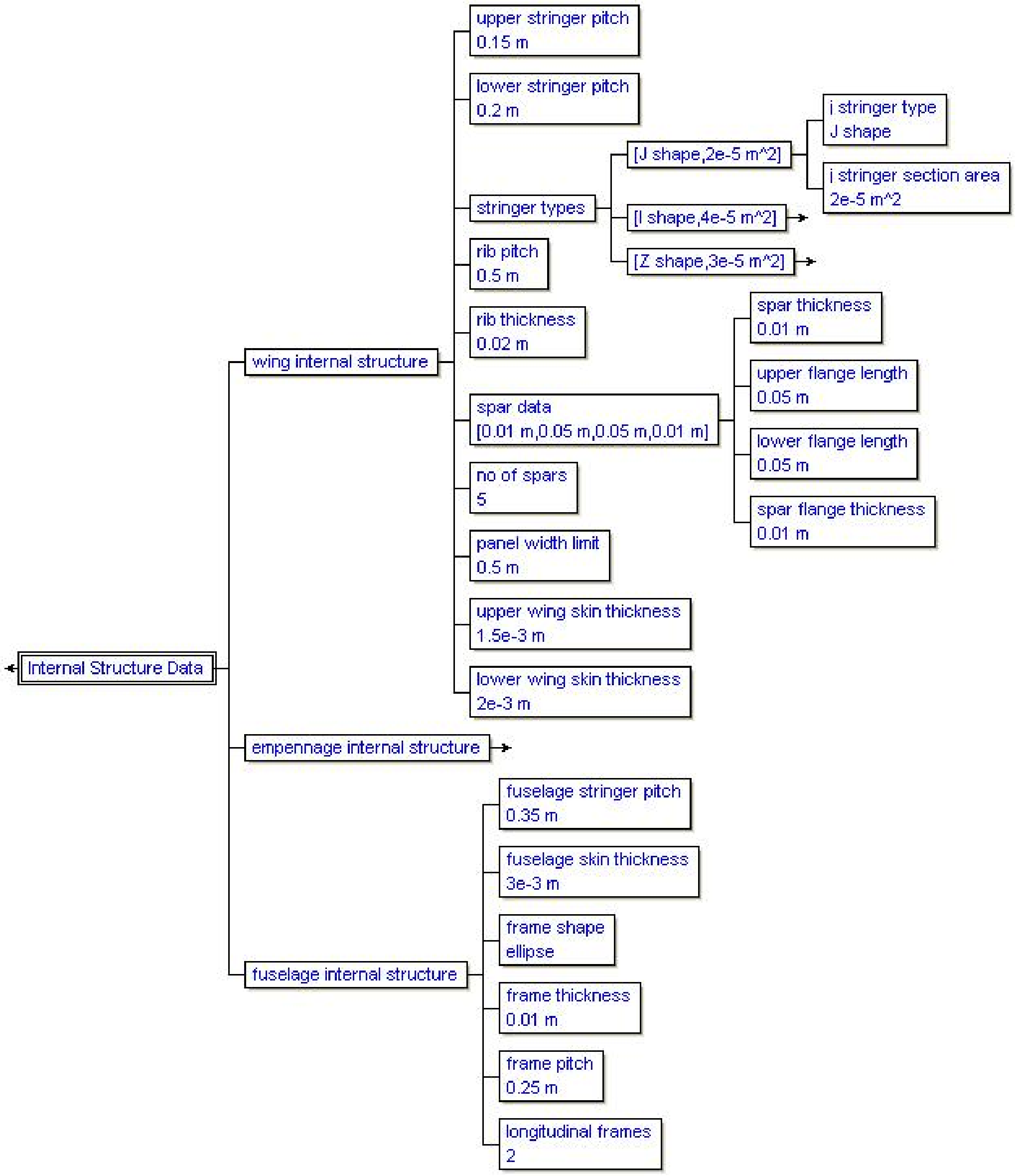


Figure 4.10: Internal structure data

data output for the aircraft under study is shown in Table 4.1.

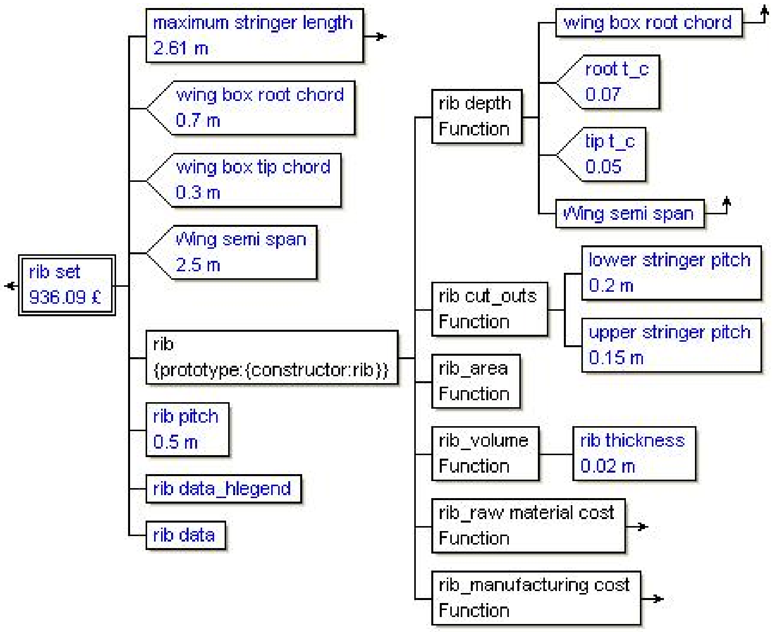


Figure 4.11: Component estimating the cost of a rib set

The cost of the rib set is calculated by estimating the raw material and manufacturing costs of each rib and adding to get the cost of the whole rib set. The raw material and manufacturing costs are estimated by calling the corresponding objects. Each manufacturing process is stored as an object in a library of processes which can calculate the cost of manufacturing of that particular process, given relevant inputs.

Table 4.1: Data output for the rib set

Rib Number	1	2	3	4	5
Rib Length (m)	0.62	0.54	0.46	0.38	0.3
Rib Depth (m)	0.0462	0.434	0.406	0.0378	0.035
Rib Area ($10^{-2}m^2$)	2.86	2.34	1.86	1.43	1.05
Rib Volume ($10^{-4}m^3$)	5.72	4.67	3.73	2.87	2.1

An object which estimates the cost of friction-stir welding shown in Figure 4.12 is given as the other example. This component calculates the cost of friction stir welding based on the length of the part. The analytical equation for the estimation of welding cost is given in Equation 4.1.

$$\Omega = \frac{l}{\omega'}\kappa \tag{4.1}$$

where

$$\Omega = Friction\ stir\ welding\ cost, \tag{4.2}$$

$$l = length\ of\ the\ part = 7.35m \tag{4.3}$$

$$\omega' = friction\ stir\ weld\ rate = 1m/min \tag{4.4}$$

$$\kappa = hourly\ friction\ stir\ welding\ rate = 120\$/hr \tag{4.5}$$

All parameter values are entered in relevant engineering units as DecisionPro™ is able to undertake unit conversion. This capability enables error checking by displaying the units of calculated variables.

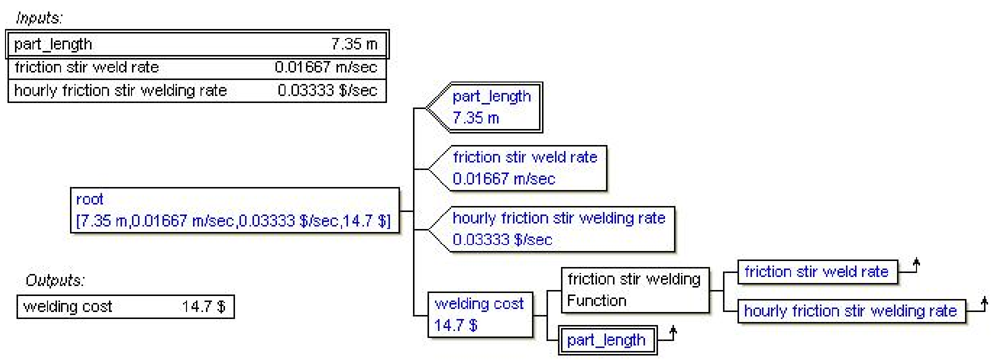


Figure 4.12: Component estimating the welding cost

An example "object" estimating the cost of a skin set incorporated in the hierarchical structure of the model is shown in Figure 4.7. The cost of the skin set is estimated by adding the cost of individual skin panels. The raw material and manufacturing costs of each panel are estimated by calling the corresponding objects or components. For example, the manufacturing cost of a metal based skin panel is estimated by calling the forming, machining and friction stir welding objects which reside in the process libraries. The object which estimates the friction-stir welding cost is shown in Figure 4.12. The cost of friction stir welding is estimated by using the length of the part welded, welding rate and the hourly cost. Similarly, the machining cost is estimated using the amount of metal removed from the panel while the forming cost is estimated from the dimensions and curvature of the skin panel. The manufacturing cost of each skin panel is estimated by adding its corresponding machining, welding and forming costs and the cost of raw material for each skin panel is estimated from its material type and its dimensions. The cost of the skin set is calculated by adding the raw material and manufacturing costs of the individual skin panels. Similarly, others structural set costs can be estimated by making use of the relevant objects for different manufacturing processes and all the structural sets in the cost model are then combined to form “Wing Cost”, “Fuselage Cost” and “Empennage Cost”.

4.4.2 Sensitivity analysis

Sensitivity analysis is employed to estimate the degree of sensitivity of each design parameter on the cost. Sensitivity analysis on the “wing cost” indicated that “wing semi span”, “wing box root chord” and “wing box tip chord" are the most sensitive process parameters as shown in Table 4.2.

Table 4.2: Sensitivity analysis

Input parameter	Relative	Absolute
Wing semi span	13.16	108169.65 £/m
Leading edge sweep	0.15	7177.44 £
Wing box root chord	0.43	12586.83 £/m
Wing box tip chord	172.25	11798276.83 £/m
Root t/c	0.26	77359.99 £
Tip t/c	0.03	10769.19 £

However, this analysis does not take into account the possible range of values for the inputs and unable to capture the effects of simultaneous changes in multiple inputs. Graphical sensitivity analysis method allows definition of the possible range between which the inputs have to be varied into cost sensitivity analysis. The sensitivity of wing cost against its geometry parameters, shown in Figure 4.13, provides visual analysis of how the cost changes as each of the geometry parameters are varied from their initial value by -30% to +30%. It is apparent that the span of the wing is the main cost driver closely followed by the root chord. Also, if any dimension increases by a structural part pitch, i.e. rib pitch, stringer pitch etc. a new part needs to be added to the internal structure which results in a steep increase of the cost. This is due to the model populating the internal structure using structural spacing rather than utilising structural analysis. This phenomenon can be observed in the tip chord plot, where there is a sharp increase at around 15% variation. At this 15% mark, the wing tip chord increases by stringer pitch which results in the addition of a new stringer, which results in a sudden increase in the wing cost. Sensitivity analysis is useful in identifying the important design parameters as the computational expense for optimisation increases exponentially with the number of design parameters.

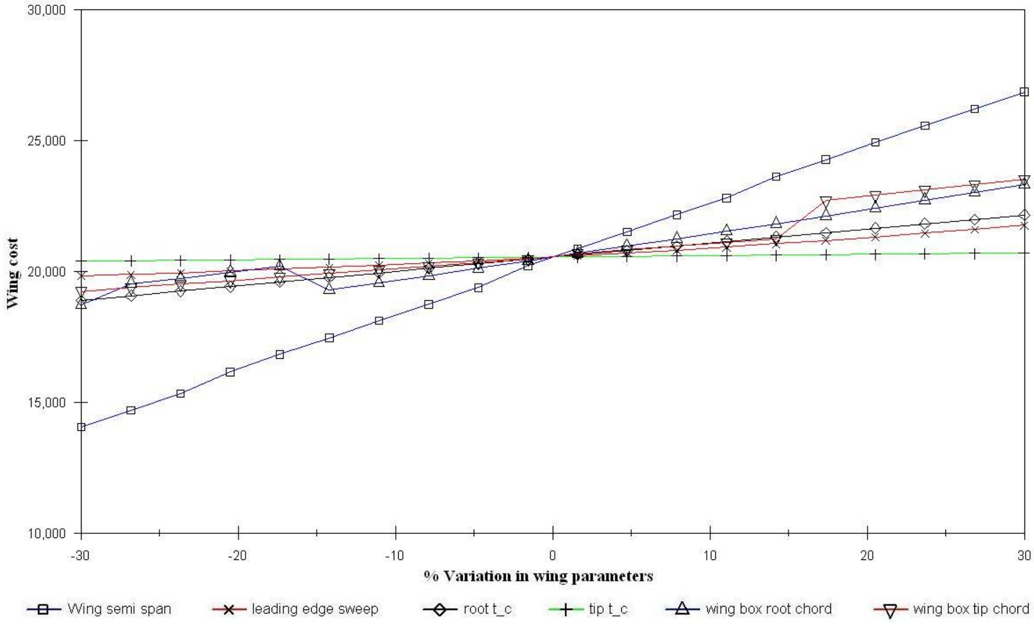


Figure 4.13: Wing cost sensitivity analysis

4.4.3 Uncertainty analysis

Sensitivity analysis helps identification of major cost drivers in the design parameters. However, uncertainty or variation in the costing data can also affect the aircraft acquisition cost. For example, the cost of aircraft structure depends upon the exact cost of raw material and any variation (or uncertainty) in the raw material cost will lead to a change in the overall aircraft cost. It is important to quantify this uncertainty in order to have confidence that the overall cost falls in a certain range of values or to estimate the probability of the cost being less than a given value.

Monte Carlo method is used for quantifying the effect of "costing data uncertainty" on the costs in the acquisition cost model. The uncertainty in the costing data is represented as probability distribuations and Monte Carlo sampling method generates random variables from these given probability distributions. It is to be noted that Monte Carlo sampling might leave large regions of the design space unexplored, especially for less number of sampling points. The acquisition cost model is evaluated for each sample point and this is repeated "n" times for a Monte Carlo simulation (where "n" is the number of observations), which produces n-values each representing a possible value for the products total cost.

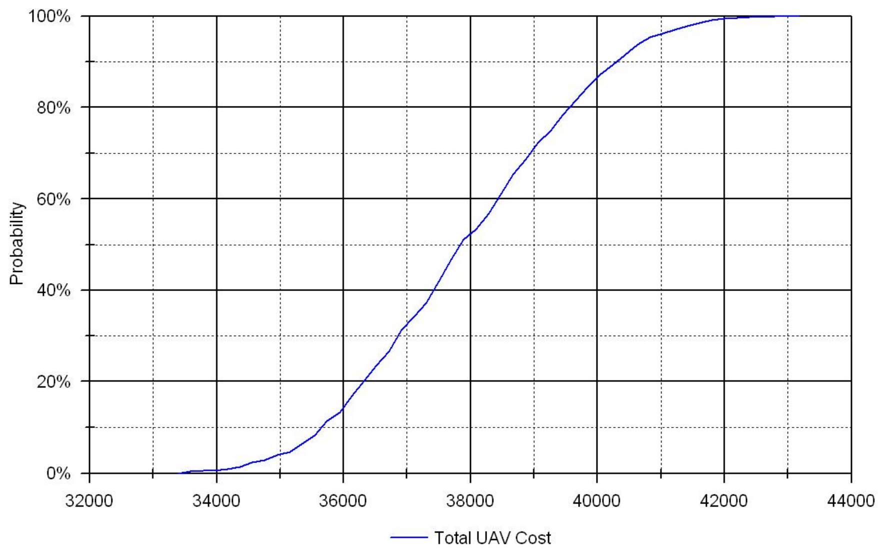


Figure 4.14: Cumulative probability distribution

The uncertainty in the raw material costing information was modelled as triangular distribution with +/- 10% variation from the initial value. Monte Carlo simulation is run 1000 times and every time the acquisition cost model is recalculated with a new number randomly selected from the triangular distribution. Monte Carlo simulations run on the model provided the mean value of the total cost at £37941.53 with a standard deviation of £1760.97. The cumulative probabilty distribution and probability frequency distribution are as shown in Figure 4.14 and Figure 4.15, respectively. The cumulative distribution function graph shows that it is 70% likely that the total cost will be less than £39000 and 95% likely that the total cost will be less than £42000. Also, if the frequency distribution approximated as a normal distribution which means that there is 95% probability that the cost will lie in the range £34419.59 to £41463.47 (two standard deviations of the mean) and there is 68% probability that the cost will lie in the range £36180.36 to £39702.50 (one standard deviation of the mean).

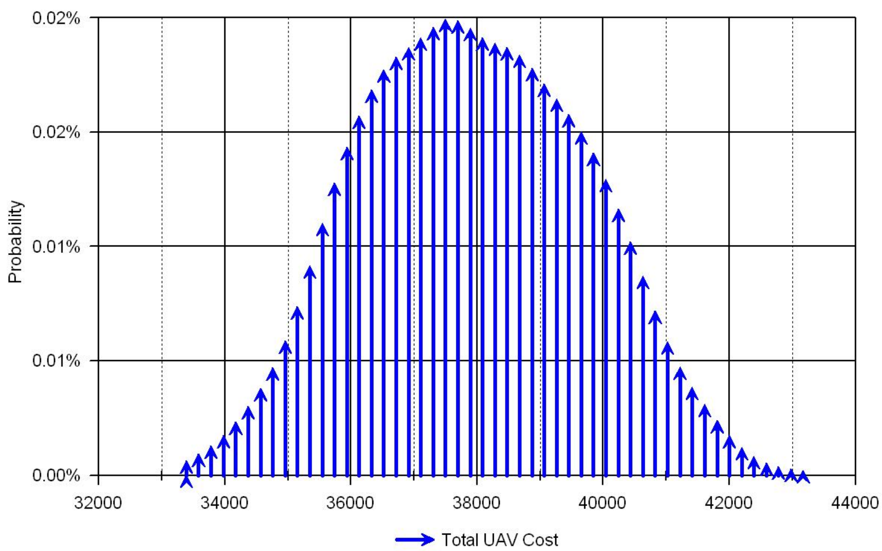


Figure 4.15: Probability density distribution

4.5 Summary

A cost model capable of calculating the acquisition costs from aircraft specifications is presented. The model improves on the shortcomings of the previous costing models and systems as follows:

- explicit product definition as input so that any changes to the design are reflected in the cost model
- hierarchical tree structure that reflects the actual physical structure of the aircraft to allow easy and intuitive navigation
- object oriented approach with libraries of materials and processes for easy integration into the cost model
- risk analysis along with visualisation of costs and their uncertainties

These characteristics make the acquisition cost model easily auditable and understood by the users/designers, which is important if cost modelling is to come into prominence within the engineering community. Also, the knowledge representation techniques utilised in the cost model allow optimal selection of materials or manufacturing processes based on cost. Finally, modelling uncertainty attached with design parameters and costing information in order to represent cost as distributions rather than discrete values enables decision making during conceptual design by recognition of most cost sensitive design parameters and understanding of the effects of uncertainties at different levels of abstraction in the cost model. Thus, the risk analysis methods incorporated into the generic hierarchical acquisition cost model with explicit product definition as input provides an elegant, flexible and comprehensive costing environment.

Life cycle cost includes acquisition costs as well as maintenance and repair costs. In order to estimate the operational costs, a simulation model is developed which is described in chapter 5.

Chapter 5

Simulation Model

In this chapter, the simulation model capable of estimating the operation and maintenance costs for a fleet of aircraft taking into account the aircraft implicit product definition, mission characteristics, and the logistics data is presented. The reasons for choosing the simulation package are outlined before explaining the developed model. The affect of aircraft performance on mission efficiency is explained before describing the process of evaluating aircraft performance using aerodynamic and performance analysis. The simulation model makes use of a modular approach which is explained in section 5.4. Then, the theory behind the simulation model is described in detail, with emphasis on mission scheduling and pre-flight inspection, mission and maintenance simulation along with description of a few modules selected from the simulation model. It is difficult to display the details of the whole model as the model is quite large; however, the portions of the model shown in this section convey the theoretical background of the model. Finally, a case study is presented and a short summary of the section is given.

5.1 Software selection

The characteristics that are identified as the requirements for the simulation model are

- Modularity: to indicate ease of maintenance of the model.
- Ease of deployment: to integrate with other software applications, especially DecisionPro acquisition cost model.
- Transparency: for ease of understanding.

The Extend Industry simulation package has been selected because it satisfies the requirements for this study and because of its flexible, open architecture which allows new objects to be developed and incorporated into the packages library easily for model building. The library objects provided as part of the Extend package are flexible enough to enable a large degree of customisation to be made without having to resort to developing new objects in its own programming language, MoDL.

5.2 Model overview

The model detailed here is a discrete-event simulation model which is capable of estimating the operation and maintenance costs of a fleet of aircraft, using the mission characteristics, implicit product definition and the logistics data as shown in Figure 5.1. The product definition includes the performance characteristics such as speed, manoeuvrability, mass, fuel burn rate and these are estimated from explicit product definition using physics-based models. The aircraft performance along with mission data affects the mission efficiency and the aircraft then need repair based on the level of damage sustained. The maintenance performed on the aircraft is subject to manpower and supply constraints, and this logistics data is also input into the simulation model. The simulation model estimates the fuel, repair and maintenance cost for each aircraft after every mission, based on the input data. These costs are then added to estimate the operation costs for the fleet of aircraft.

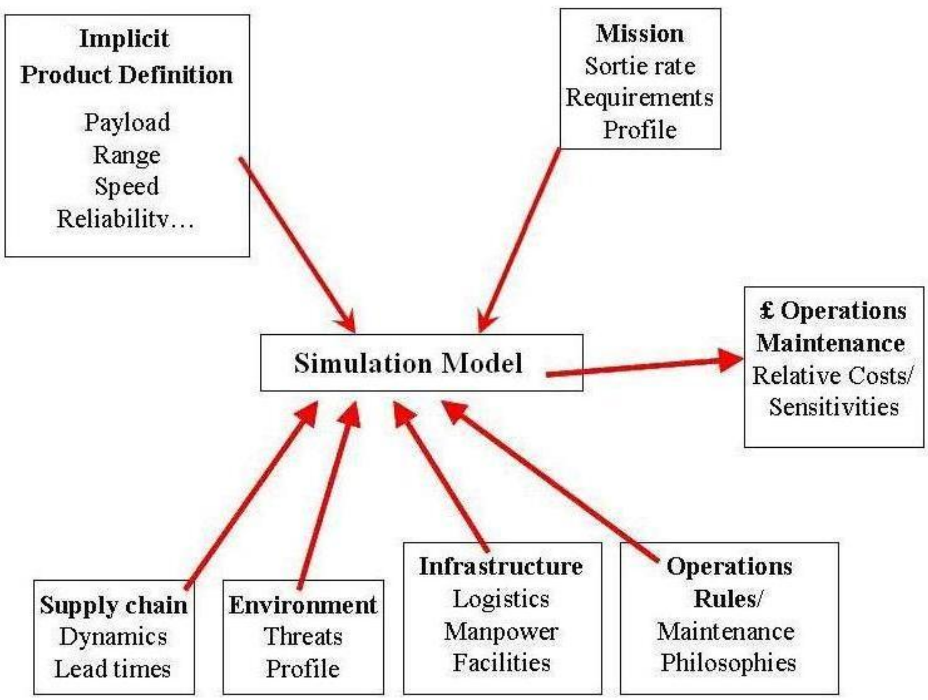


Figure 5.1: Simulation model overview

Implicit product definition includes design parameters whose affects on the cost are not easily identifiable, as below:

- Performance specifications (range, endurance, acceleration, turn radius, manoeuvrability, cruise and maximum speeds)

- Signature data (e.g. visibility, radar cross section etc)
- Critical component analysis (CCA) data

Implicit product definition design parameters are dependent on explicit product definition and the dependencies can be modelled using physics based models. A performance model has been developed to estimate aircraft performance from its explicit design parameters. Similarly, signature and FMECA data can be estimated using simple signature analysis and reliability analysis respectively.

Table 5.1: Combat missions and their classifications

MISSION	SPECIFIC MISSION EXAMPLES
Air Superiority	Air Attack, Air Supremacy
Interception	Air Defence
Interdiction	Attack pop-up or moving target, Counter Air
Close Air Support	Covert Re-supply, Close Air Support
Reconnaisance	Long Range or Covert Tactical Reconnaisance

Regarding the mission data, this research assumes that there is a limited range of mission and threat descriptions that can be performed. This is not an unrealistic assumption, given that each air base has a limited set of aircraft and a limited number of generic mission activities. The most common military missions can be classified into air superiority (AS), interception (air defence - AD), interdiction (ID), interdiction/strike (IDS), close air support (CAS) and reconnaissance [115]. A list of the most common missions along with their classification is given in Table 5.1.

5.3 Implicit product definition

This implicit product definition is presented in the context of aircraft performance specifications, concentrating on aerodynamic and performance analysis. Aerodynamic analysis is used to estimate the lift-drag polar from the aircraft geometry specifications. Performance analysis model uses standard flight dynamics equations along with the aerodynamic coefficients to estimate the aircraft performance parameters.

Table 5.2: Performance characteristics required for different missions

MISSION	REQUIRED CHARACTERISTICS
Air Superiority	Turning speed, Climb performance, Acceleration, Manoeuvrability
Air Defence	Climb performance, Acceleration, Maximum speed and Manoeuvrability
Interdiction	Maximum low altitude speed, Range and Manoeuvrability
Close Air Support	High Manoeuvrability, Low altitude flight, Range
Reconnaissance	Ceiling, Range and Endurance

An aircraft's performance can be measured using a variety of variables such as maximum speed, manoeuvrability, ceiling, range, etc and different performance variables are paramount at different times in the mission. Also, for maximum effectiveness, different performance parameters assume different orders of importance depending upon the mission data. However, aircraft performance can be broadly classified into manoeuvre performance, mission performance and field performance (take-off and landing). The main requirements of the aircraft for each of the missions mentioned in Table 5.1 are different, but the following Table 5.2 tries to capture the combat aircraft properties required for successful mission execution. In this study, the aircraft performance includes all the important performance parameters mentioned in Table 5.2 and the mission efficiency is estimated using the mission data along with the performance characteristics required for performing that particular mission.

5.3.1 Aerodynamic analysis

The aerodynamic parameters for the aircraft are calculated using the full potential (FP) method developed by QinetiQ and made available by ESDU International plc [116]. FP is an inviscid CFD (computational fluid dynamics) method that calculates the flow field and aerodynamic forces of three dimensional wing and wing-body combinations. It makes use of a relaxation process to solve finite-difference forms of the full nonlinear velocity-potential equation for the flow around the three-dimensional geometry. The FP package comprising of grid generator, flow solver and post processer, was developed and released by ESDU.

FP imposes a number of restrictions on the geometrical configurations. The wing is assumed to be symmetric while the fuselage is assumed to be axially symmetric about the aircraft centreline which runs along the length of the aircraft. Wing planforms can have straight or curved leading- and trailing-edges with slope discontinuities (kinks) and the wing geometry is specified by a number of span wise control sections while the fuselage geometry is specified by providing different cross-sectional radii along the length of the aircraft. Also, even though there are no precise restrictions, an FP run might be unsuccessful if the wing taper ratio is small or forward wing sweep is large and also if the (maximum) radius of the fuselage is too small or too large in relation to the wing chord.

FP generates the computational mesh using a conformal mapping scheme before computing the exact solution to the inviscid compressible three dimensional potential flow using finite-differencing scheme. The spanwise aerodynamic (lift and drag) coefficients are calculated by integrating the computed pressure coefficients at each wing section and the overall wing aerodynamic coefficients are calculated by integrating along the span. The fuselage contribution to the lift is obtained from the lift per unit span computed at the most inboard wing grid section and the body contribution to the drag coefficient is obtained from the fuselage lift estimate by assuming that the total aerodynamic force on the body (obtained by vector addition of the body lift and drag) acts at right angles to the fuselage axis. A correction factor based upon the ratio of maximum fuselage radius to wing span is used for estimating the fuselage contributions to the overall lift and drag coefficients. The analysis is completed when the lift and drag coefficients have achieved required degree of convergence. A multi-grid scheme is used to improve the convergence speed. The analysis starts off with a coarse grid of 7200 cells proceeding to a medium grid of 14400 cells and the finest grid (of upto 115200 cells) is employed in the final stage of computation. The overall process takes approximately 5 minutes on a single processor desktop.

FP is wrapped using several Matlab functions developed by Toal as it is not possible to run FP in batch mode [117]. Since automation is imperative for analysing a series of varying aircraft geometry, a series of Matlab functions were developed to construct the necessary input files for FP, run the FP post-processor and parse the output data. Also, another Matlab function is developed by to estimate the viscous drag coefficient as the FP package only provides the vortex and wave drag coefficients [118]. The function estimating the viscous drag includes a number of modifications to the simplified method provided by ESDU [119], [120].

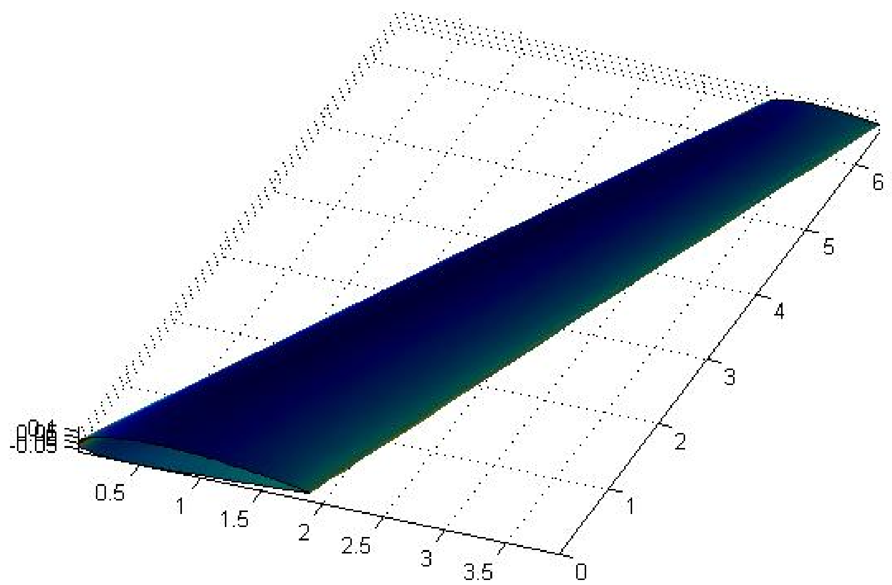


Figure 5.2: 3D wing pressure distribution

The FP wing geometry is defined by a number of control (aerofoil) sections, together with the types of interpolations to be employed between them while the fuselage has rotational symmetry and its geometry data is provided in pairs of coordinates of longitudinal position and body radius, and the type of interpolation to be employed between successive pairs. This data is extracted from aircraft geometry parameters such as wing span, root chord, tip chord, sweep angle, taper ratios and fuselage dimensions. Thus, the explicit aircraft product definition is used as the input geometry required for grid generation and aerodynamic analysis. An example case of aerodynamic analysis on wing-body at a mach number of 0.25 and at a 1° angle of attack is analysed. The wing has a span of 13m, root chord of 1.9m and a sweep of 25° while the fuselage has a radius of 1.3m which tapers of at nose/tail. The airfoils at root and tip are characterised by NACA 24xx foil, with "xx" being replaced by the percentage of thickness to chord ratio at root and tip, respectively. This aircraft is used for the simulation model case study described in section 5.8. The pressure distribution over the wing is shown in Figure 5.2. The fuselage pressure distribution is invisible as the fuselage aerodynamic coefficients are calculated using correction methods as explained earlier in the section. The lift and drag coefficients are estimated as 0.289 and 0.0117, respectively. These aerodynamic coefficients are used to estimate the performance of the aircraft using standard flight dynamics equations.

5.3.2 Performance analysis

The aircraft performance parameters are calculated by using performance analysis model. The performance analysis model uses standard flight dynamics equations, aircraft aerodynamic coefficients along with the standard atmospheric tables (to account for the mission altitude) to estimate aircraft performance. This performance data is utilised by the simulation model to evaluate the efficiency of the aircraft mission.

The aircraft performance parameters described for use in the simulation model are shown in Table 5.2. The aircraft's powerplant system is assumed to be turbojet and all the parameters are estimated using the corresponding flight dynamic equations. These equations are not detailed here as the standard flight dynamics equations can be found in aircraft design books such as Raymer et al [96], [121]. The weight of the aircraft is estimated using Raymer's parametric equations. The aircraft weight, geometry data, along with the aerodynamic coefficients are used to calculate the stalling speed, cruise speed and the maximum speed of the aircraft. A simple manual iterative process is utilised to achieve a compatible solution as the aerodynamic coefficients are dependent upon the aircraft mach number (or speed) and vice versa. The range and endurance of the aircraft can be estimated using the cruise data. Aircraft maneuvrability (climb rate, level and vertical turn radius) is estimated from specific excess power which is calculated using the drag data. A simple model estimating the stealth parameters such as radar cross section, visual and aural detectability from aircraft geometry is also implemented. This is achieved by assuming a linear relationship between the stealth parameters and the area of the aircraft estimated from the geometry parameters. It is noted that this assumption is not true, but the exact quantification of the relationships is beyond the scope of this work.

5.4 Model architecture

The structure of the discrete-event simulation model which is capable of estimating the operation and maintenance costs of a fleet of aircraft is shown in Figure 5.3.

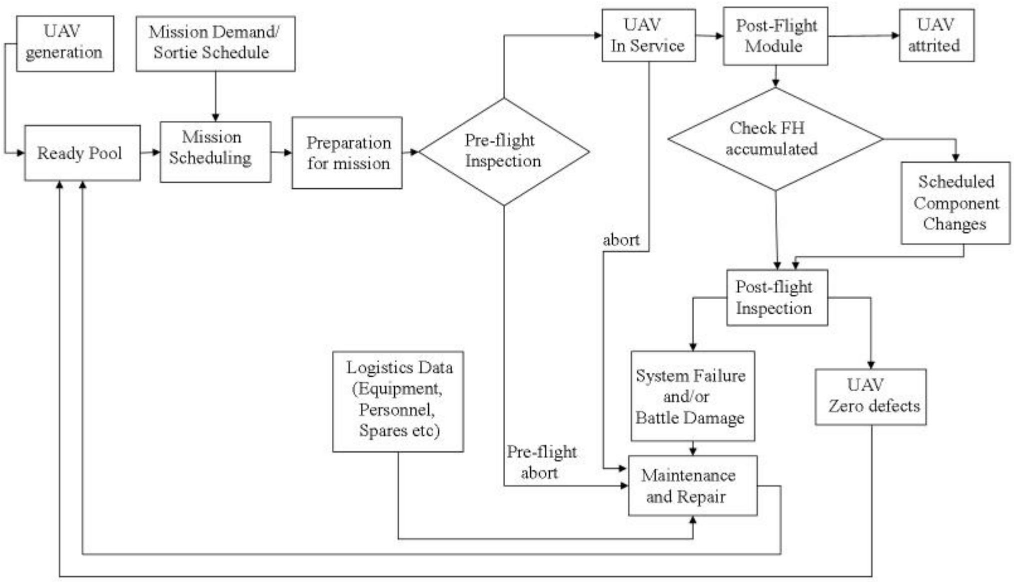


Figure 5.3: Simulation model architecture

The first step is the preparation of a flying schedule covering each aircraft over the time span to be simulated. The rate at which missions are called, the numbers of aircraft required, and the mission lengths can be generated from statistical distributions or as a pre-determined schedule. Aircraft are drawn from a ready pool, inspected, and launched on the mission. In the course of the mission, system failures are experienced and the aircraft receive combat damage. Aircraft are lost and missions are aborted according to specified probability functions. When missions are completed, aircraft are recovered and serviced. Required scheduled and unscheduled maintenance tasks are performed to return the aircraft to a ready status. The maintenance performed on the aircraft is subject to manpower and supply constraints, and aircraft wait for maintenance when resources are unavailable. Statistics are generated at the end of a simulation to evaluate the combat effectiveness of the aircraft under various sets of conditions.

The topmost level of the model, i.e. Level 0, is shown in Figure 5.4. The model's items start in the top-left corner of the page and they flow along the connectors, generally from left to right and top to bottom, which is a convention adopted by the Extend™modelling tool.

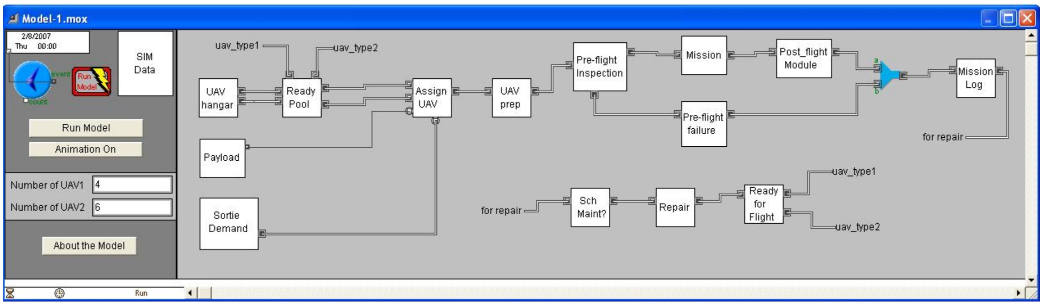


Figure 5.4: Simulation model

The data used for simulation, including the input and output, are stored in the form of global array managers in the module "Sim Data" as shown in Figure 5.5. In building of the model, it has been endeavoured not to hardcode numerical values but to enable such variables to be read in, wherever possible, from an external source like a plain ASCII text file, a spreadsheet, or a relational database. Flexibility in the model has been designed in so that the missions, number of aircraft, and the number of systems per aircraft can be adjusted readily. This data-based approach allows a combination of missions and aircraft to be constructed without having to modify the structure of the model. In this instance, all necessary items of data for the simulation model are imported from an external Microsoft access databases into their respective global array managers at the start of a simulation run in order to ensure speed and flexibility.

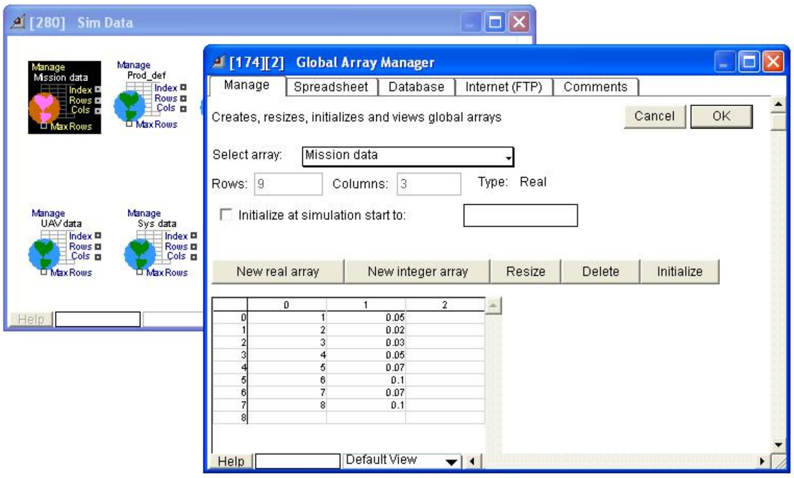


Figure 5.5: Simulation data

5.5 Mission scheduling and pre-flight inspection

Aircraft are drawn from a ready pool, inspected, and launched on the mission. In this model, only military missions are considered and they are limited to specific scenarios as mentioned in Table 5.1. Also, the air base is assumed to have two types of aircraft: combat aircraft with low aspect ratio for the closer to ground military missions and high altitude long range (HALE) aircraft for the reconnaissance missions. When a mission is called, the model checks the aircraft ready pool to determine if the required numbers of the suitable aircraft are available i.e. if it's a reconnaissance mission, the model checks to see if it has the required number of HALE aircraft and vice versa. If the minimum number of aircraft is not available, the model waits until the required aircraft become available.

The rate at which aircraft are assigned to missions is known as mission scheduling and mission scheduling details are included in "sortie_demand" module shown in Figure 5.4. Mission scheduling is represented in the simulation model as a

- Deterministic Advanced Schedule
- Stochastic Distribution

Deterministic advanced schedule contains different missions that need to be performed at different intervals, each mission requiring a specific number of aircraft for a specific duration. The schedule is determined in advance and it allocates a time for the take-off of the aircraft to perform a given mission. Stochastic Distribution generates the rate at which missions are called as a probability distribution. For example, a mission schedule can be based on a user-specified average time between missions and an exponential probability distribution. The mission lengths and the number of aircraft can also be specified as random distributions.

The rate at which missions are called, the numbers of aircraft required, and the mission lengths specified as a pre-determined schedule is shown in Figure 5.6. This predetermined schedule is used for the case study explained in section 5.8 and it can be repeated once the specified time (168 hours) is completed.

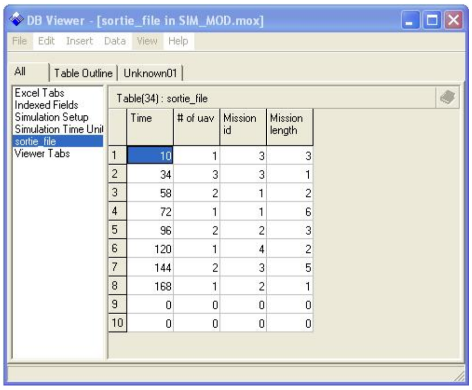


Figure 5.6: Sortie demand

The preparation phase for the aircraft, as shown in "UAV prep" module of Figure 5.7, includes the loading of applicable equipment, ground crew pre-flight inspection, and accomplishment of those maintenance tasks discovered in the preparation routine. Aircraft are then launched and flown on their specified missions, when all of the required aircraft have successfully completed the pre-flight check.

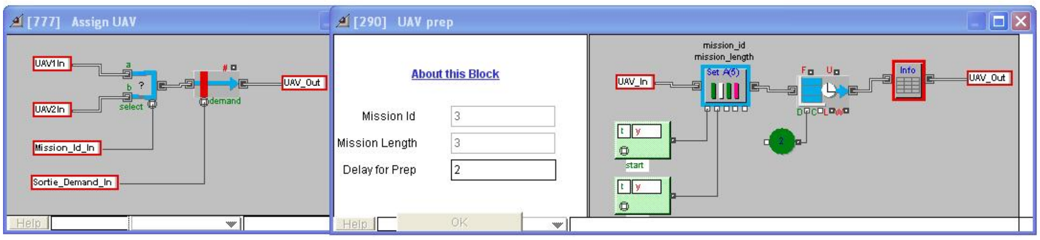


Figure 5.7: Pre-flight preparation

5.6 Mission simulation

Aircraft may experience system failures and combat damage in the course of the mission. The systems can fail due to battle damage or unreliability or both and aircraft can be lost depending upon the level of failure. Survivability and reliability analysis are performed in the simulation model to determine the systems that experienced battle damage or reliability failure, respectively. The mission outcome then depends upon the ability of the aircraft to withstand both the damage mechanisms and system failures.

5.6.1 Survivability analysis

This section details the basics of aircraft combat survivability and the techniques that are used in the simulation model to assess the battle damage. The capability of an aircraft to avoid or withstand hostile environments, including both man-made and naturally occurring environments is known as aircraft survivability [122], [123]. The more specific term aircraft combat survivability refers to the capability of an aircraft to avoid or withstand a man-made hostile environment. It can be measured by the probability the aircraft survives an encounter (combat) with the environment. The inability of an aircraft to "avoid" the man-made hostile mission environment (guns, approaching missiles, exploding warheads, air interceptors, radars, and all of the other elements of an enemy's air defence) is measured by P_H, the probability the aircraft is hit by a damage causing mechanism, and is referred to as the susceptibility of the aircraft. The inability of an aircraft to "withstand" the damage caused by the hostile environment is referred to as the vulnerability of the aircraft to the damage mechanisms. Vulnerability can be measured by the conditional probability the aircraft is killed given that it is hit, $P_{K|H}$. The ease with which an aircraft is killed in a hostile environment is measured by the probability the aircraft is killed, P_K. The probability of kill of the aircraft is given by the joint probability the aircraft is hit and it is killed given the hit i.e. the product of the probability of hit (the susceptibility) P_H and the conditional probability of kill given a hit (the vulnerability) $P_{K|H}$. Thus,

$$Probability\ of\ Kill = Susceptibility * Vulnerability$$

Or

$$P_K = P_H * P_{K|H} \tag{5.1}$$

Similarly, the probability of a system kill given a hit on the aircraft is known as system kill probability ($P_{k|H_i}$). The kill probability of an ith system given a random hit on the aircraft $P_{k|H_i}$, is the product of the probability that the system is hit (given the hit on the aircraft) $P_{h|H_i}$ and the probability the system is killed given a hit on the system $P_{k|h_i}$. Thus,

$$P_{k|H_i} = P_{h|H_i} * P_{k|h_i} \tag{5.2}$$

During the mission simulation, the capability of the aircraft or the systems to survive the hostile environment is measured by these probabilities. These probabilities are dependent upon the aircraft performance, survivability equipment and weapons carried by the aircraft, tactics implemented during the mission and the threat scenario. The susceptibility and vulnerability probabilities have to be assessed for a given aircraft in the mission-threat scenario to determine the probability of survival of the aircraft in that selected scenario.

In the simulation model the survivability probabilities are estimated using historical data and survivability analysis software, both of which are adequate for singular analysis, i.e. survival probability estimation for a given aircraft. However, a novel hybrid approach is developed combining both these approaches for optimisation studies (where evaluations of survivability probabilities for a sequence of aircraft with varying designs is required).

Historical data

Historical Data method involves making use of pre-determined probability data. The probability data it is usually gathered from the available literature and/or expert knowledge. However, such data would be only valid for a particular kind of aircraft and a given mission. The battle damage rate for each mission is simulated from the specified range. The aircraft failed due to battle damage are obtained by comparing a uniformly generated random number u_1 with the susceptibility (P_H) obtained for that mission.

$$u_1 < P_H \Rightarrow \textit{Battle damage has occured} \tag{5.3}$$

The system(s) to which the battle damage has occurred is found using the battle damage probabilities for the different systems. A uniform random number u_2 is simulated and compared with the probabilities that the system is hit given a hit on the aircraft ($P_{h|H_i}$).

$$u_2 < P_{h|H_i} \Rightarrow i^{th} \textit{ system is damaged} \tag{5.4}$$

Similarly, each battle-damaged subsystem is further classified as critical, major, or minor. This is done by comparing random number u_3 with the probability of the kill of the subsystems ($P_{k|H_i}$).

$$u_3 < P_{k|H_i} \Rightarrow \textit{the damage is critical} \tag{5.5}$$

Otherwise, the system is said to be suffering from either major or minor damage and this is dependent upon their respective probabilities.

Survivability analysis tool

The pre-determined battle damage probability data would be only valid for a particular kind of aircraft and a given mission. The data needs to be adapted for other aircraft and missions that are being considered in the simulation model. An alternate solution would be the utilization of survivability analysis software, such as AGILE (Analytic Gaussian Intersection for Lethality Engagement). AGILE is a computer lethality prediction tool or more specifically, it calculates the aircraft kill probability (P_K) and the individual systems kill probabilities($P_{k|H_i}$) given the threat and vulnerability data [124].

AGILE makes use of Gaussian functions to perform the analysis and the level of modelling detail can be controlled by choosing an appropriate number of Gaussian components to represent the data. Gaussian components are used because their intersections can be computed very efficiently using an analytical formula (hence the acronym Analytic Gaussian Intersection for Lethality Engagement) and uncertainty in the endgame geometry can be represented directly by Gaussian components, reducing or avoiding the need for Monte-Carlo methods. The aircraft vulnerability, threat lethality density and the aircraft shape are all represented using sums of Gaussian functions as shown in Figure 5.8. The figure shows the fragment damage on the aircraft utilised in the case study in section 5.8. The tool includes different component models (i.e. fragment damage model, fuzing model, close burst model and direct impact model) and these component models can be deactivated if they are not relevant for the given mission threat scenario. Uncertainty in either the endgame trajectory or target/missile configurations can also be modelled.

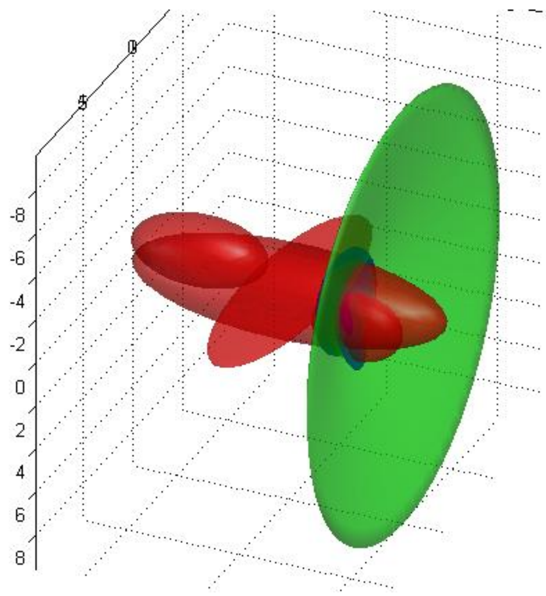


Figure 5.8: AGILE survivability analysis tool [124]

Novel hybrid approach for survivability estimation

For a given mission scenario, the pre-determined battle damage probability data is limited to a particular aircraft design and that data is not relevant for another aircraft design. For other aircraft that are being considered in the simulation model, the data needs to be adapted and this is difficult as the data is based on literature/expert knowledge. On the other hand, a survivability analysis software such as AGILE can be used to estimate the kill probabilities for any given aircraft design but they are not convenient for iterative use such as optimisation studies. A hybrid method is proposed which utilises principles of both methods to estimate survivability in an efficient manner.

An aircraft design is chosen as a baseline configuration for the simulation model. The survivability probabilities for this aircraft are calculated by using survivability analysis software. This survivability data can be adapted to estimate the aircraft hit probabilities for other similar aircraft designs. This is achieved by comparing the aircraft's performance against that of the baseline aircraft's performance. For example, if the aircraft is faster than the baseline aircraft, its hit probability would be lower. These relationships are quantified by plotting the change of hit probability with different performance parameters (using survivability analysis software) and fitting a function through the plots. The probability of getting hit for any aircraft can be identified using this approach. However, the battle damage probabilities for the individual aircraft systems are assumed to be same as that of the corresponding baseline aircraft systems. This is not strictly true as the probability of each system getting hit is dependent on the design of the aircraft, but the precise quantification is out of the scope of this work. The system battle damage probabilities (of the baseline aircraft) are also classified into critical, major, and minor according to the level of damage. Thus, a novel hybrid approach is utilised to estimate aircraft combat survivability in the simulation model.

5.6.2 Reliability analysis

This section details the basics of reliability engineering and the techniques that are used in the simulation model to assess the system failure rate. According to Kapur & Lamberson [125], reliability is the probability that an item will perform a required function without failure under stated conditions for a stated period of time. The system failures that occur during the course of a mission for an aircraft are related to their reliability measures. A reliability analysis is the analysis of systems and sub-systems in an effort to predict the rate at which an item fails. Hence, in order to predict the systems that fail during the course of a mission, reliability analysis is required. As there is no precise way to determine when exactly a failure occurs, fundamental definitions of reliability analysis depends largely on concepts from probability theory. Reliability function, expected life, hazard function and failure rate provide the basis for quantifying the reliability of a system and these concepts are detailed here.

The reliability function, $R(t)$, is the probability that a system does not fail in the time interval $(0, t)$. The reliability function can also be represented as

$$R(t) = 1 - F(t), \tag{5.6}$$

where $F(t)$ is the probability that the system will fail by time t. If the time to failure, T, has a probability density function $f(t)$, then

$$R(t) = 1 - \int_0^t f(t)\mathrm{d}t, \tag{5.7}$$

The expected life, or the expected time during which a system will perform successfully, is defined as

$$E(t) = \int_0^\infty f(t)t\mathrm{d}t = \int_0^\infty f(t)R(t)\mathrm{d}t, \qquad (5.8)$$

Since, the systems of the aircraft are renewed through maintenance and repair, expected life, $E(t)$, is also known as the mean time between failures (MTBF) or mean time to failure (MTTF).

The reliability measures are usually estimated using historical data or reliability analysis software. The historical data method is used in the simulation model due to the complexity of reliability analysis software. The historical data method involves making use of pre-determined reliability data. The data is based on the available literature and/or expert knowledge. But such data, again, would be only valid for a particular kind of aircraft and a given mission. The unreliability of each system is obtained using the time between scheduled maintenance operations as the value of the time in the unreliability expression. The time value (t) is incremented each time by the sortie duration once the sortie is completed. A uniform number u_4 is simulated and compared with the unreliability values of each subsystem. If u_4 is less than the value of unreliability, then it is considered to have failed. Similarly all the other systems failed due to unreliability are noted.

5.6.3 Mission outcome

Mission outcome is dependent upon the ability of the aircraft to withstand battle damage and system unreliability. This is the study of identification of critical components and their damage-caused failure modes. This procedure consists of selection of aircraft kill level, gathering the description of aircraft, and determination of the critical components of aircraft and their damage-caused failure modes for the selected kill levels.

Aircraft kill levels include several categories of aircraft kill that measure the degree to which the aircraft suffers performance degradation. The categories generally used are attrition kill and mission abort kill. Attrition kill is a measure of the degree of aircraft damage that it is incapable or economically infeasible of being repaired, so that it is lost from the inventory. A mission abort kill is the measure of degree of aircraft damage that prevents the aircraft from completing its designated mission, but is not sufficient to cause a loss of the aircraft to the inventory. In the simulation model, attrition kill is considered as an aircraft kill.

The components whose damage or loss could lead to an aircraft kill are referred to as critical components and the identification process is known as critical component analysis (CCA). CCA identifies the essential systems that the aircraft must preserve to continue its flight and if the combination of systems that suffered critical damage (due to combat damage and/or reliability failure) corresponds to the classified critical subsystems according to the CCA analysis, then that particular aircraft is considered to have attrited and is subtracted from the total available aircraft. It should be noted that, in the simulation model, there is no provision to abort the mission irrespective of the level of failure or damage . Mission abort kill critical component analysis could be used to determine the effect of non-critical damage on the individual aircraft i.e. whether the damage is mission aborting. However, this is beyond the scope of this work and not implemented in the simulation model.

5.6.4 Simulating mission outcome

In the course of the mission, system failures are experienced and the aircraft receive combat damage, as shown in Figure 5.9. Survivability and reliability analysis are performed to determine the systems that fail due to battle damage and/or unreliability.

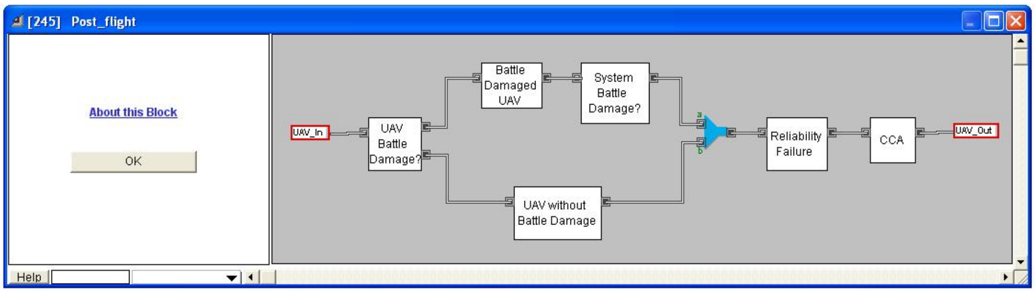


Figure 5.9: Survivability and reliability analysis

The probability of battle damage for the aircraft during different missions is obtained by comparing the aircraft's performance against that of the baseline aircraft's performance, whose battle damage probability is estimated (before the simulation model run) using a lethality prediction tool, AGILE. This battle damage probability is compared against a random number to determine whether the aircraft encounters battle damage, as shown in Figure 5.10.

The battle damage probabilities for the individual aircraft systems are modeled using discrete probability distributions, which are dependent on the design of the aircraft. The system battle damage probabilities are also

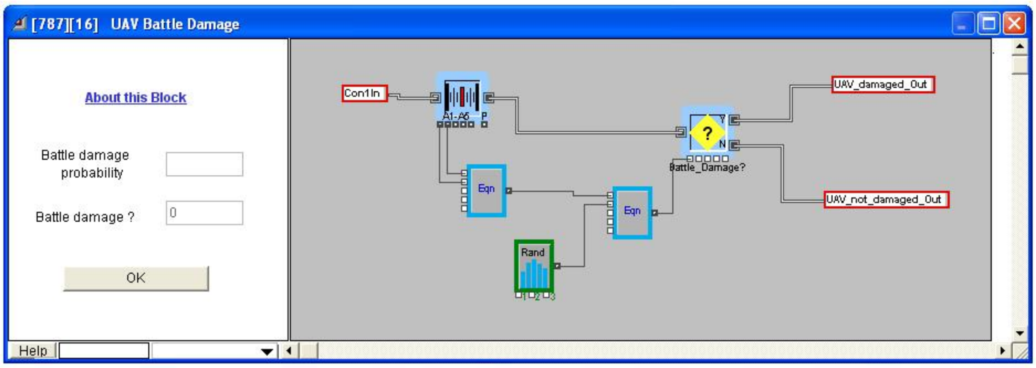


Figure 5.10: Aircraft battle damage

classified into critical, major, and minor according to the level of damage and again these system damage probabilities are compared against a random number to determine the level of damage. These rules are implemented in an Extend™ "DE Equation" standard library block using ModL, the Extend™ proprietary scripting language, as shown in Figure 5.11.

The systems that failed are identified by using reliability analysis expressions in the "Reliability Failure" module and critical component analysis is performed to determine the aircraft that are attrited. All events that occurred during the mission are logged.

5.7 Maintenance simulation

Aircraft follow a maintenance sequence that is determined by the system type and maintenance needs. There are two major types of maintenance, scheduled (preventive) and unscheduled (corrective), Scheduled maintenance is performed after pre-determined number of flight hours are accumulated and unscheduled maintenance is performed in the case of an aircraft malfunction.

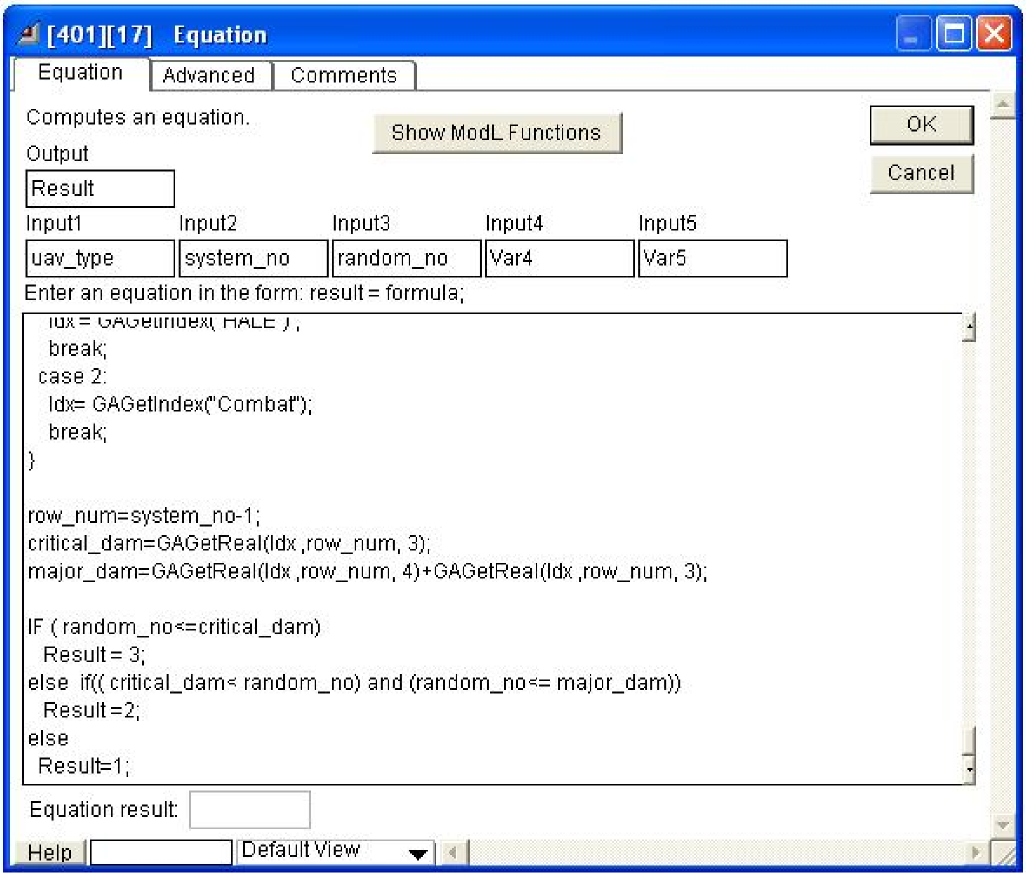


Figure 5.11: Code to determine the level of battle damage

When missions are completed, aircraft are recovered and a post flight inspection of the aircraft is performed i.e. the aircraft is inspected to determine the level of maintenance needed. Firstly, the aircraft is checked for the amount of flying time i.e. number of hours it clocked up. If this reaches a pre-defined level of use (flying hours) specified by the vendor, or according to the maintenance organization policies, it undergoes preventive maintenance. If the aircraft does not require scheduled maintenance, the aircraft is disassembled and inspected for any system failures to determine the level of repair needed for each system. For some systems, a simple repair (R) would be in order while for others, a total overhaul (OV) would be necessary to bring the system up to the desired quality level. Some systems would be evaluated and labeled as NCFR, or no cause for repair. Finally, the systems which are critically damaged need to be replaced. The systems are tested before being assembled into aircraft and the aircraft then return to service.

The level of repair necessary is directly linked to the events that happened during the mission. The state of the aircraft at the end of each mission is checked i.e., the aircraft systems are examined to see whether there is a failure due to battle damage or unreliability or both. The level of damage, both battle damage and system failure, for each system is classified as critical, major, or minor. If the damage is found critical, then that particular system is considered beyond repair and it has to be replaced. If the damage is major, then a total overhaul of the system is necessary while a minor damage would only need a simple repair. Both system replacement and overhaul are done at the depot level (OV) while simple repair is performed at the field level (R) i.e. systems whose damage is critical or major are repaired at depot level while minor classified system repair is performed at field level. Additionally, system failures and anomalies are discovered during pre-flight inspections as well. The aircraft that suffered the damage, again, require maintenance and repair based upon the level of failure.

The repair work in the field and depots require logistic support, i.e., personnel, equipment, and spares are required to accomplish the maintenance tasks. These logistic factors also result in the repair costs. The total maintenance cost is calculated as the sums of the individual costs, which are outlined below:

- total labor cost,
- the cost of unscheduled repairs, i.e. spares and equipment cost
- the scheduled-maintenance cost i.e. replenishables cost, and
- the new systems cost

However, the depreciation costs and the costs of holding the inventory (for spares and new systems) are not included.

5.7.1 Simulating maintenance and repair

In the simulation model, a thorough inspection of the aircraft is performed before they are assigned to a mission. If any failures are noted during this pre-flight inspection, the aircraft are sent to the corresponding maintenance facility depending upon the degree of failure. Also, all the aircraft enter the maintenance facility at the completion of a mission. When missions are completed, a post flight inspection of the aircraft is performed and required scheduled and unscheduled maintenance tasks are performed to return the aircraft to a ready status. All aircraft are inspected to determine the exact level of maintenance needed, as shown in Figure 5.12. In the event of repair aircraft are disassembled and necessary repair is performed. The personnel, equipment, spares and the time required to accomplish the tasks are defined and placed in the model logistics data bank and the maintenance and repair costs are estimated using the resources expended for the repair.

The first step in the “Repair” module is to identify the systems that suffered reliability failure or battle damage or both. This is performed using

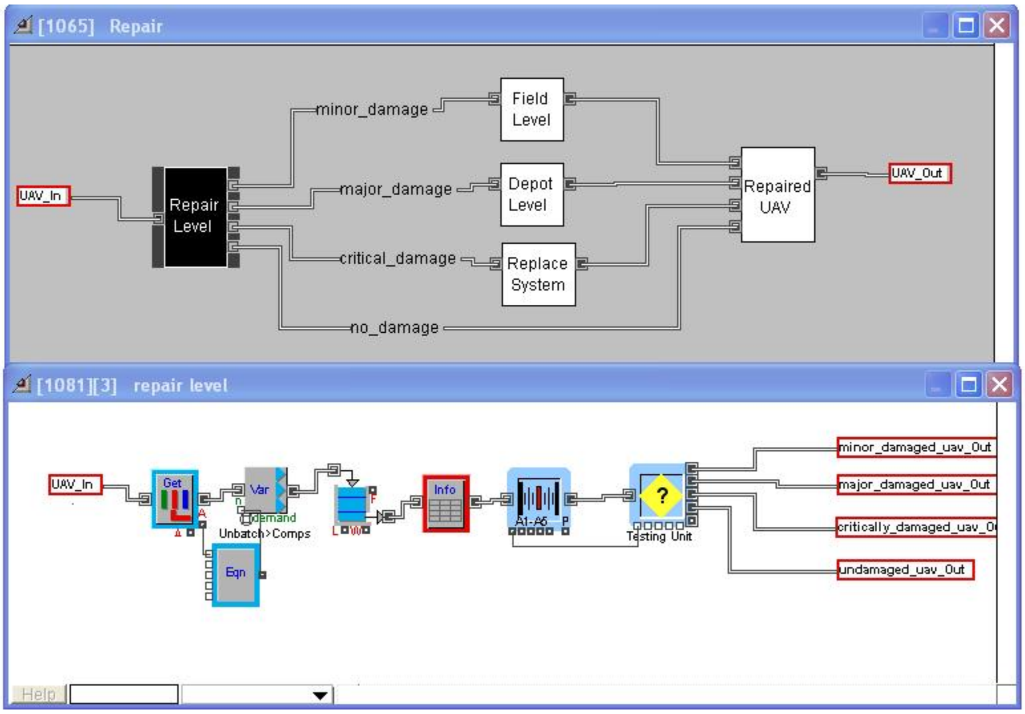


Figure 5.12: Aircraft repair

the data logged during the mission simulation. The level of damage is also ascertained from the mission log i.e. whether the failure is critical, major or minor. If the system suffers from reliability failure or combat damage alone, then the level of failure is the level of the corresponding reliability failure or combat damage. The thing to note here is that if the system suffers both, the level of damage is the cumulative affect of both system failure and battle damage (as in real situations). Hence, if a system suffers from both a minor system failure and a minor combat damage, the overall affect is that the system suffers a major level damage. This is a conservative approach which utilises the cumulative effect of the battle damage and system failure [67]. Similarly, if the system suffers from both a minor system failure and a major combat damage (or vice versa), then the level of damage is critical and the system has to be replaced. If the damage is found critical, then that particular system is considered beyond repair and it has to be replaced. If the damage is major, then a total overhaul of the system is necessary while a minor damage would only need a simple repair. Both system replacement and overhaul are done at the depot level while simple repair is performed at the field level i.e. systems whose damage is critical or major are repaired at depot level while minor classified system repair is performed at field level. The maintenance and repair costs are estimated using the resources expended for the repair. The resources include the labour costs, spares cost and the cost of new systems, in case of system replacements.

The aircraft are maintained in order of arrival, i.e., no prioritization of jobs is considered in the model. If the technicians or the required spares are unavailable, the aircraft is put in a wait queue till they become available. But, in the simulation model, infinite capacity is assumed i.e. there is always abundant supply of personnel and spares. Thus, the repair costs are calculated by estimating the resources required to perform the necessary maintenance and repair. The repair costs are logged against the corresponding system and the cumulative costs for the whole aircraft are also noted.

5.8 Case Study

The aircraft in this case study is a high-altitude long endurance aircraft and thus only long range reconnaisance, covert tactical reconnaisance, covert re-supply and air defence missions are considered. Aerodynamic analysis is performed on the aircraft and the estimated aerodynamic coefficients are utilised in Raymer's parametric equations to evaluate aircraft performance [96]. The case study uses pre-determined mission schedule, previously shown in Figure 5.6, which is repeated every week i.e. every 168 hours. Each mission requires a specific number of aircraft and for a specific duration as seen in "# of uav" and "Mission length" columns, respectively. Each of the four missions mentioned earlier are associated with a different and unique mission id. Aircraft are launched and flown on their specified missions according to this schedule during which they may experience system failures and combat damage. All the simulation parameters are same as those that of metal based aircraft described in the case study in section 6.2

The simulation is run initially for a period of 30 days ($\tilde{7}$00 hours) to identify the number of aircraft that will ensure that all the missions are achieved. It is to be noted that infinite capacity is assumed for repair i.e. there is always abundant supply of personnel and spares. Even though there are no queues for repair, the inspection and repair process is time consuming which might lead to delays in aircraft returning to mission-ready status. If the required number of aircraft are not available when a mission is called, the simulation model waits until they become available. Figure 5.13 shows the mission delay times for a fleet of 8 and 9 aircraft, respectively. It is observed that until half way through the simulation time period all the missions are performed on time. However, as time progressed aircraft needed to be serviced for battle damage and system failure which resulted in delay of the return of aircraft to ready status. This meant that back-logs occured for some missions and the wait time is shown in Figure 5.13. The fleet of 8 aircraft could not cope with the mission demand and as a result three missions had to be cancelled due to lack of aircraft. The fleet of 9 aircraft performs better and results in less number of mission delays but two missions still had to be cancelled due to lack of aircraft.

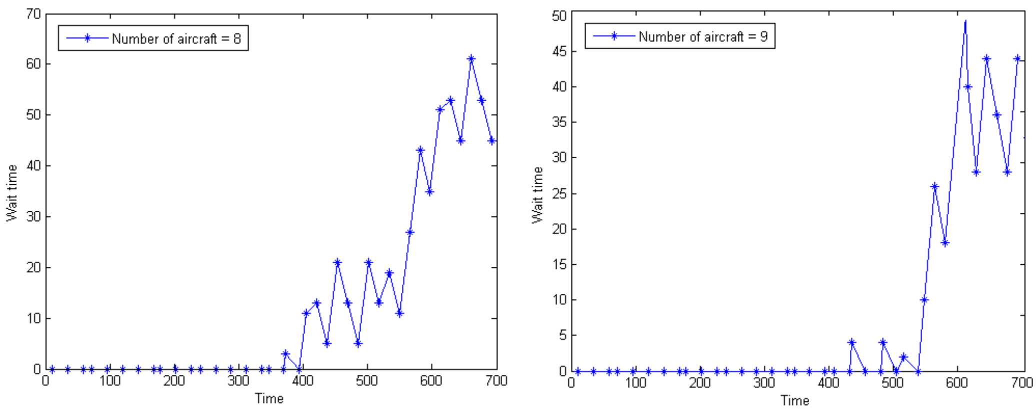


Figure 5.13: Mission delay times for fleet of 8 and 9 aircraft

The simulation model is run again with fleet of 10 and 11 aircraft, respectively. The results are shown in Figure 5.14. Again, it is observed that fleet of 10 aircraft resulted in significantly lower number of mission delays but one mission still had to be cancelled. The fleet of 11 aircraft managed to successfully complete all the missions with minor mission delays. Thus, the simulation model can be utilised to identify the capacity required to complete a mission schedule in an efficient manner.

The aircraft that suffer battle damage and system failures are identified by performing survivability and reliability analysis, respectively. The maintenance and repair costs are estimated using the resources expended for the repair. The results of the simulation model are described in detail in section 6.2. However, the sensitivity of the repair costs due to battle damage alone with respect to the battle damage probability is evaluated. It is as-

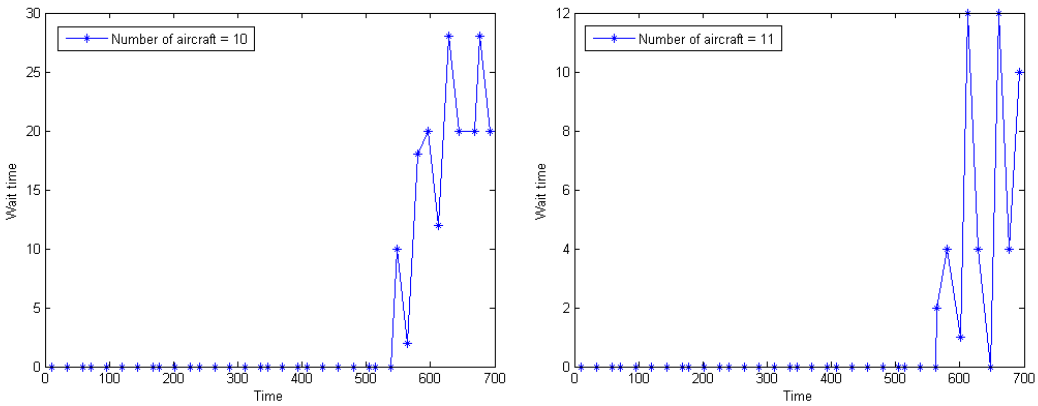


Figure 5.14: Mission delay times for fleet of 10 and 11 aircraft

sumed that the battle damage probability for all four missions is 0.05 and the probabilities are incremented by value of 0.05 until they reach the value of 0.145. The variation of repair costs with this variation in battle damage probability is shown in Figure 5.15. This study is repeated five times to include the effects of random variables in the simulation model. It is observed that the repair cost varies almost linearly with battle damage probabilities which is in line with the theoretical basement of survivability analysis using historical data.

5.9 Summary

A discrete-event simulation model capable of estimating the operation and maintenance costs of a fleet of aircraft is described. The model structure is presented before describing the individual parts of the simulation model. The model developed in Extend™ improves on the shortcomings of the previous costing models and systems by incorporating a novel method to link aircraft performance with survivability analysis. The aircraft performance parame-

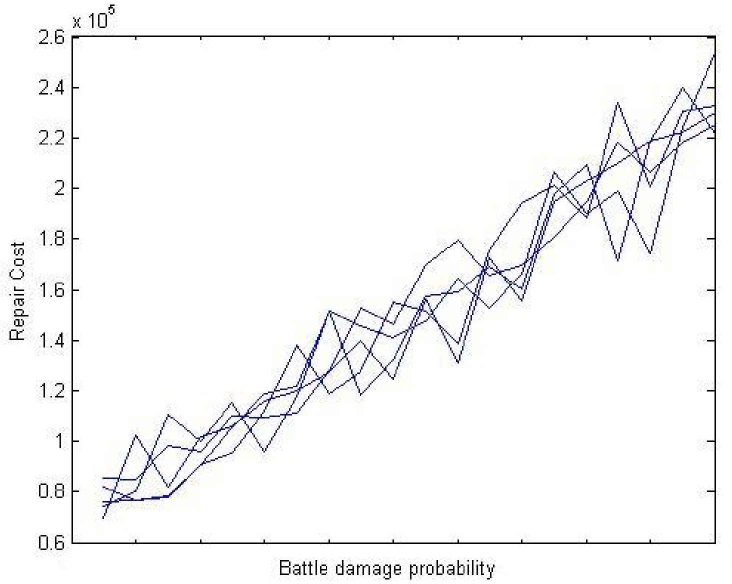


Figure 5.15: Repair cost vs battle damage probability

ters are calculated by using aerodynamic analysis along with performance analysis models and a novel hybrid approach to estimate survivability in an efficient manner is presented. The simulation model estimates the maintenance costs of a fleet of aircraft using the mission characteristics, implicit product definition and the logistics data as input. Thus, any changes in the design are reflected in the simulation model. The model's modular approach allow easy and intuitive navigation which provides an elegant, flexible and comprehensive costing environment.

The simulation model along with the acquisition cost model forms the basis for the LCC framework. The LCC framework is described and three case studies are presented in chapter 6.

Chapter 6

Design support tool

A framework capable of calculating the whole life cycle cost given the mission requirements and the aircraft product definition is detailed. This life cycle cost framework is then used as a design support tool and three different studies are provided in this chapter. The studies include trade-off analysis, cost based design optimisation and real time cost estimation using secure dynamic web services.

6.1 Life cycle cost framework implementation

A framework capable of calculating the whole life cycle cost given the mission requirements and the aircraft product definition is as shown previously in Figure 3.2. In order to realistically model the LCC estimation framework, it is necessary to build sufficient complexity into the system to illustrate the methodology. However, to keep the project manageable, limits are imposed on the scope of the problem. In this study, LCC includes only the acquisition and operational costs. The disposal costs and design development costs are not included as it is out of the scope of this work. A knowledge base has been to set up to include some representative aircraft components, manufacturing processes and materials, with a hierarchical model which extracts the relevant information from the database to estimate acquisition costs. Similarly, a simulation model extracts information from a database containing aircraft product definition, mission characteristics, repair and logistics data to estimate the operational costs. This data is modeled as closely as possible on the information from literature and aerospace companies, notwithstanding their reluctance to release this information to outsiders. The limitations on the scope of the study are:

a. Acquisition cost estimation

- **Aircraft configuration**

  The aircraft configuration is limited to conventional aircraft, delta wing and blended body wing configurations (i.e. rotorcrafts, biplanes or other unusual configurations are not considered).

- **Internal structure**

  The aircraft structure is populated/dimensionalised using the structural spacing data input. It should be noted that sparse or dense internal structure might lead to structurally unsound aircraft.

- **Tooling/Assembly costs**

  It should be noted that assembly and tooling costs are not included in the acquisition cost model.

- **Manufacturing database**

As a starting point for the methodology, it is assumed that process details and bill of materials are available in database format at the company, and in sufficient detail to link to the hierarchical model (Chapter 4) for cost estimation.

- **Limited number of products and processes**

  This research assumes that there is a limited portfolio of aircraft structural descriptions, material descriptions and activity descriptions in the manufacturing knowledge base. This is not an unrealistic assumption, given that each company has a limited set of production resources, and a limited number of generic processing activities.

- **Scope**

  A predefined manufacturing process sequence to manufacture the key structural parts (which are limited to those mentioned in the internal structural representation) is specified. Thus, it is not conducive to estimate the cost of radically new designs or cost comparison between different manufacturing approaches.

b. Operational cost estimation

- **Aircraft configuration**

  The scope of the simulation model is limited to a few kinds of aircraft in operation over a period of time. In this study, they are broadly classified into HALE and Combat aircraft.

- **Specified missions**

  This research assumes that there is a limited range of mission and threat descriptions that can be performed. This is not an unrealistic assumption, given that each air base has a limited set of aircraft and a limited number of generic mission activities.

- **Simulation database**

  It is assumed that product details, mission and threat scenarios are available in database format at the company, and in sufficient detail to link to the simulation model for cost estimation.

- **Survivability analysis**

  It is assumed that battle damage probability of an aircraft can be estimated by comparing its performance against that of a baseline aircraft. However, the battle damage probabilities for the individual aircraft systems are assumed to be same as that of the corresponding baseline aircraft systems.

- **Cumulative damage**

  If an aircraft system suffers both battle damage and system failure, the level of damage is the cumulative affect of both system failure and battle damage (as in real situations).

- **Maintenance philosophy**

  The aircraft are maintained in order of arrival, i.e., no prioritization of jobs is considered in the model. Also, infinite capacity is assumed i.e. there is always abundant supply of personnel and spares to perform the repair.

6.2 Case study: composites v metals

This is a classic case of cost vs. performance trade off study. It is widely believed that composite materials are better than aluminium based alloys for structural components of aircraft, but they are more expensive to acquire and manufacture. But this does not give an accurate picture as the operation costs are not taken into account. Thus, a life cycle cost comparison between a fleet of metal-based UAVs and a same-sized fleet of non-metal based UAVs is performed, with both the UAVs having identical geometry characteristics.

The UAV configuration chosen for this study is a surveillance/reconnaissance aircraft and it has a wing span of 15m, length of 9m, and height of 2m. A fleet size of 10 is chosen, but the fleet size can also be varied to examine whether metal-based or non-metal-based achieved better LCC per UAV. Both the UAVs have identical geometry and the propulsion system is also assumed to be same; the study here is to identify the better material choice over the whole life cycle between metal-based and composite UAVs with the same explicit product definition (except for the UAV structural material).

The acquisition costs are estimated first for both the vehicles. This is performed by calculating the dimensions of the individual parts of the UAV from the high level dimensions such as wing span, sweep, chord length, fuselage length, width and height. The structure of the UAV considered here is fairly simple and generic. It has a conventional configuration with fuselage, wing and tail. The wing consists of stringers, spars, ribs and an outer skin. The number of stringers, spars or ribs is variable and can be modified and the cost model structure in itself is independent from this variation. The fuse-

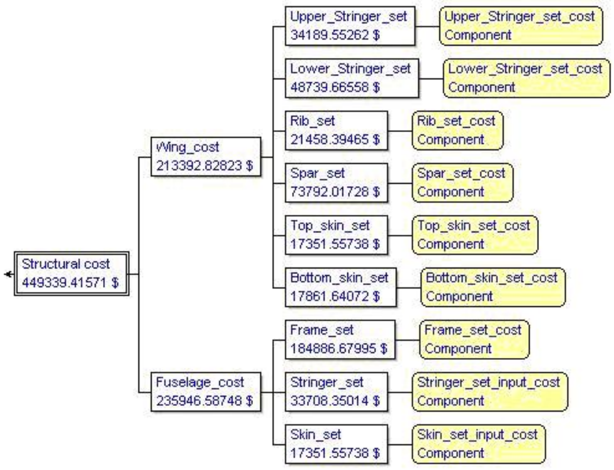


Figure 6.1: Structural cost for the metal based UAV

lage is assumed to have a semi-monocoque structure with frames, stringers and skin. Again, the number of frames and stringers can be varied. In this case study, the wing has 3 spars, 15 stringers and 10 ribs while the fuselage has 8 frames and 15 stringers. The dimensions of these individual parts are then calculated from the high level geometry and are assumed to be the same for both aircraft. This is because structural analysis is not included in our framework, which is necessary to dimension the aircraft structure depending upon the choice of material.

The raw materials and the manufacturing costs for each part are estimated from their dimensions. The costs of all the structural sets are then added to achieve the overall acquisition cost of the UAV. Figure 6.1 and Figure 6.2 show the estimated structural cost of metal based and non metal based UAVs, respectively. It was observed that the structural cost of the non-metal-based UAV is higher than that of a metal-based UAV. This can

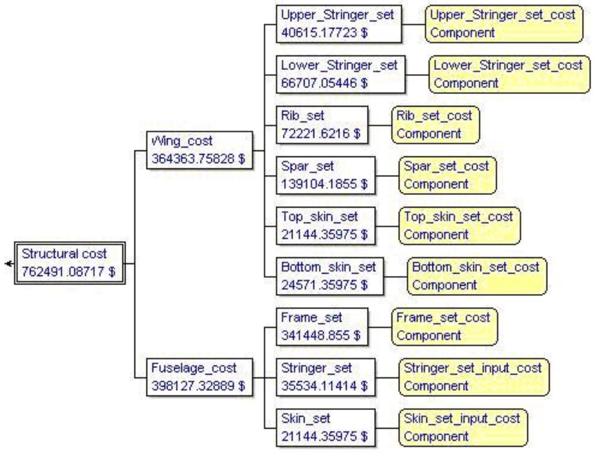


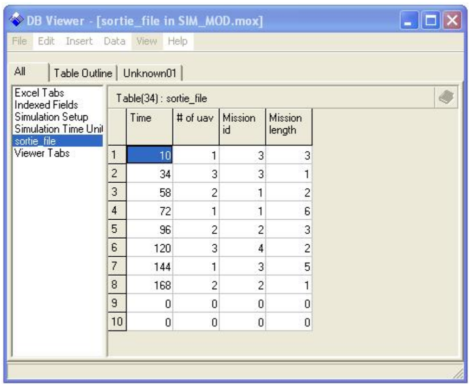
Figure 6.2: Structural cost for the non metal based UAV

be attributed to the high raw material and manufacturing costs of composite materials. It should be noted that the tooling and assembly costs are not included in this study.

The operation and maintenance costs for both fleets are then estimated using the simulation model. The UAVs are assigned missions according to a sortie file, shown in Figure 6.3, which is input into the simulation model. Since the UAVs are of the high-altitude long endurance type, only the following missions are considered

- Long Range Reconnaisance,
- Covert Tactical Reconnaisance,
- Covert Re-supply,
- Air Defence.

The sortie file used for the case study is shown in Figure 6.3 is repeated



	Time	# of uav	Mission id	Mission length
1	10	1	3	3
2	34	3	3	1
3	58	2	1	2
4	72	1	1	6
5	96	2	2	3
6	120	3	4	2
7	144	1	3	5
8	168	2	2	1
9	0	0	0	0
10	0	0	0	0

Figure 6.3: Sortie schedule

every week i.e. every 168 hours. Each mission requires a specific number of UAVs and for a specific duration as seen in “# of uav” and “Mission length” columns, respectively. Each mission id corresponds uniquely to one of the missions listed above. UAVs are launched and flown on their specified missions according to this schedule. Aircraft may experience system failures and combat damage in the course of the mission. The battle damage rate is different for metal based and non metal based UAVs, as shown in Table 6.1. This difference is attributed to the fact that composite aircraft perform better than metal aircraft. Both aircraft have same aerodynamic properties and the same propulsion system, but the composite aircraft is lighter, hence, it is more agile and faster. Also, composite aircraft are stealthier compared to metal based aircraft. The precise quantification of these differences is beyond the scope of this work, hence an estimation is is made using the historical data and engineering intuition. Further study needs to be conducted for the accurate representation of this difference.

The system(s) to which the battle damage has occurred is found using the battle damage probabilities for the different systems. These battle damage

Table 6.1: Battle damage rates for metal and non-metal based UAVs

Mission ID	Mission Type	Non Metal UAV battle Damage rate	Metal UAV battle damage rate
1	Long Range Reconnaisance	0.0023	0.0031
2	Covert Tactical Reconnaisance	0.0011	0.0020
3	Covert Re-supply	0.0021	0.0032
4	Air Defence	0.0015	0.0019

probabilities are assumed to be same for both the metal based and non metal based UAVs. The battle damage and classification probabilities are as shown in Table 6.2. These probabilities are a representation of the data gathered from industry reports and the available literature [65], [66].

Table 6.2: System damage rates and their classification probabilities

System	Battle Damage Probability P_{h/H_i}	Classification Probabilities		
		Critical (P_{h/H_i})	Major	Minor
Fuselage	0.41	0.2	0.3	0.5
Wing	0.23	0.3	0.3	0.4
Fuel System	0.12	0.4	0.3	0.3
Power Plant	0.09	0.5	0.3	0.2
Controls	0.07	0.3	0.2	0.5
Avionics	0.08	0.2	0.3	0.5
Landing gear	–			

The systems that fail during the course of a mission are determined by peroforming reliability analysis, making use of pre-determined reliability data. The reliability measures are assumed to be the same for both metal based and non metal based UAVs. Table 6.3 gives the TBO values and the Weibull parameters for different systems of aircraft. The unreliability of each subsystem is obtained using the time between overhaul (TBO) values as the value of the time in the Weibull expression as explained in subsection 5.6.2.

Table 6.3: The reliability Weibull parameters

System	Weibull Parameters	
	n	t_0
Fuselage	-	
Wing	2.0	450
Fuel System	1.7	350
Power Plant	2.1	350
Controls	2.0	1100
Avionics	-	-
Landing gear	2.0	5000

The maintenance and repair costs are estimated using the resources expended for the repair. The resources include the labour costs, spares cost and the cost of new systems, in case of system replacements. A resource requirement and a distribution of the task time is associated for each system both maintenance types i.e. depot level or field level maintenance. For example, the inspection and repair times, number of spares required and their average cost and finally, the number of technicians required for completing the repair for all the systems in aircraft, at the depot level, is shown in Table 6.4. This data represents the base values for maintenance times, personnel and spares cost and are defined from available literature and engineering intuition. A similar table, containing the times, personnel required and the spares cost at the field level for all the systems, is input before the start of the simulation to estimate the repair costs at the field level.

All the other parameters in the simulation model are assumed to be same for both the vehicles. The logistics data is also the same for both the vehicles i.e. the repair times, repair costs, spares and personnel required are assumed

Table 6.4: Repair data

System	Inspection time (hrs)	Repair time (hrs)	Number of Spares	Personnel	New System cost	Mean cost of spares
Fuselage	3	14	8	3	50000	1200
Wing	4	16	8	2	25000	1000
Fuel System	4	18	7	2	15000	500
Power Plant	3	12	30	3	35000	600
Controls	4	16	10	3	20000	650
Avionics	4	14	10	2	15000	450
Landing gear	3	12	5	3	10000	500

to be same. These assumptions are not strictly true, but this can be refined when data becomes available for both the aircraft. However, the fuel burn rate is lower for the composite aircraft due to its lesser weight. This difference is estimated using Breguets equation and the fuel burn rates for both the aircraft are as shown in Table 6.5.

Table 6.5: Fuel burn rates for metal and non-metal based UAVs

Fuel Burn Rate (Kg/min)	Climb	Cruise	Maneouver	Descent
Non Metal low altitude	5.6	4.6	7.5	5.1
Non Metal high altitude	6.1	4.9	9.4	5.2
Metal UAV low altitude	6.7	5.5	9	6.1
Metal UAV high altitude	7.2	5.9	11.3	6.3

The simulation model was run for both the fleets of UAVs for one year. The repair cost, spares cost and the fuel costs for UAVs in both fleets are shown in Table 6.6. It can be observed that the operational costs for the fleet of metal based UAVs are higher than that of the fleet with non-metal based UAVs. This is because of the high battle damage rate and higher fuel consumption of the metal based UAVs.

Table 6.6: Operation costs for fleets of metal and non-metal based UAVs

	Non-Metal UAV fleet data			Metal based UAV fleet data		
	Repair Cost	Spares Cost	Fuel Cost	Repair Cost	Spares Cost	Fuel Cost
1	28800	135000	336682	9900	106600	388296
2	16850	80300	320752	7700	20350	417393
3	14750	68450	357922	17750	165350	391482
4	42450	262450	300403	39150	262800	319050
5	18400	93300	295799	9950	112650	387027
6	16600	121450	317577	13400	83000	421650
7	40700	314250	325710	25400	153400	3647525
8	3300	37500	3559734	18900	80000	324999
9	23400	186150	297396	17050	92700	405297
10	15150	114550	341825	5550	13350	361962

The life cycle cost of the fleet of UAV is calculated by combining the acquisition cost model and the simulation model. This is achieved by using a shell script, which calls both the models sequentially. The files output from both the models are then read and parsed to calculate the whole life cycle cost and this LCC can then be output in the required format.The simulation model was then run for different time periods, starting from one year to ten years and the LCC for the both fleets of UAVs is plotted as a cost vs time graph as shown in Figure 6.4. It is observed that even though in the first few years the fleet with non-metal based UAVs cost more than the fleet with metal based UAVs, in the long run the overall life cycle cost for the fleet of non-metal based UAVs is lower than that of the metal based UAV fleet, which can be attributed to the lower operational costs of composite UAVs.

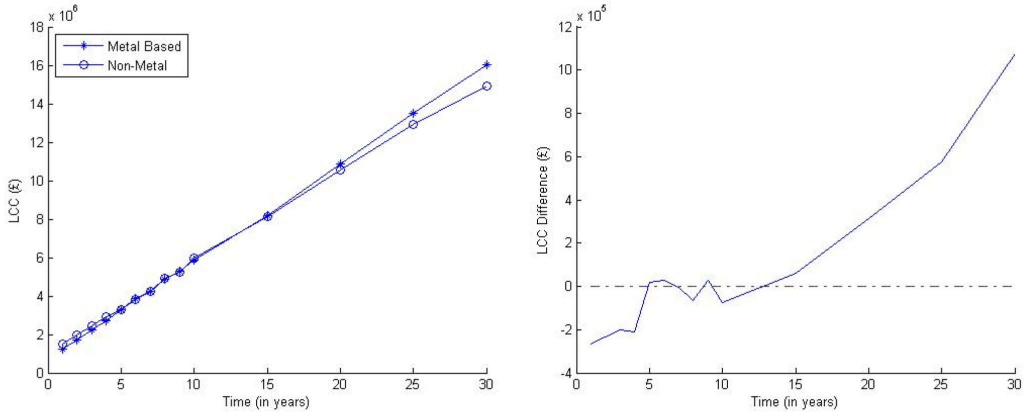


Figure 6.4: LCC and the LCC difference plotted againts time

6.3 Optimisation studies

The LCC framework developed is utilised to facilitate direct comparison between different configurations to perform trade-off studies as detailed in section 6.2. The LCC framework can also be used to identify the best (or cheapest) possible "design" by integrating the framework into the conceptual design process. The models are run in batch mode to allow cost estimation to be performed on a series of aircraft with varying geometry. In other words, automating the framework allows optimization to be performed without human intervention as shown previously in Figure 3.2.

OptionsMatlab, a design exploration and optimisation package in Matlab environment, is used for the optimisation studies [126]. OptionsMatlab provides access to most design search and optimisation algorithms whilst retaining flexibility by enabling the users to define the objective and constraint functions that describe their problem as Matlab functions. It also supports a number of Response Surface Model (RSM) algorithms that allow optimisation to be carried out cheaply using approximations of the values of the objective function and/or constraints. OptionsMatlab is invoked by using an input structure that describes the users problem, and configures the design search and optimisation algorithm to be used. A number of optional fields may also be adjusted and the results are returned to the Matlab workspace in an output structure.

The aim of the optimisation process is to find an aircraft design with minimum cost. In reality, a complex set of aircraft parameters are used as design variables for conceptual design optimisation but, for the present research, aircraft parametric geometry parameters are chosen as the set of design variables. More specifically, wing geometry parameters are used as the design variables for the optimisation studies. The optimisation paradigm includes various aircraft analysis components such as acquisition cost model, aerodynamic analysis and simulation model. All these aircraft analysis components outlined in chapter 3 have the flexibility, detail and automation to be well suited for the optimisation process. These analysis components are combined with optimisation package to perform acquisition cost optimisation, maintenance and operational cost optimisation and finally, life cycle cost optimisation.

In the optimization process, new designs are based on variation of existing product designs i.e. the methodology assumes that new designs to be produced are based to some extent on producing parts using similar structures and processes to those already being used by the company. Since the cost estimation process is based on using data from previously made components, there has to be a process detail record of a similar part or process from which the new part can be modelled.

6.3.1 Acquisition cost optimisation

The optimisation configuration chosen for this study uses the high level wing geometry dimensions such as wing span, sweep, chord length, fuselage length, width and height to estimate and optimise the acquisition costs. The fuselage parameters are assumed to be constant while the baseline wing has a semi-span of 6m with 10° sweep with a chord of 0.7m. Also, NACA 2407 airfoil is used at root while NACA 2405 airfoil used at the tip, with sections varying linearly between root and tip. Span and sweep are chosen as design variables for this optimisation case study and the semi-span and sweep are bounded between [2, 10] and [10°, 30°], respectively. This is a bound-constrained optimisation problem with the aircraft optimised for minimum acquisition cost.

The optimisation process employs design of experiments (DoE) in OptionsMatlab and makes use of response surface methods. The DoE search is used to efficiently sample points across the multi-dimensional parameter space represented by the design variables. A number of different DoE search methods are available within the Options package, which can be configured using the optional input fields while the number of points to be evaluated can be configured by altering the input structure. The current optimisation process makes use of latin hypercube search with 25 initial DoE evaluations, as shown in Figure 6.5.

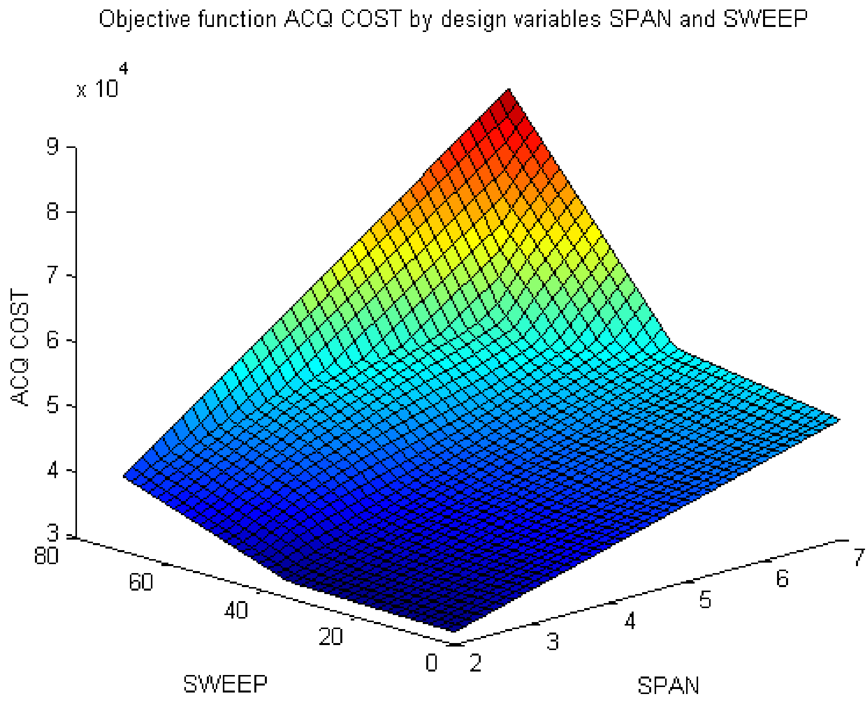


Figure 6.5: Acquisition cost design of experiment evaluations

These objective function (acquisition cost evaluations) calculated at the DoE points in the design space are used to construct a model of the entire design space, making use of response surface modelling. This model is then optimised with a genetic algorithm (GA) method using 1000 function evaluations. The function evaluations required for the GA are performed against the RSM (rather than evaluating the acquisition cost directly). The GA then suggests five update points at which the original data set can be improved and these number of update points can be configured in the optimisation structure input. Thus, the response surface methodology facilitates in computational efficiency by reducing the number of objective function evaluations by approximating the value of objective functions based upon the results of direct evaluation of the acquisition cost model. Since the model used to evaluate the design variables is an approximation of the acquisition cost model, it should not be considered to be equivalent to direct evaluation. The results of a search over a RSM are verified by direct evaluation of the objective functions at the returned design update points. The update points provided by the RSM are used as candidate points for a second DoE study. This process can be repeated until the convergence criteria is reached or if the number of evaluations have been completed.

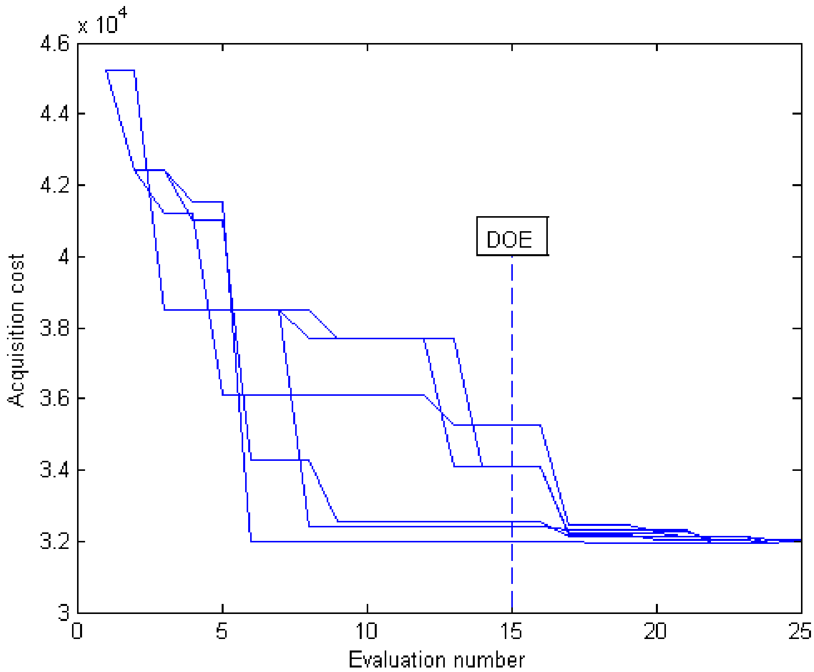


Figure 6.6: Acquisition cost convergence

The convergence history of the objective function against number of evaluations, for different optimisation studies, is as shown in Figure 6.6, with the optimum acquisition cost value around £ 32,150 for all the optimisation studies. The design variables at which this is achieved are 2m span and 10° sweep, which are the lower bounds of span and sweep, respectively. The result is as expected since minimising the acquisition cost will result in a wing with lower span and less sweep according to the parametric geometry definition shown in Figure 4.1.

6.3.2 Maintenance and operations cost optimisation

The baseline aircraft configuration chosen for this study is a HALE aircraft and the aircraft is analysed and optimised using high level wing geometry dimensions such as wing span, sweep, chord length, fuselage length, width and height. The wing has a semi-span of 5m with 14° sweep with a chord of 1.3m. Also, NACA 2411 airfoil is used at root while NACA 2408 airfoil used at the tip, with sections varying linearly between root and tip. Span and leading edge sweep are chosen again as design variables for this optimisation case study and they are bounded between [4m, 10m] and [10°, 25°], respectively. The mission altitude is 7500m and the aircraft cruise mach number is 0.25, both of which are assumed to be constant for all missions. This is a bound-constrained optimisation problem with the aircraft optimised for minimum operations cost.

The operation and maintenance costs of a fleet of aircraft are estimated using the discrete-event simulation model with the mission characteristics, implicit product definition and the logistics data as inputs. The aircraft performance affects the mission efficiency and the aircraft then need repair based on the level of damage sustained, as explained in chapter 5. Since the aircraft under study is a surveillance/reconnaisance aircraft, specific excess power is chosen as the only measure of aircraft performance, to reduce the problem complexity. More performance parameters can be included, but specific excess power is sufficient for the purposes of demonstration. Also, other performance parameters require iterations between aerodynamic and mission analysis while specific excess power can be calculated easily from drag required at cruise conditions. This is achieved using aerodynamic analysis by estimating the drag coefficient at the required lift coefficient. The aerodynamic analysis of the wing is carried out using full potential solver FP and a viscous drag correction employing VGK as explained in section 5.3.1. The weight of the aircraft is estimated from aircraft geometry using the corresponding Raymer's parametric equations and this aircraft weight is used to calculate the required lift coefficient [96]. Aerodynamic analysis is performed on the aircraft four times to estimate the angle of attack for producing the necessary lift i.e. four aerodynamic analysis are performed for every objective function evaluation. This is to estimate the required setting angle for the required lift by utilising interpolation techniques. From the required setting angle, total drag is estimated by adding the viscous drag prediction to the wave and vortex drag predictions from FP.

The aircraft are assigned missions according to a sortie file, similar to the one shown in Figure 6.3, which includes only the high-altitude long endurance type missions. The aircraft performance calculated is used to estimate the mission efficiency (or battle damage probability) by utilising the novel hybrid approach for survivability estimation detailed in section 5.6.1. The aircraft then needs repair based on the level of damage sustained and the simulation model estimates the fuel, repair and maintenance cost for each aircraft after every mission. These costs are then aggregated to estimate the operation costs for the fleet of aircraft.

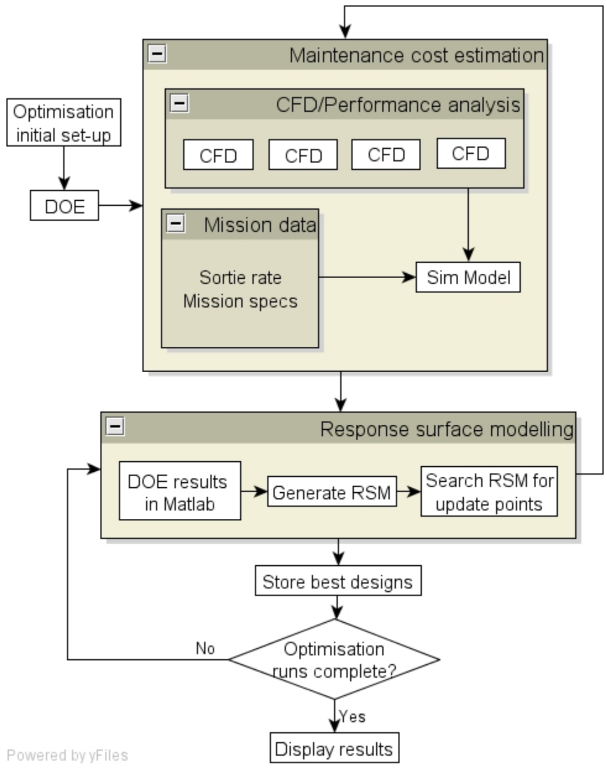


Figure 6.7: Optimisation structure

The optimisation process employs design of experiments in OptionsMatlab along with response surface methods to estimate the minimum operational cost as shown in Figure 6.7. The DoE makes use of latin hypercube search with 15 initial evaluations which are used to construct a response surface model of the entire design space. Each evaluation takes around 25 minutes on a single processor desktop. Thus, RSM is again used to create a surrogate model of the design space and GA is used to optimise the surrogate model. The GA provides 5 update points which are used as candidate points for a second DoE study and this process is repeated twice to improve the convergence speed.

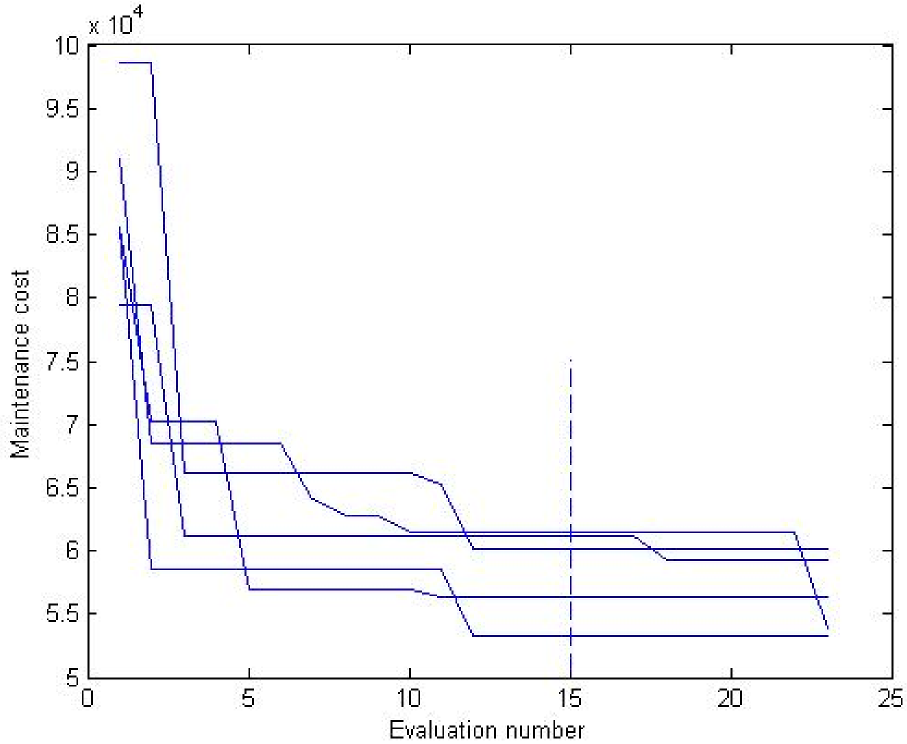


Figure 6.8: Operational cost convergence

The convergence history of the objective function against number of evaluations, for different optimisation studies, is as shown in Figure 6.8, with the optimum operational cost value around £ 53,420 for most optimisation studies. The design variables at which this is achieved are 9m span and 23° sweep, which are near the upper bounds of span and sweep, respectively. The high value of span is as expected since wing with a higher aspect ratio performs better aerodynamically which leads to lowering the operational cost. The reason for the sweep converging to a higher value can be attributed to the fact that it appears in the Raymer's parametric weight equation [96]. Both variables affect the estimated weight of the aircraft which inturn affects the required lift coefficient and thus result in a slightly different solution. A better solution can be achieved by incorporating sophisticated weight estimation techniques which is described as part of future work in Chapter 7.

6.4 Web deployment

The models developed have been published on the local internet network for remote access; the LCC framework developed is integrated with a secure dynamic website to facilitate real time comparison between different aircraft configurations. The website is being tested on the local network and once robustness is achieved, it is planned to deploy the website on a secure web server for public access.

6.4.1 Motivation

This relates to the characteristics outlined for improving cost estimation in Chapter 3, accessible cost models assist designers in making modifications to the design for cost reduction in early stages. The World-Wide Web (WWW) is a powerful business technology that has evolved rapidly over the last decade. The internet has become a new channel of communication among customers and suppliers in business, which attracted the attention of several organisations. An improved level of service can be achieved by dissemination of knowledge worldwide using platform independent architecture.

Manufacturing cost estimation has been performed using web based technologies; for example Zheng et al [127] developed a web-based machining parameter selection system for life cycle cost reduction while Ben-Arieh et al [47] performed web-based cost estimation of machining rotational parts. Aircraft cost models such as “Airframe Cost Model”, “Advanced Missions Cost Model” etc, which are simple online cost models that enable quick turnaround, rough-order-of-magnitude cost estimating, have published on-line by NASA. A web based aircraft life-cycle cost model for use of military government program offices is under development by Northrop Grumman Information Technology.

Cost models deployed using web technologies will allow these models to be shared with a wider audience. The designers can achieve accurate and fast cost estimation utilizing the web services by submitting the aircraft design parameters to a central server that links to the acquisition cost model and simulation model. The central server provides the designer with the cost data, without compromising the sensitive data such as mission data or the manufacturers' cost data. Also, using standard web browsers will help in reducing the number of licenses required of the software used to develop the cost models.

6.4.2 Structure

This section describes the general architecture of the web service system. The basic structure of the system, also called the activity diagram in unified modelling language (UML), is described in Figure 6.9. The figure shows that the designers and the cost models are connected to the web service module.

This module interacts with the cost models sending them design parameters and receiving costing information, which is forwarded on to the designers.

The users/designers need to register with the web server, which can be achieved by providing their contact information along with their log-in information (such as user-id, password and reminder question in case the password is lost). The users can then log-in to the website using their user-id and password. The aircraft product definition is submitted and the aircraft geometry needs to be verified before proceeding to cost estimation. If the geometry is not physically plausible, the aircraft product definition needs to be revised and submitted again. Once the users are satisfied with the aircraft, they request the website to estimate the costs using the aircraft product definition as input and browse the cost information when it becomes available on the website.

The website allows the users/designers to register, maintain and update their accounts. The main purpose of the website is to act as a link between the user/designer and the cost model by managing accounts, receiving user data, invoking the cost models and transferring the cost data back to the user. It also provides information about the theoretical basement and the assumptions behind the cost models. The aircraft product definition is received from designers and this information is saved into the corresponding local/remote database by the website. The cost models are invoked according to the user requests and the data is passed on to the relevant model for cost estimation. The cost information is extracted from the models' databases and displayed on the website.

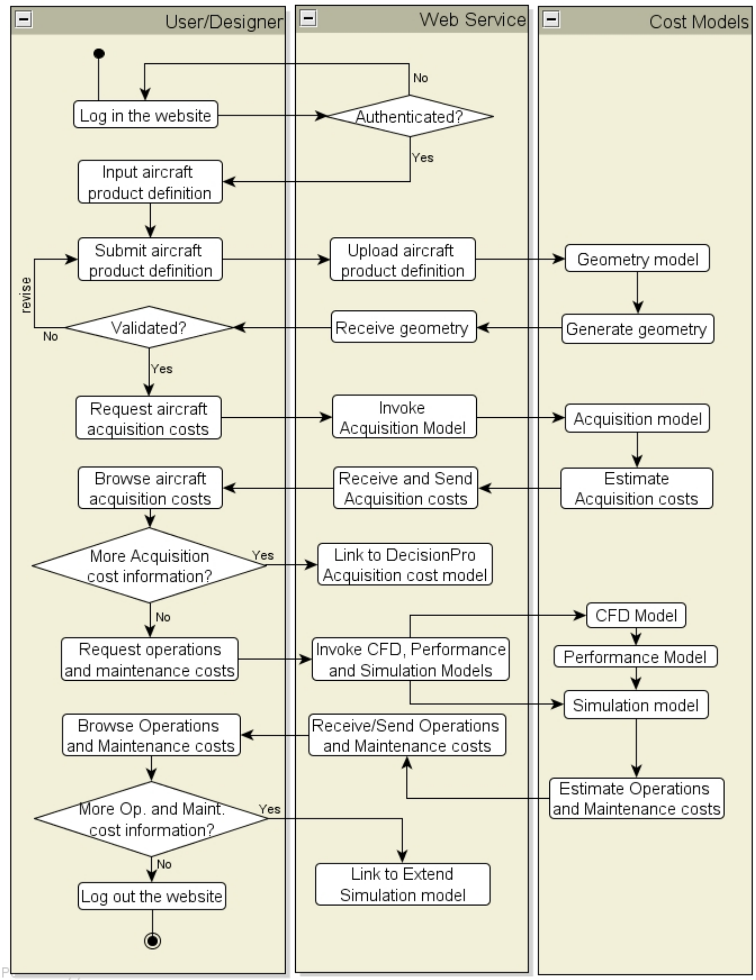


Figure 6.9: Web service structure

6.4.3 Website

The server provides an integrated environment for cost estimation with a website as the front-end. The website is built using ASP.Net and C# in visual studio (which is an integrated development environment (IDE) from Microsoft) as shown in Figure 6.10. The website has a secure log-in process so only the registered users can access the information. An overview of the models is then provided as can be seen on the menu on the left hand side.

The users can proceed to cost estimation by providing the aircraft product definition. The main aim of the server is to extract the information input by the user, send it to the relevant cost models and export the information back to the user.

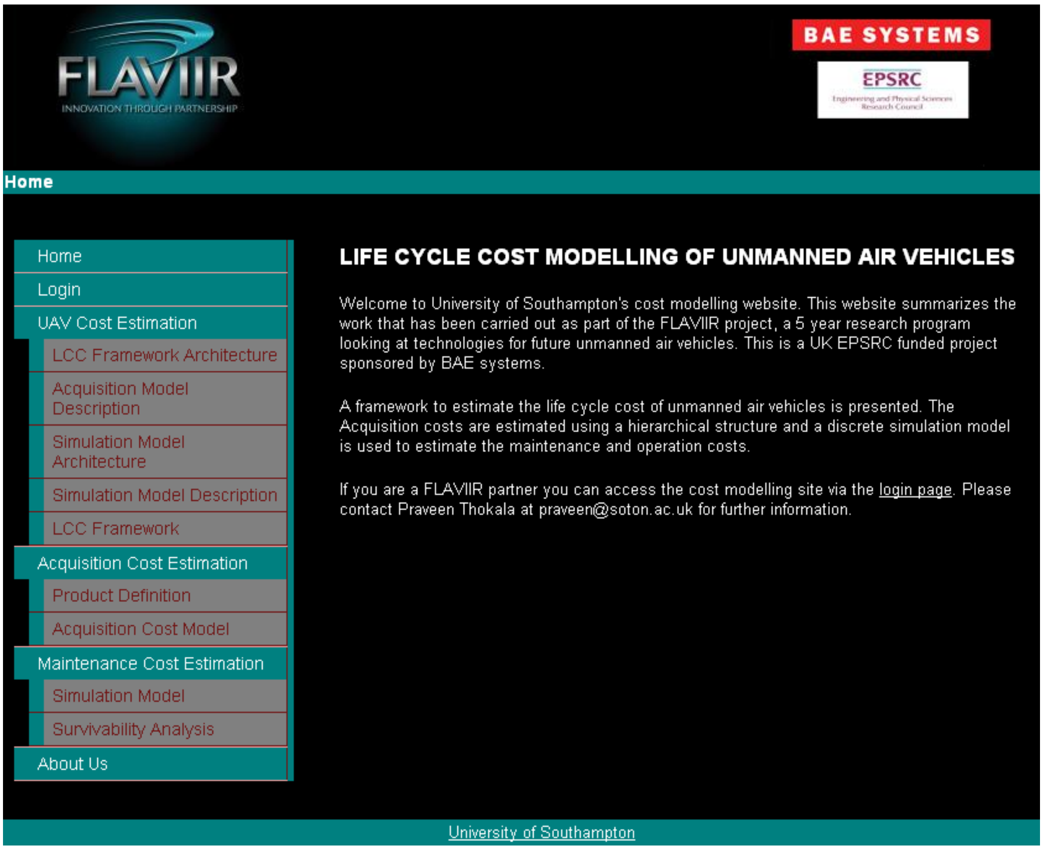


Figure 6.10: Home page of the website

The aircraft product definition is input by the user via the browser form to include the complete aircraft product definition as shown in Figure 6.11. The geometry parameters are linked to the parametric geometry definition provided in section 4.2. The material web form is a drop down list which provides the option to select from metal-based and composite based materials. The forms for weight and power plant specifications are self explanatory.

The units are provided on the labels for each form in order to avoid any discrepancies. All the fields in the web forms need to be completed and the website flags up an error asking for the relevant inputs if any forms are left unfilled. The aerodynamic coefficients are the only exception as the aerodynamic model can estimate them from the geometry. However, if the aerodynamic coefficient web form values are filled, the coefficients estimated by the aerodynamic model are overwritten by the values input by the user. This is because the aerodynamic model in the server uses an inviscid, full potential method which might not be as accurate as the CFD models utilised by the users.

Figure 6.11: Aircraft product definition input form

The product definition information input by the user is saved into a place and data format relevant to the cost models. The figure shows the source code behind the product definition webpage, seen in Figure 6.12, in the developing environment, Visual Studio. The tab on the right hand side includes all the web pages (.aspx format) included in the website along with their source codes (either .aspx.cs or .aspx.vb format). For aesthetic purposes and ease of use, the website also utilises stylesheets, sitemap and a master page which are seen in the figure as “StyleSheet.css”, “Web.sitemap” and “FlaviirMasterPage.master”, respectively. The website also has a mandatory “web.config” file which contains the database, security and error settings. This file is especially important as the database and security settings can affect the login and data transfer processes.

The geometry parameters input on the web forms in Figure 6.11 are saved into text files using the code shown in Figure 6.12. The files, “wing_data.txt” and “fuselage_data.txt”, are saved into the folder “Acq_Model” which contains the acquisition cost model and this is achieved by specifying the paths on the server. The data also needs to be appended with units such as “deg” and “m” so that the text file contains data in a format which is usable by the acquisition cost model. Before proceeding to cost estimation, 3-D geometry of the aircraft is developed from the aircraft product definition making use of the geometry model explained in section 4.2. The geometry is displayed on the website in a different webpage “Acquisition_Cost_Estimation.aspx”, shown in Figure 6.13, once the user clicks the “show geometry” button on the top right hand corner of the product definition page shown in Figure 6.11. The product definition can be updated in case of an unsound aircraft using

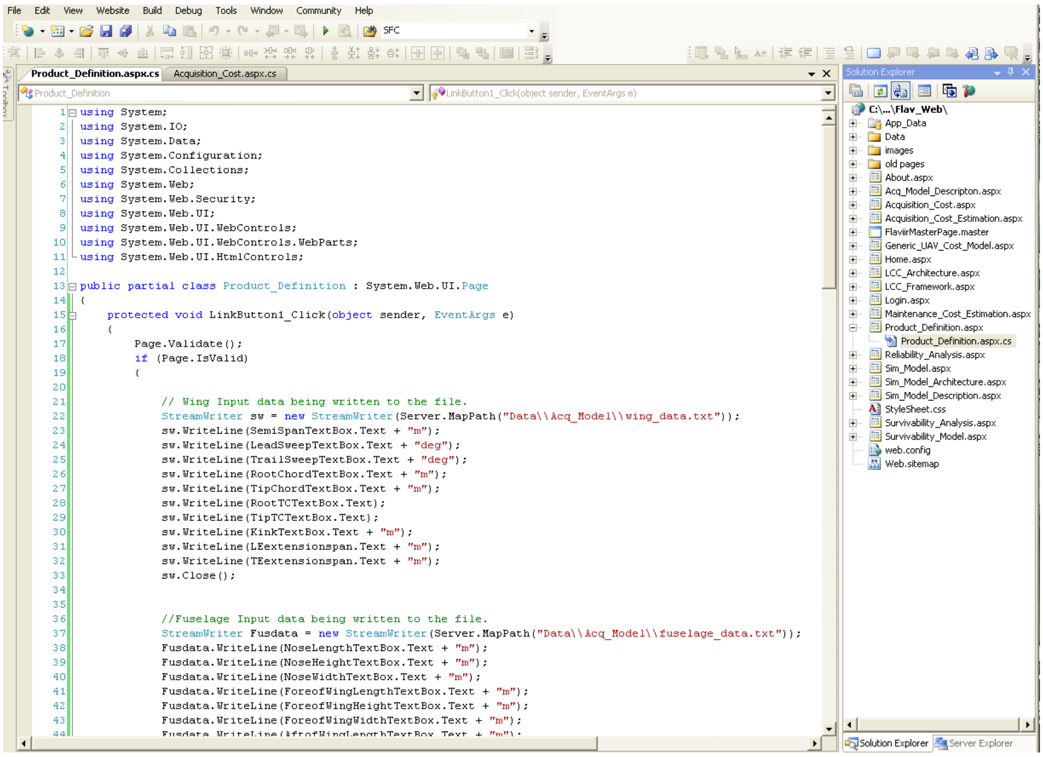


Figure 6.12: Source code page for product definition web page

the "Update Product Definition" hyperlink.

If the aircraft is satisfactory, the user can proceed to acquisition cost estimation by using the "Run Model" button, which runs the acquisition cost model on the server. This is achieved by using the code which invokes the model sitting in the server using the source code shown in Figure 6.14. The click of the "Run Model" button starts the batch file "ACQ.bat" which runs the acquisition cost model. The acquisition cost model runs using text files which contain the data input by the user/client. The acquisition costs are also output as text files "wing_cost.txt" and "fuselage_cost.txt". This cost information is displayed on the client-side website by clicking on the "Wing Cost" and "Fuselage Cost" buttons. The source code again for these

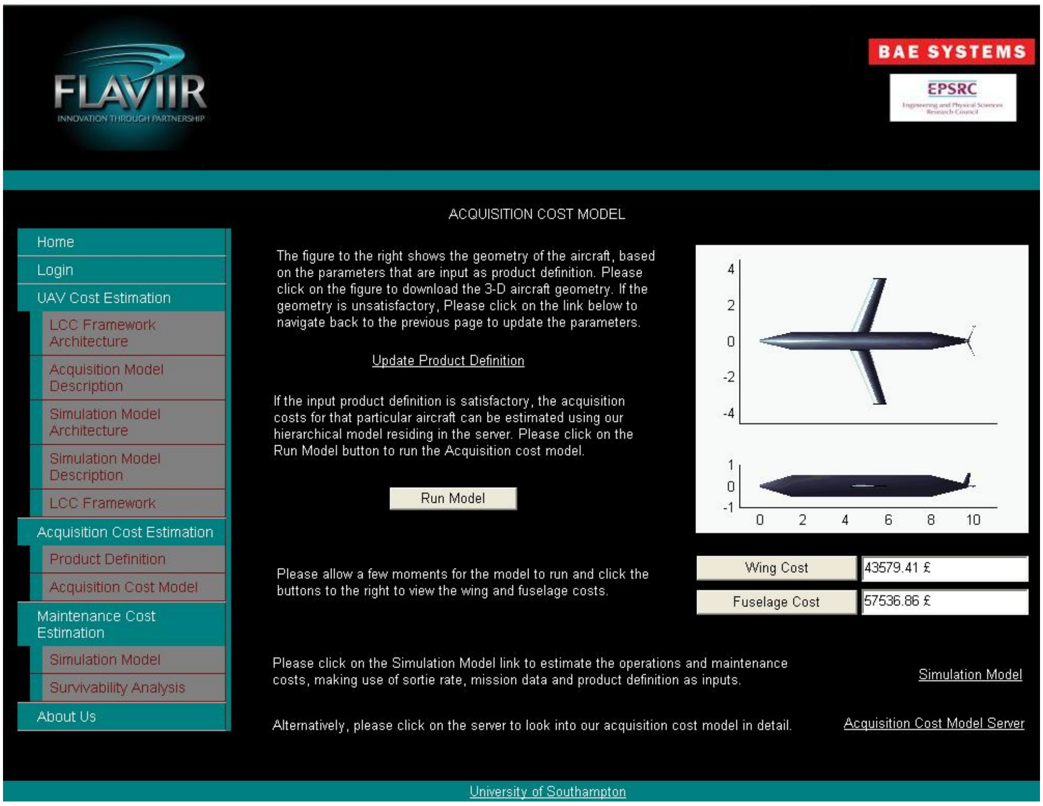


Figure 6.13: Acquisition cost model webpage

processes is shown in Figure 6.14.

The user can browse the acquisition cost information in detail by visiting the server which hosts acquisition cost model using the "Acquisition cost model server" hyperlink on the bottom right hand side corner of the webpage shown in Figure 6.13. The user can also estimate the operations and maintenance costs of the aircraft by clicking on the "Simulation Model" hyperlink, which will navigate the user to the webpage shown in Figure 6.15. This webpage contains the aircraft performance characteristics calculated using aerodynamic analysis along with the performance models. This aircraft product definition is access database format and this data can be updated us-

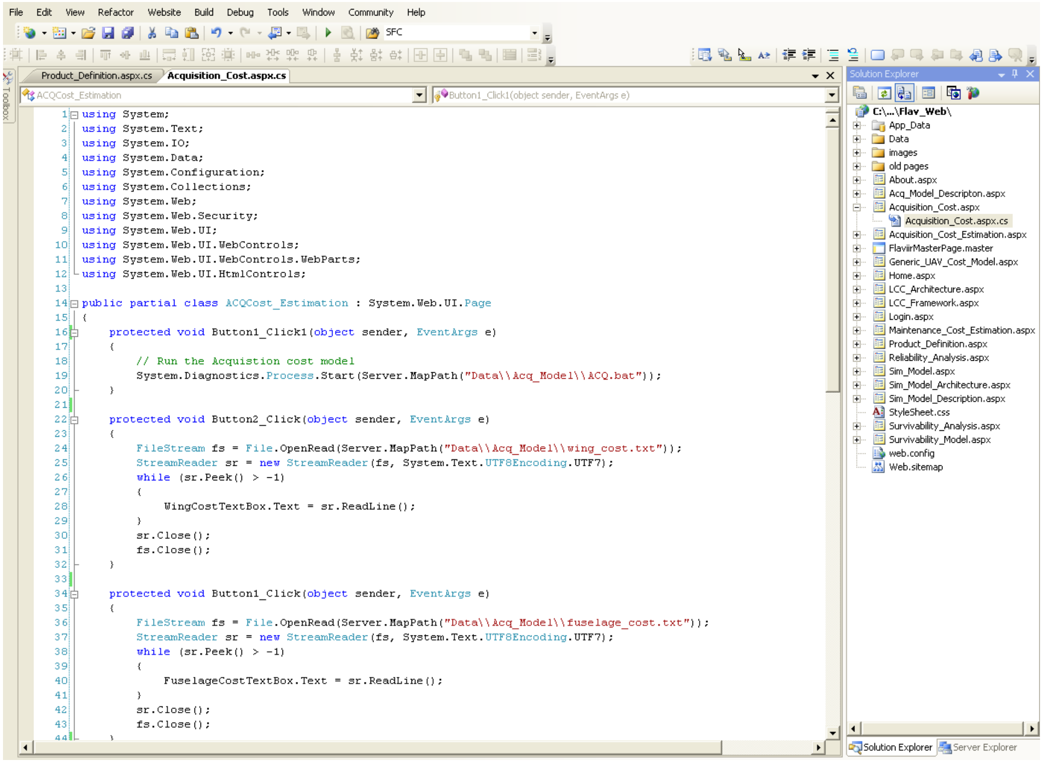


Figure 6.14: Source code for acquisition cost webpage

ing the "edit" buttons shown to the left of the performance parameters. The mission details are as shown in the figure and a fixed time period of 30 years is used for the simulation runs. All other parameters such as logistics, sortie rate, etc are assumed to be constant and the reason for this is to provide a quick estimate without overwhelming the user with too much information. The user can acquire operations and maintenance costs by using the "Run Model" button and if the user so wishes, the simulation model along with input data can be downloaded for further study.

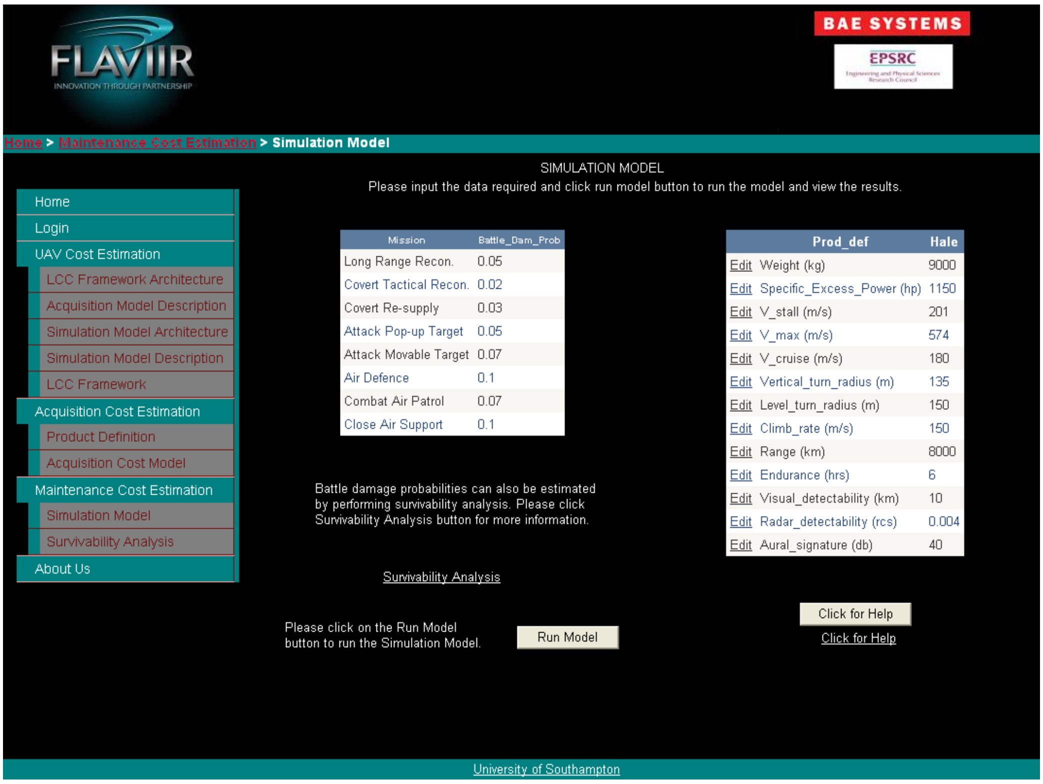


Figure 6.15: Simulation model webpage

6.5 Conclusions

A framework to estimate the life cycle cost of unmanned air vehicles is presented. Automating the framework allowed trade-off studies and optimization to be performed without human intervention. The framework developed is integrated into the design process to facilitate the comparison between different configurations and can also be used to evaluate the cost penalty of survivability enhancement concepts.

Chapter 7

Conclusions and future work

In conclusion, a brief synopsis of the primary conclusions and contributions of the present research work is presented in this chapter. An extension of the present work is presented as a brief outline of ongoing and future work.

7.1 Research summary

A framework to estimate the life cycle cost of aircraft is developed, using its product definition as input. The acquisition cost model developed has the capability to estimate the product acquisition costs of an UAV from its design specifications. A discrete-event simulation model is developed to estimate the repair and maintenance costs for a fleet of aircraft. The LCC framework that is developed is used to perform trade-off studies, multidisciplinary analysis and optimization. The models have also been published on the local internet network for remote access. It is to be noted that the interest of this research is relative costing (i.e. identifying the better design) rather than estimating the absolute cost of an aircraft.

7.1.1 Product Definition

The framework developed here has the capability to estimate the costs of any aircraft, given its product definition. This is achieved by having product definition as input to cost models, so that any change in the design is reflected in the calculated cost. The product definition of an aircraft is classified in a novel manner into explicit and implicit product definition. Explicit product definition includes the design parameters whose effects on the cost are easily recognisable and includes the geometry parameters (i.e. dimensions of the design), material type, and power plant specifications. Implicit product definition on the other hand includes design parameters whose affects on the cost are not easily identifiable and includes aircraft performance, signature and CCA data. The implicit product definition parameters are estimated from explicit product definition using physics-based models.

7.1.2 Geometry Model

The geometry of the aircraft is achieved by utilising a parametric representation of the aircraft geometry which enables three-dimensional representation of the aircraft. This parametric representation is a part of the explicit product definition and includes the shape and dimensions of wing, fuselage and empennage. The parametric representation is flexible enough to represent conventional, canard and blended body wing (BWB) configurations. A tool is built in Matlab to provide the three dimensional visualisation of aircraft using its para- metric geometry representation and this acts as a sanity check to verify whether the aircraft is realistic before proceeding with the cost estimation.

7.1.3 Standard Data Structure

A standard data structure is developed, for both explicit and implicit parameters, to be incorporated into the model so that any given aircraft can be represented using this standard structure. The framework estimates the LCC of the given aircraft using this standard data structure, making the framework capable of estimating the costs for any given aircraft that can be represented by this structure. The standard data structure for the acquisition cost model is the explicit product definition which is the 3-D geometry parametric representation, input as text files. The standard structure for the input data into the simulation model contains the mission characteristics, logistics parameters along with implicit product definition in the format of spreadsheets or access databases.

7.1.4 Acquisition cost model

The acquisition cost model uses explicit product definition as input so that any changes to the design are reflected in the cost model. The model has a hierarchical structure that reflects the actual physical structure of the aircraft to allow easy and intuitive navigation. Libraries of materials and processes have been created for integration into the cost model and this object oriented approach makes the cost model consistent, easy to maintain and permits reuse of components. Sensitivity analysis is also performed to identify the important design parameters. The acquisition cost model developed has the capability to estimate the costs of aircraft structures manufactured using metal-based materials as well as non-metal-based materials.

7.1.5 Aerodynamic and performance analysis

The aerodynamic parameters for the aircraft are calculated using full potential (FP) method developed by QinetiQ and made available by ESDU International plc. FP calculates the flow field and aerodynamic forces for a wing-body combination in a subsonic freestream, including the effects of shock waves for the flow around the 3-D geometry. The aircraft performance parameters are calculated by using performance analysis model, which uses standard flight dynamics equations and aircraft aerodynamic coefficients along with the standard atmospheric tables to estimate aircraft performance.

7.1.6 Survivability and reliability analysis

In the simulation model, reliability of the aircraft is estimated using historical data method which estimates the probabilities of system failures. This method involves making use of pre-determined reliability data based on the available literature and/or expert knowledge to estimate the time between failures. The susceptibility and vulnerability probabilities are assessed for a given aircraft in the mission-threat scenario to determine the probability of survival of the aircraft in the selected scenario. In the simulation model the survivability probabilities are estimated either using historical data or survival analysis tool (AGILE™). A novel hybrid approach which utilises principles of both methods to estimate survivability in an efficient manner is also presented.

7.1.7 Simulation model

A discrete-event simulation model is developed which is capable of estimating the operation and maintenance costs of a fleet of aircraft using the mission characteristics, implicit product definition and the logistics data as input. The simulation model utilises a novel methodology to link aircraft performance with survivability analysis for estimating the maintenance costs. The aircraft performance along with mission data affects the mission efficiency and the aircraft then need repair based on the level of damage sustained. The maintenance performed on the aircraft is dependent upon the level of repair. The simulation model estimates the fuel, repair and maintenance cost for each aircraft after every mission, based on the input data and these costs are then aggregated to estimate the operation costs for the fleet of aircraft.

7.1.8 Generic LCC model

A framework capable of calculating the whole life cycle cost of aircraft has been developed by having aircraft product definition as input, so that any change in the design variables is reflected in the calculated cost. This process of estimating the LCC from explicit product definition alone is a novel approach. The LCC of an aircraft includes the material and the manufacturing costs along with the costs necessary for operation, maintenance and repair of a fleet of aircraft. From the aircraft geometry specifications and the material type, the raw material and manufacturing costs are estimated by the acquisition cost model using an activity based costing approach. The simulation model gives an estimate of the cost of maintenance, operation, and repair making use of the aircraft's implicit product definition, mission details and logistics data as inputs. These costs, when combined, give the whole life cycle cost of the aircraft.

7.1.9 Design tool

The LCC framework developed is integrated into the concept design process to facilitate the comparison between different configurations. A life cycle cost comparison between a fleet of metal-based UAVs and a same-sized fleet of non-metal-based UAVs is performed. Automating the life cycle cost framework has allowed for trade-off studies and cost-based optimization to be performed without human intervention. The models are run in batch mode which supports the automation required for optimisation.

7.1.10 Web deployment

The models developed have been published on the local internet network for remote access; the LCC framework developed is integrated with a secure dynamic website, built using C# and ASP.NET, to facilitate real time cost estimation. The website allows the user to verify the aircraft geometry, developed using MATLAB, before estimating its costs. The users then input the aircraft data using forms and SQL database entries before running the models remotely on the server. The models run using the data input by the user and the results are then output back on the website, thereby providing instant service to the user. The website is being tested on the local network and once robustness is achieved, it is planned to deploy the website on a secure web server for public access.

7.2 Contributions of Research

The LCC framework is evaluated here in terms of whether it achieves its stated purpose and the overall research goal, as well as the individual objectives, and measures of success set out in the Introduction (Chapter 1). The research question, purpose and objectives are restated here for convenience, together with an assessment of the LCC framework to satisfy each requirement.

7.2.1 Research Question

"How can cost be modeled using the aircraft product definition to allow integration with conceptual design?"

A combination of two conceptual aircraft design methodologies is used in the development of this framework to link the aircraft design to the life cycle cost. The LCC framework utilises ABC approach which identifies the activities that consume resources and estimates the costs. This is achieved by utilising explicit product definition as input to the LCC framework so that any change in the design is reflected in the calculated cost.

7.2.2 Research Purpose

"The purpose of this research is to provide information to product designers (or managers) that will enable them to make informed design choices."

The LCC framework was designed to present product cost information back to designers, during the conceptual design stage, in a manner that allows them to immediately see the cost of different aircraft designs. The framework returns sufficient cost data to analyze the cost of each part in the aircraft, and provide cost breakdowns in terms of traditional cost categories. A new cost estimate is constructed using the information available each time the user prompts the LCC framework. By allowing designers to input alternative designs, the effect on cost can quickly be determined by designers. The users can modify the aircraft design to seek improvement in the functional value of their designs, while reducing the costs.

7.2.3 Research Objective

"The desired result of this study is a framework for life cycle cost estimation, which could be used to perform trade-off studies and multi-disciplinary analysis."

A framework capable of calculating the whole life cycle cost given the mission requirements and the aircraft product definition is developed. Trade-off analysis, cost based design optimisation and real time cost estimation using secure dynamic web services are performed, thus, demonstrating the capability of the LCC framework as a design support tool.

Sub-objectives were:

- **Validation of the cost models**

  The cost models could not be validated due to the difficulty in capturing costing information from literature and aerospace companies, notwithstanding their reluctance to release this information to outsiders. However, the models are developed to reflect real life scenarios using activity based costing. The observations made by varying inputs for the cost models are similar to the expected results, thereby, validating that the models are behaving as expected. If the data were available, the cost models could be validated. Furthermore, the cost models could be updated by utilising error analysis.

- **To assess the needs of aircraft designers by analyzing typical trade studies used during the conceptual design phase**

  The framework enables them to collect the information they need to carry out trade studies by allowing designers to input alternative designs or process parameters and determining their effect on cost. A classic case of cost vs. performance trade off study, a life cycle cost comparison between a fleet of metal-based UAVs and non-metal based UAVs is performed in order to demonstrate this capability.

- **To provide a development framework for design decision support system**

  The theoretical basement for the LCC framework is based on activity-based costing methodology which is widely accepted. The choice of activities is decided by the users and is not limited only to the existing systems, manufacturing processes and maintenance tasks. The methodology will allow users to look at any system, process or activity in the enterprise and to capture cost information about those activities. In section 7.3 the scope of this system for other applications will be considered, together with the suggestions for further research work in this domain.

7.2.4 Measures of success

The qualitative measures which were identified in subsection 1.3.3 as important characteristics of the LCC framework are elegance, flexibility, extensibility, cost and portability.

The approach to designing the LCC framework was to use commonly used software development techniques which would make the system more accessible to users across different disciplines. The methodology relies heavily on using object-oriented activity-based costing techniques which are covered extensively in product costing and management accounting literature. The cost estimating method is therefore easily explainable to users in engineering, production, and accounting fields. Thus, this method is **elegant** compared to the methods using statistical techniques which the designers find difficult to understand.

The LCC framework uses a standard data structure which will allow a variety of users to enhance, adapt or link the system. Thus, the LCC framework provides a ready **flexible** platform for incorporating future developments and enhancements to the decision support system. The choice of costs needed to be estimated is decided by the users and the framework can be modified depending upon the need. The framework can also easily be **extended** by adding other models, analysis tools or expanding the existing models.

The **cost** to implement the LCC framework in any given organisation is small in comparison to other activity-based cost systems, or parametric costing systems. The LCC framework has the advantage that it does not require any re-design of the existing accounting or production information systems. This information captured from the organisation just needs to be imported into the desired text or database forms relevant for the cost models. The simplicity of explanation and use may also enable organizations take over the system without continued support from design consultants.

The **portability** of the system is assured by virtue of the combination of a widely used software packages, which allows for easy encapsulation. The databases used for the framework were constructed using Microsoft Access, but the framework would be compatible with a number of major database formats. Furthermore, the LCC framework developed is integrated with a secure dynamic website to facilitate real time remote cost comparison between different aircraft configurations.

7.3 Novel aspects of the research

The LCC framework developed here has the capability to estimate the costs of aircraft by having product definition as input to cost models, so that any change in the design is reflected in the calculated cost. The LCC framework contains cost models built using activity based costing methodology which allows users to identify the costs associated with each system/part. This is not possible in existing cost models which use statistical techniques along with historical data to identify the relationships between the product design and costs. The LCC of an aircraft is estimated using its product definition as input. The aircraft product definition is classified in a novel manner into explicit and implicit product definition. The implicit product definition parameters are estimated from explicit product definition using physics-based models and thus, explicit product definition alone is required to estimate the LCC of an aircraft.

The acquisition cost model has a hierarchical structure that reflects the actual physical structure of the aircraft to allow easy and intuitive navigation. Libraries of materials and processes have been created for integration into the cost model and this object oriented approach makes the cost model consistent, easy to maintain and permits flexibility to add more material/process objects. Since the acquisition cost model uses ABC with explicit product definition as input any changes to the design are reflected in the cost model. Sensitivity and risk analysis are also performed to identify the important design parameters and uncertainty in cost information, respectively. The acquisition cost model developed has the capability to estimate the costs of aircraft structures manufactured using metal-based materials as well as non-metal-based materials.

The simulation model capable of estimating the operation and maintenance costs of a fleet of aircraft is developed. The model's modular approach allow easy and intuitive navigation which provides an elegant, flexible and comprehensive costing environment. The simulation model utilises a novel methodology to link aircraft performance with survivability analysis for estimating the maintenance costs. The aircraft performance along with mission data affects the mission efficiency and the aircraft then need repair based on the level of damage sustained. Implicit product definition is estimated from aerodynamic analysis (full potential method) and performance analysis while survivability analysis to estimate battle damage rates and reliability analysis to estimate system failure rates. The battle damge probabilities in the simulation model are estimated a novel hybrid approach which combines the historical data with survivability analysis software. Since the simulation uses the mission characteristics, implicit product definition and the logistics data as input to estimate the costs, any changes in the design are reflected in the simulation model.

7.4 Future Work

A number of avenues for promising research have been identified during the course of this work and are discussed briefly in this section.

Acquisition cost model needs to consider tooling and assembly costs along with the raw material and manufacturing costs. Also, the knowledge base can be improved to include more material, manufacturing process and structural libraries. Furthermore, non-conformance (i.e. scrap and re-work costs) costs can be estimated in manufacturing process models through process capability analysis by estimating the proportion of parts that are scrapped due to manufacturing errors. This will also help designers in reducing the non-conformance cost by proper selection of design dimensions, tolerances and materials.

Similarly, the simulation model can be expanded to include more missions and different aircraft. Also, there is a need to incorporate mission abort kill critical component analysis to determine the effect of non-critical damage on the individual aircraft i.e. whether the damage is mission aborting. If the failure or damage is non-aborting, the aircraft continues on the mission and if the failure or damage is mission aborting, the aircraft immediately begins the return to base. Furthermore, different maintenance philosophies need to be integrated into the simulation model to examine the affects of logistics on the operations and maintenance costs.

The aerodynamic analysis needs a few iterations to achieve convergence as it depends upon aircraft speed and the aerodynamic coefficients in turn affect the aircraft performance. Thus, efficient integration of aerodynamic and performance models is necessary for iterative processess such as comprehensive optimisation studies.

Also, prior to cost estimation, structural analysis needs to be performed making use of the data from aerodynamic analysis to avoid structurally unsound aircraft. The internal structure is currently populated from the structural spacing data which can lead to sparse or dense aircraft structures, depending upon the structural spacing. Thus, finite element analysis (FEA) needs to be performed to examine whether the aircraft can sustain the mission loads and if necessary, to identify the optimal internal structure such that the aircraft will not succumb to structural failure. This also relates to "weight analysis" and a more sophisticated weighting method needs to be incorporated into the LCC framework.

The website needs to tested on a server for robustness in order to be deployed on a secure web server for public access. The deployment of the cost models through standard web browsers will allow these models to be shared with a wider audience, especially within the industry and their partners, reducing the number of software licenses required. Computational expense for risk analysis such uncertainty analysis via Monte-Carlo simulation and cost sensitivity analysis for large models can be reduced by utilising grid services in conjunction with the web capabilities. The cost models can be linked to wide variety of analysis models due to efficient data transfer and the platform independent nature of the web services. For example, the costing web service can be integrated with CAD models, CFD analysis and FEA models to perform MDO.

Value driven design is an emerging topic in the aerospace engineering community which makes use of a mathematical value model in a formal optimization framework to balance performance, cost, schedule, and other measures to identify the best possible outcome. Collopy states that “surplus value” should be the metric for a product in the competitive market [128]. This approach takes economics into account by defining the value of the product as benefit/profit of the product minus all the costs, which is the key to succeed in a competetive market and the value of the product can be defined as a single objective function using value models. The value model can be used for several applications: system trade studies, technology evaluation, optimal design and value based acquisition [129], [130]. It is planned to use this value driven methodology in contrast to cost-centric methodology to improve the conceptual aircraft design process.

Appendix A

Calculating Specific Excess Power

The first step is to calculate the wing area, S_w, from the wing dimensions (in m) and convert into ft^2. Then, aspect ratio (Ar) and taper ratio (lam) are calculated as below

$$Ar = SemiSpan^2/Sw$$

$$lam = (RootChord + LE_{ext} + TE_{ext})/TipChord$$

where

$$TE_{ext} = Trailing\ edge\ extension$$

$$LE_{ext} = Leading\ edge\ extension$$

The dynamic pressure is estimated from the cruise conditions.

$$q_i = 0.5 * rho * V^2 * 0.0208854;$$

where

$$rho = density\ at\ cruise\ altitude$$

$$V = velocity\ of\ the\ aircraft$$

The wing weight in pounds can be estimated using the following parametric equation.

$$W_{wing_i} = 0.036(Sw_i^{0.758})(W_{fw}^{0.0035})(\frac{Ar}{cos_{sw}})^{20.6}(q_i^{0.006})(lam^{0.04})(\frac{t_{max}}{cos_{sw}})^{-0.3}(6000^{0.49})$$

where

$$W_{fw} = weight\ of\ the\ fuel\ in\ lb$$

$$cos_{sw} = cos(LeadSweep)$$

$$t_{max} = maximum\ airfoil\ thickness$$

The total weight of the aircraft (W_{total}) is estimated from the wing weight using

$$W_{total} = (W_{wing_i} + 1800) * 0.45359$$

The required lift coefficient can be estimated from the aircraft weight as

$$CL_{req} = \frac{W_{total} * 9.81}{0.5 * rho * Sw * V^2}$$

The angle of attack is increased until the required lift coefficient is achieved and the drag coefficient at the same flow conditions is calculated using the FP method along with the viscous correction. The total drag is estimated and the power required is calculated by multiplying the drag with cruise velocity.

$$Drag = (0.5 * rho * Sw * V^2) * CD$$

$$Power_{req} = Drag * V$$

Finally, the specific excess power is calculated by subtracting the power required from the available power of the powerplant.

$$S.E.P = Power_{avail} - Power_{req}$$

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