



CRANFIELD UNIVERSITY

RAJKUMAR S. PANT

GENERALISED COST OPTIMISATION OF
SHORT-HAUL TWIN-TURBOPROP AIRCRAFT
INCLUDING AIRPORT CONSIDERATIONS

COLLEGE OF AERONAUTICS

Ph.D THESIS

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CONSIDERATIONS**

Supervisor: Prof. J. P. Fielding

February 1997

*This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy.*

Dedicated to the memory of my grandfather

Shri Bhagwan Vallabh Pant

A great visionary who taught me the true meaning of
education

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Rajkumar S. Pant

Abstract

In this thesis, a methodology is proposed for the conceptual design and optimisation of twin-turboprop Commuter & Regional aircraft suitable for operation over a specific short-haul route. Using this methodology, the optimum configuration and flight profiles of such aircraft for operation over various stage-lengths can be obtained. By significantly modifying an existing computer code for synthesis and trajectory optimisation of Commuter aircraft (CASTOR), a new code (CRAGER) has been developed to estimate the Generalised cost of travel incurred by a passenger for air-travel between two cities. A new sub-module has been developed for the geometric sizing of a suitable airport as per ICAO/FAA recommendations, and estimation of the Airport cost, i.e. the cost associated with setting-up and operating this airport at one of the two cities. This module is incorporated into CRAGER. Generalised cost is assumed to consist of the Access cost, Flight cost, Time cost and the Airport cost, and is proposed as a new objective function to be minimised.

In an exploratory case study, the efficacy of two stochastic optimisation methods viz. Genetic Algorithms (GA) and Simulated Annealing (SA) was demonstrated for handling complicated objective functions related to aircraft conceptual design. In particular, the SIMANN SA code was found to be quite robust and easy to implement, and came up with better solutions compared to conventional gradient based optimisers for multi-modal objective functions. As an example of the application of the proposed methodology, several case studies were carried out for business travel in India, using both CASTOR & CRAGER. Based on a survey of existing regional airports in India, the airports were classified under three levels, enabling estimation of Airport cost associated with operating a specific aircraft. A model was developed for predicting the demand for business travel in India between a metropolitan city (hub) and another city located near-by (spoke).

The case studies revealed the non-linear nature of the airport sub-module, due to the airport classification system followed by ICAO & FAA. It was seen that when the annual travel demand is low, the Generalised cost is dominated by the Airport cost and the Time cost. With increase in annual travel demand, however, the Flight costs dominate the Generalised cost, hence larger aircraft have lower Generalised costs. High-capacity aircraft were seen to have a low Flight cost, but this advantage was more than overcome by the excessively high Airport and Time costs associated with them. Compared to pressurised aircraft, the un-pressurised commuter aircraft suffer from severe penalties due to limitations imposed on their cruising altitude and descent profile. Finally, the optimum 50 seater aircraft obtained by CRAGER had better or marginally lower *DOC* and Generalised cost compared to existing aircraft.

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Chapter 1

Introduction

1.1 Evolution of civil aircraft design

Aircraft conceptual design can be termed as the process of determining an aircraft configuration that satisfies a set of user-specified requirements. In the early days of aviation development, the design process was strongly driven by the performance capabilities desired from the aircraft, especially in the case of combat aircraft. The designers were either trying to extend the performance envelope of their previous aircraft, or to out-perform the competitor's aircraft. The evolution of the aircraft design process lead to increased sophistication, which resulted from ever more demanding requirements. These ever-increasing requirements for aircraft design from the pioneering days of aviation to the 80s have been lucidly brought about by Burgess [1]:

When Wilbur and Orville Wright first set out to build the Wright Flyer, they had only one requirement (to meet) viz. controlled, 1-g powered flight. Around the start of WW 1, airplanes were designed to meet specific maneuver and other performance requirements. In the 40s and 50s, design requirements included pressurization, handling qualities and corrosion considerations. In the 60s, requirements were expanded to include energy maneuverability capabilities, damage tolerance, reliability, and nuclear hardening. In the 70s, observability and fly-by-wire control systems were added. And in the 80s, supportability, productibility, and affordability were tacked on.

In the context of civil aircraft design, two additional factors that have assumed significance are the tightening of noise regulations in mid-1960s, and an order of magnitude increase in the price of fuel in mid-1970s.

In the early days of civil aviation, most aircraft conceptual design and optimisation methodologies concentrated on obtaining the feasible aircraft configuration that met the mission & performance objectives at the lowest possible all-up mass, or Take-off mass (M_{TO}), as it is generally referred to. This was because the performance was severely limited by the power-plant capabilities, hence the lighter the structure of the aircraft, the more its performance capability for a constant engine size. It was quite common (and it still is) to design an aircraft around an established engine, rather than the other way around.

Aeronautics is one of the most heavily regulated activities of mankind, and the reason for that is safety [2]. Minimum standards of safety in aircraft design and operation are adopted and enforced by the governments all over the world, in the form of air-worthiness regulations and operating rules. These regulations act as constraints in aircraft design, because any configuration that fails to meet any one of them is to be deemed infeasible, however promising it may appear. These regulations are progressively tightened with the passage of time, since developments in technology enable superior and safer designs to be produced, and also due to increased public pressure and awareness. An example of this is the introduction and progressive tightening of the acceptable noise levels of the aircraft.

With the acceptability of aircraft as an established mode of public transportation, especially as the only viable means for long-distance travel, many airlines came into existence all over the world. Operational and economic parameters then started to become additional driving forces in the aircraft design process, apart from the performance and mission parameters. Soon, operational safety, reliability, maintainability and ease of manufacture started becoming watchwords in aircraft design. This trend was exemplified with advent of the fuel crisis in mid-70s, when mission fuel consumption & operating costs became important and sometimes the main drivers. The design of commercial aircraft started being strongly driven by economic parameters, and Direct Operating Cost (DOC) became the most commonly accepted figure-of-merit for comparison of such aircraft¹.

1.2 The complementary roles of aircraft & airport

Aircraft need an airport to operate from, and hence they are major components of the air-transport system. Development of a new airport to start or augment an air-transport network is a very time and capital intensive activity, and is usually preceded by an extensive cost-benefit analysis. Development of an airport involves a huge investment, most of which is “sunk” in the initial few years of its inception.

¹A more detailed discussion on DOC as well a methodology for its estimation for commuter and regional turboprop aircraft is provided in Appendix F.

If a particular route does not turn out to be profitable, the airline can divert their aircraft on other routes, or even sell their aircraft to recover a part or whole of their initial investment. But if an airport is not found economically viable after it has been developed, very little of the initial investment can usually be recovered².

Owing to the extremely high capital costs associated with airport development, the sizing and layout of the airport assume a large importance. Design guidelines for airport layout and sizing have been issued by the International Civil Aviation Organisation (ICAO) [3] and Federal Aviation Authority (FAA)[4]. One of the key issues to be addressed by any airport planner is how to provide for the future growth of the airport. Historically, as aircraft size and traffic volume increased, runways had to be lengthened, terminal facilities expanded, and additional support facilities provided [5]. The cost of carrying out further extensions and enlargements to the airport have been, in general, far in excess of what they would have been, if suitable provisions were made earlier. This is especially true for the land area under the direct ownership or control of the airport authority. The creation of an airport usually leads to increased business activity around it, hence with the passage of time, it becomes increasingly difficult to acquire more land for the airport to be expanded in size. Thus, a balance has to be achieved between the initial investment on equipment and land and provision of excess land area for future development.

1.3 Financing of airports

A big question associated with airports is who pays for it ? In the past, airports were owned by government bodies such as the British Airport Authority (BAA) in the UK, local municipalities, counties or even the states themselves in the USA and the National Airport Authority (NAA) in India. However, due to the substantial growth in air transport in recent years, there is increasing public and political recognition that the sector should be self-supporting, with a minimum of public subsidies [6]. The ICAO council has also suggested that the level and structure of aeronautical charges and policies on commercial activities of the airport should be reviewed to ensure that the users share the full economic cost of providing the airport and ancillary service to the community, including appropriate amounts for interest on capital investment and depreciation of assets [7]. There is evidence of increasing private sector participation in airport financing and operation. For instance, BAA was privatised in 1987 and floated on the London Stock Exchange as BAA plc, in which the public could buy shares. There are many factors that affect the choice of public or private ownership of airports viz., economic, social, environmental and political. There are several ways in which a part or whole of the airport can be

²An exception to this are the cases where the real estate prices increase to such an extent that it may be even profitable to close down the airport and sell off the land.

privatised e.g. sale of existing airports, long-term leases of airports to private firms, contract operations of airports, creation of new terminal facilities by what is known as the *build-operate-transfer* strategy or the creation of new airports as private business ventures. Examples of all these types of privatisation are provided in [6].

NAA of India has budgeted a sum of Rupees³ 150 billion during the next 5-year plan and Rs 320 billion for 1997-2002 for development of airport infrastructure, most (if not all) of which is aimed to be generated from self-financed projects [8], [9]. NAA is reported to be keen to adopt the *build-operate-transfer* strategy for all new investment intensive infrastructure related projects; many of which are already in progress. It is felt that any new such project or setting up a new airport will have to be carried out with the majority (if not total) participation and financing of the private sector.

1.4 Peculiarities of short range business travel

It is generally accepted that for low demand levels and for short range operations, turboprop commuter & regional aircraft offer a great advantage over the turbofan/jet types, both from the point of view of operating costs as well as the field length requirements. They do suffer from a poorer passenger appeal and lower perceived safety levels (especially in the developed countries) but they are still quite popular as they offer a major cost advantage. Many small commuter aircraft are unpressurised, hence there are operational limitations on their cruising altitude & rate of descent. However, owing to lower block times, the amount of discomfort that is associated with this is not very high. To some extent, these drawbacks of the small capacity commuter/regional aircraft can be compensated by providing better frequency [10].

It is a well-known fact that short-range aircraft suffer from inherently high cost per seat-mile compared to the long range ones. Coupled with this is the problem of high demand elasticity (i.e. price sensitivity), since alternative modes of transportation e.g. private automobile & rail, offer a very stiff competition. To meet a given level of passenger travel demand, it is always beneficial to operate fewer flights with larger aircraft from the operating cost point of view. This results in low frequency, which corresponds to a low quality of service from the point of view of passengers. Further, the costs associated with setting up the airport infrastructure are also higher for larger aircraft. There is thus a compromise solution at which the total system costs are the lowest. Previous studies have shown that due to high access & time costs, operation of large capacity aircraft for short haul routes does not necessarily produce a minimum cost solution [11]. As is evident, the optimum aircraft/airport combination is greatly affected by the demand for air-travel, which,

³1 US \$ $\approx$ 35 Indian Rupees (Rs) in 1996.

in turn is greatly affected by the availability of seats.

1.5 Integrated Configuration & Trajectory Optimisation

A typical mission of a civil transport aircraft consists of 5 segments viz. Take-off, Climb, Cruise, Descent & Landing. For long-haul aircraft, the mission is dominated by the cruise segment, since the time spent (and the fuel consumed) in this stage is a very large proportion of the total. Hence, in the conceptual design stage, it is usually sufficient to optimise for this segment alone. For instance, the Breguét range formula is used for estimating the cruise segment mass fraction⁴, while typical segment mass fractions for Take-off, Climb, Descent & Landing phases, listed in the classical aircraft design textbooks ([12], [13], [14]) are considered sufficient. But for the aircraft designed specifically for short-haul operations, the climb & descent segments start becoming larger and larger fractions of the total mission, as the stage length becomes smaller and smaller. For example, the optimum flight profile for minimum fuel consumption for short-stage missions have been reported to be saw-tooth shaped, with little or no cruise segment at all [15].

For design & analysis of short-haul aircraft, there is thus a need for a much detailed analysis of the climb and descent segments. This needs accurate modelling of the engine behaviour with altitude and forward speed, so that the parameters such as SHP available, fuel consumption & the residual thrust in the exhaust could be determined at point during the aircraft's mission. For turboprop aircraft, this problem is compounded by the presence of the propeller, since the propeller performance is also affected by changes in forward speed and altitude. Thus, for mission-optimised short-haul aircraft, it is not only sufficient to arrive at the best configuration, but also the best way in which the aircraft is flown i.e. there is a need for integrated configuration & trajectory & optimisation.

1.6 Generalised Cost and Time related costs

Generalised Cost is the term used to denote the total cost of travel incurred by a passenger, and it includes both direct cost in terms of the actual fare paid for the travel segment, and the indirect costs related to the time spent in travel and the costs incurred in access etc.

⁴Segment Mass Fraction is the ratio of the aircraft mass at the end & start of the segment.

The concept of *value of time* ($\mathcal{V}$) has also been discussed widely in transportation research literature, especially in road & rail transport. Simply stated, $\mathcal{V}$ represents the perceived money equivalent of a unit of time spent by the passenger in travel. As defined by Oort [16], $\mathcal{V}$ is a reflection of the utility (or disutility) that a traveller attaches to the time spent for the different parts of the trip. A high $\mathcal{V}$ thus indicates that the passenger attaches a high opportunity cost to the time spent in travel, given their activity at the destination. However, it is very difficult to arrive at a number that represents average $\mathcal{V}$ of passengers, because it is a function of several factors such as the gross income level, reason for travel (business or leisure), split of travel time between employee and employer etc. There seems to be no clear-cut agreement on how to determine its value; recommendations by various researchers for $\mathcal{V}$ vary from 94 % to 167 % of the average gross hourly income [17]. The perceived $\mathcal{V}$ is usually higher for the waiting and loading/unloading time (i.e. the time spent in security clearance and baggage check-in and collection), since it seems to be wholly unproductive from the point of view of passengers. Some business travellers are able to utilise a part of the journey time by the use of portable computers, but fatigue during travel usually precludes the full use of travel time, especially in short journeys.

Most public transportation systems have to follow a time-table or schedule that has to be published in advance, so that passengers may plan their journey accordingly. The need for travel by the passenger does not, however, always match these schedules or time-tables. In general, passengers have to *defer* or reschedule their journeys in line with the schedule of the public transportation system. If this time cannot be gainfully utilised by the passenger, then it represents a kind of wastage, especially if the passenger has a high $\mathcal{V}$. In terms of air-travel, *defer time* (T_{defer}) can be defined as the average time by which the passenger has to reschedule his/her journey in keeping with the flight schedules operated by the airlines, since a flight may not be available to match exactly with the need for travel.

Finally, the Access time (T_{acc}) i.e. the time needed to reach the airport from the point of journey commencement (and to reach the final destination at the other end) is also to be considered. For short range business travel, the access and defer times assume a great importance, since they are usually of the same order of magnitude at the actual journey time.

1.7 Objectives of the current research

Due to the excessively competitive nature of commuter and regional transport operations, it is quite common these days for aircraft manufacturers to involve themselves in the operations and financial planning of the airlines. The need for a conceptual

design and analysis tool which could be used by aircraft manufacturers as well as airlines has been summed up by Simos [18] as:

In the long term, it would be desirable to develop a hybrid algorithm which could define an aircraft design for a particular route structure. Such a program could be used in designing more efficient task-oriented commuterliners, as well as to give an indication to the operator of how closely any existing competitor aircraft approaches the ideal design tailored to his particular needs.

The main aim of the present research was to address this need by developing a methodology for estimation of the generalised cost of travel of a passenger on a specific route. Configuration and flight profile of a twin-turboprop commuter & regional transport aircraft for short-haul operations that correspond to minimum generalised cost could then be obtained. The model was to be principally aimed at new routes, and provisions made to include the costs related to setting-up and operating airports suitable for the operation of the specific aircraft into the generalised cost equation. A system cost approach was to be followed with a view to minimising the overall cost of setting up an air-transport network for transporting a given number of passengers between city pairs. The same model should also be modified to carry out comparative analyses of existing aircraft, to enable an airline to select the most appropriate aircraft for its own route(s).

The problem was formulated as follows :

Given a fixed number of passengers $N_{pax_{ann}}$ to be transported between two cities separated by a distance X_{stage} , determine the optimum configuration and flight profile of an N_{pax} seater twin-engined turboprop aircraft and the associated airport which corresponds to the minimum generalised cost C_{gen} per trip per passenger, where :

$$C_{gen} = C_{acc} + C_{flt} + C_{time} + C_{apt} \quad (1.1)$$

and :

C_{gen} = Generalised cost of travel

C_{acc} = Access cost

= Money & time spent in travelling to the airport

C_{flt} = Flight cost

= Cost incurred by the airline in transporting a passenger over X_{stage}

C_{time} = Time cost

= Cost related to travel and defer time per passenger

$$C_{apt} = \text{Airport cost}$$

$$= \text{Amortisation of the cost related to setting up \& operating}$$

$$\text{the airport per passenger}$$

To accomplish the above task, a computer code was to be developed to model and optimise all aspects of the task. A direct coupling between the aircraft parameters and the corresponding airport was to be provided, by developing a sub-module for geometrical sizing, layout and estimation of setting up and operating a regional airport. The applicability of the code was to be demonstrated through a series of case studies for short-range business travel, and lessons learnt about the design of aircraft and airports for such operations.

Chapter 2

Review of Literature

2.1 Introduction

Having formulated the aims of the present research and the outline of the work to be carried out, a review of existing literature was carried out. The aim of this review was to locate a computer based methodology for conceptual design and optimisation of turboprop engined aircraft, that could be suitably modified for application in the present work. Apart from this, it was necessary to obtain information related to the concept of Generalised cost and value of time, and airport design. It was also felt essential to locate and critically examine any previous study in similar or related area, and the recommendations made for future work therein. This chapter provides a review of literature on the above subject matter. Further, it was necessary to have a look at various optimisation techniques that have been used in the past for engineering design problems, which are discussed in Chapter 3.

2.2 Conceptual aircraft design methodologies

In recent times, the single most important factor that has revolutionised the way in which an aircraft is designed is the computer. Prior to its invention, research and design were conducted through limited analytical derivations and experimentation. Design studies, trade studies, and performance evaluations were confined to a small number of options that could be calculated by a finite number of people. These days, a major part of aircraft design work is carried out on the computer, and many more trade-offs can be examined by the designers in much lesser times.

For nearly two decades, attempts have been made to develop computer based

conceptual aircraft design methodologies all over the world. The earliest attempts to mechanise the design process involved purpose built slide rules and plates in the early fifties e.g. Driggs [19]. By mid-sixties, many preliminary design methodologies using digital computers were being reported [20], some of which even talked about graphical interfaces [21]. Aeronautical companies and research establishments (such as the RAE¹) also began exploring such techniques [22].

Two different approaches have been followed in developing such methodologies. The first one was to couple an optimisation algorithm to a fairly simple design synthesis program (mainly using closed form expressions and empirical or semi-empirical relationships) for estimating mass, aerodynamics & performance to achieve a configuration that lead to the optimum value of an objective function. The work carried out at RAE falls mainly under this category, and has been reported extensively in literature, both for commercial transport aircraft [23], [24] and combat aircraft [25], [26].

The second approach consists of developing more sophisticated methodologies for the detailed engineering analysis of a user defined aircraft with a specified geometry and power-plant. A satisfactory design configuration can then be identified by an experienced user, by carrying out parametric studies in which the main design variables are perturbed. An extensive discussion of both types of methods viz. the mathematical optimisation and the parametric evaluation is given by Wallace [27]. Howe has also reviewed various procedures for computerised design analysis, and has brought out the need to achieve a correct balance between the designer and the computer [28].

A typical example of a parametric analysis method is the GASP (General Aircraft Synthesis Program) developed at the NASA Ames research centre in USA [29], which has been recently used for conceptual design of a three lifting surface turbofan aircraft by Basto Nunes [30]. A more modern and sophisticated method belonging to this category is the ACSYNT (AirCRAFT SYNThesis) code which was developed by NASA Ames Research Centre and CAD Laboratory at Virginia Polytechnic & State University [31]. The code is now being developed and maintained by the ACSYNT Institute, which is the result of a joint R&D project between US government laboratories, academia and industry. ACSYNT functions as a parametric feature based surface modeller for an aircraft, without the need for the designer to input points, lines, curves and surfaces, as in other solid modelling systems. Unlike other codes of this type, it was designed from the outset to be coupled to a non-linear constrained optimiser for sensitivity studies. It has been structured in such a fashion that more sophisticated analysis modules could easily replace the existing ones as and when they are made available. Another example of such a code is GATEP (General Aviation Twin Engined Propeller aircraft) developed by Simos [18].

¹The Royal Aircraft Establishment of UK, now renamed as Defence Research Agency.

Various aerospace companies and research organisation also have developed their own conceptual and preliminary design codes, with varying capabilities and features. CPDS (Computerised Preliminary Design Synthesis) is an advanced system for conceptual design of subsonic & transonic aircraft, developed by Boeing [32]. It is a two level design system, with increasing accuracy of analytical method as the level increases. A computer program called OPDOT (Optimum Preliminary Design Of Transport airplane) was developed by Arbuckle and Sliwa [33] for optimisation of a jet powered transport aircraft. A computer aided dialog-system for conceptual design of civil aircraft design has also been developed at TsAGI, USSR. In this method, the aircraft capacity and range are given as requirements, and certain constraints are imposed on derived parameters such as approach speed, field lengths, fuel tank volume and climb gradients. The desired configuration of the aircraft (such as the location of the engines, flap type, aerofoil type and number of passengers seated abreast) is specified by the designer through an interactive dialog mode, and the optimum values of 5 parameters viz. wing area, engine thrust, aspect ratio, wing sweep and cruise Mach number are then obtained. Some application of this methodology are discussed by Denisov in [34]

More recently, a multi-level design synthesis procedure called MIDAS (Multi-disciplinary Integration of DA Specialists) has been developed by Diamler-Benz Aerospace Airbus [35] for developing the next generation Supersonic Commercial Aircraft. MIDAS aims at providing a flexible and efficient design process while effectively using the talent available within the organisation [36]. This is achieved by providing suitable couplings between the various specialist departments within an organisation. A global model of the aircraft performance and economy exists at the top most level, as a function of its specifications and a set of design variables. The analysis routines in this global model are provided by various specialist departments, and progressive improvement in the design is made by modifying the global model, till convergence is achieved.

Some conceptual design codes are also available commercially such as RDS (which comes in two versions, RDS-STUDENT & RDS-PROFESSIONAL) [37] & AAA (Advanced Aircraft Analysis) [38]. The differences in the conceptual design methodologies of ACSYNT, RDS-STUDENT & AAA have been discussed by Kaul and Rokhsaz [39] by applying them to analyse the Boeing 727-100 aircraft. In the academia too, many conceptual design computer codes have been developed, such as ADAS (Aircraft Design & Analysis System) [40] at Delft University of Technology, CAPDA [41] at Technical University, Berlin, PRADO [42] at Technical University Braunschweig, and AIRPROD (Aircraft Initial PROject Design) [43] at Loughborough University, UK.

All the above mentioned codes use some form of conventional computer programming languages e.g. FORTRAN & PASCAL. Due to the sequential nature of these languages, the codes have limited flexibility i.e. their logical sequence cannot

be altered to make the most use of the data and information available at any stage in the analysis. This has lead to several attempts by researchers to explore the use of Artificial Intelligence (AI) techniques. Furthermore, the use of AI techniques emphasises on an interactive approach in which the judgement and knowledge of the designer is used to speed up and direct the design process. A detailed description of many such codes has been provided by Pasaribu [44], which include PASS (Program for Aircraft Synthesis Studies) of Stanford University, RUBBER AIRPLANE of MIT, DSIDES developed at Houston University, ADROIT (Aircraft Design by Regulation of Independent Tasks) of Cranfield University and ACES (Aircraft Configuration Expert System) of Aeritalia and CSI Piemonte of Italy. Recently, a commercial aircraft design package called PIANO has been developed by Lissy Ltd, Loughborough, written in LISP, which is an AI language.

Most of the above codes are either proprietary in nature, or are not available at sites other than where they were developed, hence they could not be applied for the present work. None of the above methods have a detailed airport layout and cost estimation module; instead, they use Take off & Landing field lengths as user specified constraints. The commercially available packages such as RDS and AAA were principally aimed at parametric studies and analysis of a specific user-specified geometry, and hence were unsuitable. Further, very few of the above mentioned codes had the capability of analysing turboprop engined aircraft, which are much more difficult to analyse compared to the turbojet or turbofan engined aircraft, due to the increased complexity caused by the presence of the propeller. In a previous study [45] related to G.A. aircraft (which is described in more detail later and in Chapter 6), a methodology for direct coupling between the aircraft configuration & operational parameters was outlined. Two mission related parameters viz. cruising altitude & speed were optimised along with the aircraft configuration in terms of passenger capacity, wing parameters & type of landing gear. An attempt was made to accurately model the climb and descent modules G.A. aircraft over short stage lengths for air-taxi operations. However, the methodology was considered to be far too simplistic for direct application in the present work. Loftin [46] has provided several formulae for parametric analysis and performance estimation of propeller driven aircraft. But these formulae were also found to be unsuitable and quite outdated for present work.

2.3 CASTOR code

The GATEP code described above was coupled to a flight profile optimisation routine called SCOPE [15] in a SERC² sponsored collaborative project between Loughborough University & Short Brothers plc in mid-Eighties. The resulting code was

²Science & Engineering Research Council, UK.

called CASTOR which stands for *Commuter Aircraft Synthesis and Trajectory Optimisation Routine*. This code was found to be ideally suited for application in present work, since it was specifically developed for analysis of turboprop aircraft. Furthermore, the source code of this program was listed in [47]. However, in view of the fact that it was nearly a decade old, it was critically analysed, and several areas that needed modifications and/or improvements were identified. It was also decided to check the validity of some of the sub-modules of this code with the data related to present day commuter & regional transport aircraft. A description of the various sub-modules of CASTOR is provided in Chapter 5, and the various modifications that were carried out are discussed in Chapter 9.

2.4 Literature on Generalised Cost & Time related costs

Generalised cost is a well established concept in transportation literature, and many studies have been carried out to estimate and compare the generalised cost of travel by various modes of transportation e.g., rail, bus and private automobile. An approach that has been found helpful in explaining peoples' travel choices is to relate demand to a generalised cost of travel that has time and money components. According to Goodwin [48], the Department of Environment had recommended standard procedures as early as in 1970 for estimation of generalised cost, in which it was considered as a linear sum of the component variables, each with a coefficient reflecting its relative importance. Generalised cost has also been used in many cost-benefit analysis studies. It has also been applied in the analysis of air-transportation networks. Alamdari [49] has used the generalised cost of passengers as a merit function to explore the interactions between fare and service frequency in different competitive environments. MacDonald [11] has developed a model to minimise the generalised cost of travel of corporate air passengers. He has demonstrated that due to high access & time costs, operation of large capacity aircraft on short haul routes does not necessarily produce a minimum generalised cost solution.

In most of the studies related to generalised cost, the main cost components are the fare paid by the passengers and the money equivalent of time spent in travel. The access time and costs are also included in some cases. Some researchers have suggested inclusion of other cost components in the estimation of generalised cost. For e.g., Goodwin [48] suggests that apart from the fare & time terms, the generalised cost equation should also include the effort put in by the passenger during each stage of the journey, to take into consideration the discomfort experienced by the travellers by various modes of transportation. A similar concept has been suggested by Gogate et al. [50] by including a *comfort factor* in the generalised cost equation.

Inclusion of airport and time related costs in the estimation of generalised cost was also suggested in this study, which is discussed in more detail below.

2.4.1 Literature on value of time

A systematic estimation of $\mathcal{V}$ of business and leisure air-travellers in Australia (based on actual survey of passengers) revealed that there is a great difference in the $\mathcal{V}$ for leisure and business passengers, and that $\mathcal{V}$ for domestic business travel is much higher than that for international travel for business trips [51]. Gronau [52] has shown that the price of time affects the choice between air transportation and other modes of travel. He developed a theoretical model to predict the passenger choice among air, rail & bus transportation, given the trip distance and value of time. Based on a study of travel demand from New York city to neighbouring cities in 1963-65, business travellers were found to behave as if their $\mathcal{V}$ is approx. equal to their hourly earnings. However, it was also observed that $\mathcal{V}$ of an individual may vary not only with the purpose of the trip, but also with the trip time, length, time of the day and several other factors. Moreover, two individuals with the same hourly earnings may also have a different perceived $\mathcal{V}$.

Stubbs et al. [53] have provided a discussion of the concept of times savings & $\mathcal{V}$ and its affect on the demand for travel by various modes of transportation. Estimates for $\mathcal{V}$ for business travellers range from hourly earnings plus an overhead of 10% followed by the UK Ministry of Transport during the cost-benefit analysis of the Third London Airport in 1970 to twice or even thrice the hourly rate suggested by British Airways and the manufacturers of Concorde SST aircraft. More recently, Cooke [54] has discussed the concept of $\mathcal{V}$ and how it affects the decision regarding modal choice between a conventional aircraft and a high speed supersonic aircraft. Further, he provides a methodology for estimation of $\mathcal{V}$ using the data related to operation of Concorde and conventional aircraft on routes between London & New York and Paris & New York.

2.4.2 Literature on defer time

A methodology for estimation of T_{defer} for short-range business travel has been proposed by Alamdari [49], in terms of the number of hours of operation of air-line service per day (N_{hours}) and the daily flight frequency (ω_{day}). Assuming that the passengers have no preference for forward and backward rescheduling of their journey, minimum & maximum value of T_{defer} would be:

$$Min [T_{defer}] = 0$$

$$Max [T_{defer}] = 0.5 \cdot \frac{N_{hours}}{\omega_{day}}$$

Thus, the average value of T_{defer} can be assumed to be :

$$T_{defer} = 0.25 \cdot \frac{N_{hours}}{\omega_{day}}$$

It is evident that T_{defer} is inversely proportional to the frequency of operation.

2.5 Airport design and cost estimation

Airport and aircraft design have been considered as separate activities, with airports being designed to suit the operation of aircraft that are expected to operate from it, and including some margin for future developments. Because local conditions (especially the availability of land, wind-patterns, and presence of obstacles and other airports in the vicinity) strongly affect the layout of the airport, it is very difficult to follow a generic methodology for airport layout and design. However, to ensure some uniformity and to ensure adequate safety of operations, agencies such as International Civil Aviation Organisation (ICAO) and Federal Aviation Authority (FAA) have laid down some standards and recommended practices for Aerodrome³ planning, layout & design such as [3] by ICAO and [4] by FAA. These guidelines are adopted either partly or in whole by the airport certification agencies of the various countries, some of which have issued their own guidelines for licensing of airports, such as CAP-168 issued by the Civil Aviation Agency of UK [55].

The above guidelines and other aspects of airport layout and design are discussed in detail in textbooks such as [5] & [56], which includes structural design of the pavements, layout and geometric design of the airside area i.e. the runways, taxiways, aprons etc., airport drainage, marking and illumination. Caves has provided a very lucid description of the aircraft characteristics that directly affect the layout and design of airports in [56]. One of the important constituent of a civil airport is the passenger terminal. Tasic [57] has carried out an illustrative review of the latest developments in the area of operations analysis and modelling of airport passenger terminal. Most of the work has been reported in the area of conceptual design and layout of passenger terminals for large & International airports, using simulation techniques and operations research. No work was reported in this review that was specifically aimed at arriving at estimates of constructing passenger terminals for small regional airports, hence a need for further research in this area was identified.

³The words Aerodrome and Airport are used interchangeably here.

Airport cost and revenue structure is discussed by Doganis in [7], who has also highlighted the problems that beset the regional airports in developing countries viz. very low passenger throughputs, low service charges, and rebates on landing fees. Furthermore, he has outlined the need for a change in the accounting practices for reporting the performance of regional airports in developing countries, to enable them to be run as commercially oriented enterprises rather than government departments. A detailed discussion of the various aspects of airport accounting and financing is provided by Ashford & Moore in [6].

2.6 Aircraft-Airport system cost analyses

The continued growth of the domestic air travel industry has placed a strain on the capacity of airports serving larger cities. This has lead many manufacturers and government bodies (such as NASA) to investigate the market potential, aircraft technology, operating economics, ground facility requirements and the environmental impact of STOL⁴ aircraft [5]. In these analyses, the principal variables were the runway length, number of passengers and the method of providing lift. Most of these studies (e.g.[58]) concluded that the operating costs of STOL aircraft depend a great deal on the length of runway available, and that there were excessive economic penalties in limiting the runway length below 2000 ft (610 m). Based on these studies, runway lengths of 3000 ft to 4000 ft (915 m to 1220 m) were considered viable for the development and operation of STOL airports. Similar conclusions have also been reached by Howe [59] in his analysis of the penalties associated with reduction in Balanced Field Length of short-haul aircraft. The development of VTOL⁵ aircraft offers a potential solution to inter-urban transport, but their economics and noise-generation have made them less attractive than STOL aircraft, except for niche applications such as downtown Manhattan to JFK airport. A modern example of such a STOL port built within the city limits is the London City Airport [60].

A cost-benefit analysis of developing a new airport near an existing one in a developing country was carried out by Adler [61] in the form of a case study. The airport was designed for scheduled operations of a 40 seat regional aircraft, for travel demand varying from 130 to 750 passengers per day, over a period of 22 years. The benefits of developing the airport were evaluated in terms of the reduction of generalised cost of travel of passengers, which included time costs and fare paid for local travel to and fro the airport. This study demonstrated that for high value of time and low capital costs, the benefits exceed the airport setting-up and operating costs. For the assumed values of various parameters of the case study, however, the project was shown to be economically unviable.

⁴Short Take-off & Landing.

⁵Vertical Take-off & Landing.

A novel approach to cost estimation of the aircraft-airport system was presented by Caves nearly 20 years ago [62]. This report was a part of a study to assess the appropriate allocation of inter-urban modes of passenger transport over the full spectrum of range and route density. The study was aimed at low-density situations. Cost comparisons between various transport systems e.g. automobile, rail & aircraft were carried out as a part of this study. In this report, empirical procedures for estimating unit costs for aircraft and airports of varying traffic capacities were proposed. These were then used for estimating capital and operating costs for a series of air-transport systems to meet differing requirements of capacity and range. Three levels for the *air-system* were considered viz. Trunk, Regional & Local, with 2 or 3 appropriate aircraft associated with each category.

The capital and operating costs of the ground infrastructure (i.e. the airports) were determined under two heads, fixed and variable (i.e. depending on the passenger throughput). The components of the fixed costs were the runways, taxiways, land, control tower, safety services, lighting & navigation. Variable costs consist of terminal buildings for passenger and staff, aircraft aprons and car parks. Costs associated with the non-aeronautical activities as well as aircraft maintenance facilities were not considered, as the object of the study was to compare resource costs. Further, the system was considered to be optimised, i.e. no allowance was made for the facilities other than those deemed necessary for the given scheduled operations.

Estimation of airport cost components (both capital costs & operating costs) was based on data obtained from various sources in the UK, which was not according to a uniform format. Hence it was subject to gross inconsistencies, which was clearly acknowledged by the author. The aircraft operating costs were also obtained from various sources such as the airlines, manufacturers and published reports. A large amount of scatter was observed due to variations in seats available, average stage length, utilisation achieved, and accounting procedures for depreciation and operating methods.

For the third level system (which corresponded to low density short and medium haul operations), it was seen that the annual airport cost and the seat-mile cost per passenger increase drastically as the number of round trips per day fell below 4, and the stage length reduced below 100 miles. The total operating costs of this air-system also increased rapidly as the number of annual one-way passenger trips reduced below 15000.

The report concluded that by a judicious selection of appropriate aircraft and frequency of operation, the resource costs per passenger per mile can be kept competitively down. Another important conclusion was that at low frequencies and ranges, the airport costs tend to be a very large part of the total system costs. One of the strong recommendations of the study was a more accurate estimation of system costs by including the resource cost of time, which was ignored. Further,

a more systematic and consistent approach to estimation of various cost terms was also recommended.

2.7 Previous study on Air-Taxi aircraft

In a previous study ([50] & [45]), the feasibility of incorporating operational & economic parameters directly in the conceptual aircraft design procedure was investigated. A methodology for the conceptual design optimisation of a public transport vehicle for a specific network was proposed. A new objective function ($\mathcal{P}$) was developed, which was a combination of the Fare, the time spent in travel, and a Comfort Factor. The Value of Time ($\mathcal{V}$) of passengers was also considered while evaluating $\mathcal{P}$. For operation over virgin areas, the sizing of the transport termini and estimation of the costs associated with their construction was an intrinsic part of the vehicle optimisation studies.

As an example, this methodology was integrated in the conceptual design of twin-engined pistonprop and turboprop General Aviation aircraft to be employed for Air-Taxi operations over a hypothetical network. The optimum location of the airport from the city centre, and the minimum runway length required for safe operation was determined. The costs associated with construction and maintenance of a runway at each node of the network (C_{rw}) were estimated and charged to the passengers as a part of the Fare. A set of 8 aircraft related parameters which corresponded to the minimum $\mathcal{P}$ is obtained, while assigning nominal values to the remaining parameters. 8 test-cases were investigated and the sensitivity of $\mathcal{P}$ to the design variables was determined. It was found that the aircraft capacity and the cruising speed were directly dependent on the $\mathcal{V}$, and the inclusion of C_{rw} in $\mathcal{P}$ tended to drive the optimum towards lower cruising speed. In all the cases studied, turboprop aircraft were seen to have a lower $\mathcal{P}$ compared to the pistonprop type. Further description of this study is given in Chapter 6.

This study formed the baseline for the present work. It was decided to replace the algorithm for design synthesis that was followed in this study by a more robust and accurate one. A need was felt for more accurate and detailed estimation of airport related costs, for which a new airport model was developed. However, since the objective function was expected to be highly non-linear without any prior information about its possible behaviour, it was essential to identify a suitable optimisation method that could tackle such an objective function. For this, a review of existing literature related to optimisation methods suitable for engineering design problems was carried out, which is discussed in the next chapter.

Chapter 3

Overview of Optimisation Methods for Engineering Design

3.1 Introduction

In all optimisation methods, the aim is to arrive at the set(s) of variables that correspond to the *best* (i.e. minimum or maximum) value of a function, without violating any constraints. The function to be optimised is referred as *objective function*. The problem can be mathematically stated as :

$$\begin{array}{ll}\text{minimize (or maximise)} & f(x) \\ \text{with} & u_i \geq x_i \geq l_i, i = 1, n \\ \text{subject to} & g_j(x) \leq 0, j = 1, m\end{array}$$

where f is the objective function, x_i is an n -dimensional vector of variables, with upper & lower bounds u_i & l_i , respectively, and $g_j(x)$ are the imposed constraints. If no upper & lower limits are imposed on x_i , and if $g_j(x)$ is absent, then the problem is termed as *unconstrained*. Any point x_k is termed *feasible* if none of the $g_j(x)$ constraints are violated when $f(x_k)$ is evaluated.

The trivial solution to any optimisation problem is to carry out an exhaustive search, i.e. evaluate f at all possible x_i sets. The only drawback of this approach is that even for the simplest of problems, far too many function evaluations are required. In all optimisation methods, the number of function evaluations required to reach the optimum are reduced by adopting a specific strategy to step from one trial point to the other. The main difference between various optimisation methods is the mechanism by which the the next trial point is decided from the current one.

Using this feature as a means of classification, various optimisation methods can be considered to fall under one of the following two categories :

- Deterministic methods
- Stochastic methods

A brief description of some of the commonly used optimisation methods of both these types is provided in the next section. Only those methods that have been reported in literature to work well on engineering problems (with a special emphasis on aerospace vehicle design) have been discussed. More examples are available in the review paper by Ashley on application of optimisation methods in aeronautical engineering [63].

3.2 Deterministic optimisation methods

In deterministic optimisation methods, each successive trial point during the optimisation cycle is determined from the previous one in a deterministic fashion i.e. they are mathematically related in some direct way. Most of the general purpose and commercially available optimisation methods fall under this category, and they have been found to be very robust for certain applications.

3.2.1 Calculus based methods

These are the most common of the deterministic methods. They are also known as *gradient based methods* since the gradient of f (Δf) is used to generate the next trial point, where

$$\Delta f = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \frac{\partial f}{\partial x_3}, \dots, \frac{\partial f}{\partial x_n} \right) \quad (3.1)$$

It may be noted that Δf may be generated numerically or analytically. In the simplest gradient based method, viz. *steepest descent*, Δf is used to determine the direction that leads to the largest improvement in f . For instance, in a minimisation problem,

$$x_{new} = x_{old} - \alpha \cdot \Delta f \quad (3.2)$$

where α is a scalar that varies the magnitude of the step. In the initial stages of optimisation, a small value of α is used, which is progressively increased till no further improvement in f is observed¹. Once the best α for the current gradient

¹Maximum move limits are sometimes established to keep the optimiser from taking too large a step in a non-linear problem [64].

direction has been evaluated, x is updated and a new gradient direction is calculated. This process is repeated until convergence is reached i.e. when

$$\frac{\partial f}{\partial x_1} = \frac{\partial f}{\partial x_2} = \dots = \frac{\partial f}{\partial x_n} = 0 \quad (3.3)$$

The steepest descent method can be very inefficient for objective functions that exhibit a steep slope near the optimum solution, since it uses only the local gradient information and hence may require several small steps before converging. To overcome this problem, *conjugate gradient methods* such as *Fletcher-Reeves* & *Polak-Ribiere* and *quasi newton methods*² such as *DFP*³ & *BFGS*⁴ have been developed [65]. These methods utilise the partial derivative information to improve the search strategy, and differ from each other mainly in the memory requirements, and the mechanism of devising the search strategy.

Many examples of application of these methods in problems related to aerospace vehicle design are reported in literature e.g. [66] & [67] for unconstrained minimisation within one discipline of aerospace engineering and [33] & [68] for conceptual aircraft design in the presence of constraints. Such methods have also been successfully applied to multidisciplinary design problems of unconventional aircraft, e.g. a gradient based optimiser NPSOL was used for investigation of the control system of tail-less flying wing aircraft & an oblique wing aircraft [69].

RQPMIN (*Recursive Quadratic Programming for MINimization*) is another quasi-newton optimisation program developed by DRA, Farnborough, UK, which has been extensively applied in the area of conceptual design of combat aircraft is discussed in [25] & [70]. It is a gradient search procedure in unconstrained domain. Constraints are considered using a penalty function approach, and they are progressively tightened as the optimisation proceeds. The step size is also changed progressively on the design surface, till the convergence criteria is met. It can handle up to 50 design variables and up to 75 equality or inequality constraints. Further details of this method are given in [71].

3.2.2 Non-gradient methods

For optimising functions whose partial derivatives are not available or very difficult to evaluate, there do exist some deterministic methods that need only function evaluations⁵. The most popular of these is the *downhill simplex method* [65] due to Nelder & Mead. However, this method is not very efficient in terms of number of

²Also known as *variable metric methods*.

³Davidon-Fletcher-Powell.

⁴Broyden-Fletcher-Goldfarb-Shanno.

⁵Such methods are also referred to as *Direct Search* methods.

function evaluations required, and needs to be restarted from the end point to ascertain the optimality of the claimed solution. Further, for optimising an n dimensional function, it needs $n + 1$ feasible starting points as input, which may not always be possible. Powell's *directional set method* is another such method, which is usually better than the simplex method for most problems [65]. Powell's method (and its many modified versions) solve a multidimensional optimisation problem by carrying out a series of successive one-dimensional optimisations along specific directions that are determined as the optimisation proceeds. As is evident, smoothness of the objective function is a pre-requisite, and a large number of function evaluations may be needed.

3.2.3 Response Surface methods

These methods belong to the realm of statistics, and are very useful in tackling problems where the evaluation of objective function is numerically very expensive. A response surface is essentially a polynomial approximation of the actual function space, constructed by evaluation of the function at carefully selected trial points. The nature of the function is then inferred from the values obtained from the response surface. Response surface methods are very useful tools to provide an insight into the behaviour of complex phenomena over a wide range of parameter values. They can be used to eliminate some variables by sensitivity analysis [72].

A statistical method called *Design of Experiments* is frequently used for selection of the points where the response surface is generated. This method provides a means for exploring the function space with least possible number of function evaluations. For e.g., this method can generate the specific sequence of $[0.5 \cdot (n + 2) \cdot (n + 1)]$ trial points required to generate a quadratic⁶ response surface for an n dimensional problem.

A specialised application of the design of experiments called *Taguchi method*, is very useful for tackling objective functions with a very large number of discrete variables. Taguchi method does not necessarily come up with the true optimum⁷, since it is designed to put more emphasis on the most robust solution. But it does provide means to characterise the function space, by providing information about interactions, parametric trends and noise variances.

Response surface methods have been used in many engineering design problems, including aerospace applications. The ARES code used by Boeing for aircraft engine

⁶In general, the response surface model should be at least quadratic to be a useful global representation of the problem.

⁷Repeated iterations of the method with grid size refinements may be necessary to ensure that the solution is truly optimum.

design and the structural design code ANSYS are based on this method [72]. In a recent study, Hadjiilias has applied a response surface method to carry out the aerodynamic design of a wing-fuselage junction fillet to minimize the interference drag [73]. Taguchi methods have also been applied to aerospace vehicle design problems, for instance for the design of a dual mixture ratio single stage to orbit rocket powered launch vehicle [74].

3.3 Merits & demerits of Deterministic optimisation methods

Calculus based methods have been found to be very robust for smooth, continuous and unimodal functions. These methods depend heavily on the ability to evaluate Δf and assume that the function is differentiable and continuous. If the objective function of a problem can be simplified to an algebraic equation either by limiting the scope of the problem or by using approximations, these methods can be very viable and powerful tools. They can also be used to tackle the linear sub-problems of non-linear problems.

Many objective functions, however, are not easily differentiable, and may not even be continuous in the entire domain. Calculus based methods are inadequate in problems where the function space is discontinuous, as the derivatives of both f & g_j may become singular across the boundary of discontinuity. Further, it is very difficult to employ these methods if the variables are a mix of continuous & discrete numbers, which is usually the case in complex engineering problems [75]. Another serious limitation is that they are very much prone to getting stuck in the local optimum. The most common method adopted to tackle this problem is to repeat the optimisation run from many different starting points, but this is a very tedious and numerically expensive option.

Some of the drawbacks of calculus based methods are overcome by the non-gradient methods. However, they too are inefficient in tackling discontinuous and complex functions. The main drawback of response surface methods is that unless the form of the true function surface is known, it is difficult to predict the error incurred in using the response surface values rather than the true values from the analysis code. The underlying assumption that useful information about the general trends can be obtained using a response surface based on smaller number of points may not be true for many problems [72].

3.4 Stochastic optimisation methods

Stochastic optimisation methods are the ones in which the mechanism of generation of trial point involves an element of randomness. The most basic stochastic method is called *random walk*, in which trial points are generated by purely random combinations of variables. Stochastic methods are not influenced by the non-linearity and/or discontinuity of the objective function. Due to an element of randomness in their progression, they are less prone to getting stuck in a local optima. Some of the well-established stochastic optimisation methods that have been successfully applied in engineering problems are briefly described below

3.4.1 Monte-Carlo method

The simplest of the stochastic optimisation methods belong to the category of random search or Monte Carlo method. In these methods, many combinations of variables are randomly generated, and the values of the variables corresponding to all solutions that are better than the previous best are recorded. The trend of variation of the values of the optimum set of variables are carefully monitored. Based on these trends, the upper and lower bounds of the variables can be adjusted so as to increase the number of feasible solutions. The method is terminated when no worthwhile improvement in the optimum function value is observed, either over a specified period of time, or after a certain number of function evaluations have exceeded. One such method, called as *Monte-Carlo method with interactive interval reduction* has been developed by Kalker-Kalkman [76]. In this method, the optimisation code is coupled to a graphical interface, using which the variable ranges can be easily modified. The method has been used to solve a multitude of real-life engineering problems e.g. design of an externally pressurised bearing, involving a mix of continuous, integer and discrete variables [77].

Merits & demerits of Monte Carlo method

The main advantage of this method is that there is no danger of converging to a local optimum, since no information about the variation of design variables in the previous designs is retained, except the value of the objective function. The method can handle a mix of discrete and continuous variables, since no derivative information is needed. Thus various differing concepts of the design (for instance fixed or retractable landing gear) can be optimised in the same run, rather than optimising sub-groups of design variables.

The main drawback of this method is the excessively large number of function

evaluations required even for problems with a relatively small number of design variables. Thus, this method is suitable for only those problems where the calculation of objective function is not numerically expensive. Further, no information about the design domain or sensitivity of the objective function to the values of various design variables is made available to the user at the end of the optimisation process.

Monte Carlo method has been used for aerospace design applications, e.g. for the simulation of the geometry of the space shuttle [78].

3.4.2 Genetic Algorithms

Genetic Algorithms (GA) are based on the Darwinian model of survival of the fittest, and are extensively described in [79], [80], & [81]. They work by maintaining a pool of several competing designs, which is termed as the *population*. All members of the population are considered as carriers of good qualities that can be inherited by new generations, and are randomly combined to find better solutions. Each population member is generally represented by a string of binary coding⁸ that encodes the variables. These strings are analogous to the chromosomes forming the genes of the biological individual in an evolutionary chain.

GA use three mechanisms which are analogous to biological evolution viz., *selection*, *crossover* & *mutation*. In *selection*, members of the population for the next generation are decided. The probability of selection of each member to create the next generation depends on its fitness (i.e. the objective function value), and the total fitness of the population. The search proceeds towards the global optimum by iteratively selecting fitter individuals for further reproduction using *crossover*, in which the strings of two fit parents selected from the present generation are interchanged at a randomly selected crossover location. Further, an operator called *mutation* is employed to each bit with a very low probability, in which the bits are flipped. Mutation creates diversity in the population, and reduces the chances of getting stuck in a local optimum. As the iterations proceed, it is found that the subsequent populations are of an increasing quality, since the average fitness value of the population improves. The method is said to have converged if all members (or a large fraction) of the population have similar values of fitness, or if the improvement in the objective function achieved over the last few generations is below a user-specified value.

A simple GA code is described in more detail in Chapter 6. GA have been successfully applied in many aircraft conceptual design studies e.g. [82], [83] & [84]. A methodology for application of GA to problems characterised by a mix of integer, discrete & continuous variables was provided by Lin & Hajela [75].

⁸Real coding is also possible, in which the actual value of the variable is used.

Merits & demerits of Genetic Algorithms

There are some very attractive features of GA that have made them quite a popular tool for Engineering Optimisation. They work on the coding of the problem and not on the problem itself, hence the same general purpose GA code can be used for many different optimisation problems. Problem specific information can be utilised to fine-tune a GA to work better, but there is empirical evidence that even simple GA codes usually give fairly acceptable results [85]. They can be used for highly complicated and non-linear functions, as long as some measure of fitness can be calculated. It is quite easy to modify the GA code to adopt to the variations of the problem at hand. There is also a great scope for use of parallel processing in the GA code, leading to increased computational efficiency.

The main drawback of GA is that it usually requires very large number of function evaluations compared to the gradient based methods, even for the simplest of the problems. The strength of GA lies in being able to quickly identify the most promising regions of the function space, but they are not good for identifying the exact optimum, as this usually needs a very large number of generations. Even when dealing with continuous variables, GA works on a discrete representative set of those variables, hence they can be expressed only up to a certain degree of precision. Any desired level of precision can be achieved, but at the cost of increased length of the binary string, which may increase memory and run-time requirements⁹. Many trial runs may be required to tune the GA parameters in some cases, and a rigorous and universally accepted mathematical proof of the mechanism of GA is still lacking.

3.4.3 Simulated Annealing

Simulated Annealing (SA) is a stochastic optimisation method introduced by Metropolis et al. [86] and is based on the thermo-dynamical analogy of annealing of metals. It was first proposed by Kirkpatrick et al. [87] for optimisation of combinatorial problems (in which the objective function is defined in a discrete domain) and was successfully employed for objective functions involving very large number of variables (even tens of thousands). Corana et al. [88] were among the many researchers who extended the method for objective functions involving continuous variables.

When a molten metal is allowed to anneal i.e. cool slowly, it eventually arrives at a low energy state. SA tries to minimise some analogue of energy in a manner similar to annealing to achieve the global optimum. It allows excursions of the objective function away from the optimum direction once in a while, which enables it to climb out of the local optima. In the beginning, only the gross behaviour

⁹This limitation is present only when binary coding is used, and is obviated by using real coding.

of the function is explored, but as the temperature falls, the criteria for selecting non-optimal configurations is progressively tightened. The method involves very few internal calculations, is quite easy to code and implement. It has been found to be quite robust for tackling discontinuous and multi-modal problems [82] and has been demonstrated to arrive at the global optimum of test functions with an extremely high number of local optima [88].

SA has been mathematically proven to converge to the global optimum independent of starting values, given enough time to converge by using an appropriate annealing schedule [72] & [89]. In practice, however, an upper limit on the maximum number of evaluations permissible has to be imposed, hence the algorithm may not always end up in the global optimum. However, this method is able to discriminate between the *gross behaviour* of the function and the finer *wrinkles*, by locating an area in the function domain where the global optimum is likely to be present, and then developing finer details to end up at a good near-optimal local optimum, if not the global optimum itself.

Merits & demerits of Simulated Annealing

SA first builds up a rough picture of the function behaviour by moving in large steps. As the temperature falls, and the step lengths decrease, it slowly focuses on the most promising area. During the entire search procedure, movements in a direction opposite to the desired one are also possible, which allow the algorithm to climb out from the local minima, finally converging to the global or near-global minima. There is no requirement for the function to be smooth, or differentiable; Corana et al. [88] have demonstrated the efficacy of SA in arriving at the global minimum of a parabolic function punctured with holes, and Goffe et al. [90] have demonstrated its power in optimising complex statistical functions. Another feature of SA is that useful information about the sensitivity of the objective function to the design variables can be obtained by observing the variation in their step sizes as the algorithm proceeds. A large step size for a particular design variable indicates that the function is quite flat in that parameter. Thus, not only does the algorithm examine the entire domain of the function, it also indicates which parameters affect it the most. But the most important advantage of SA is that it can optimise many objective functions which are otherwise difficult or impossible to optimise by calculus-based methods.

There are, of course, some drawbacks of SA, the major one of which is that it needs a very large number of function evaluations compared to other methods (if they can solve the problem). Another weakness, shared by most Direct Search methods, is that constraints can only be handled by augmenting the objective function with a *penalty function* i.e. a function where high value is artificially assigned to the

objective function being minimised, when the constraints are violated¹⁰. Further, a few trial runs are required to “tune” some optimisation related parameters (whose appropriate values tend to be problem-specific) before the final results can be obtained. Although some guidelines are available for carrying out these trial runs, for some functions they may involve considerable effort.

Summing up, SA is suitable for optimising an objective function f if

- there is no *a priori* information about the behaviour of f , or
- f is expected to be non-smooth, multi-modal or discontinuous, and
- the global minimum of f is desired, but
- the evaluation of f is not numerically intensive

3.5 Merits and demerits of Stochastic optimisation methods

Stochastic optimisation methods are more likely to arrive at the global optimum compared to the deterministic methods, due to the presence of the random element inherent in them, which also makes them function independent to some extent. However, this random element also brings with it a couple of problems.

- Two runs of the method from the same starting point may end up with different results, depending on the path taken by the algorithm. These methods usually require a user-specified seed(s) for the pseudo-random number generators that they use. Different seeds correspond to different sequence of numbers being generated, hence the path followed by the algorithm differs. However, this very feature can be utilised to ascertain the *confidence level* on the “globalness” of the optimisation achieved. For e.g., if several runs with different sequence of random numbers employed to generate trial points end up at the same (or very similar) optimum, it is likely to be a very strong local optimum, if not the global optimum itself.
- The number of function evaluations for stochastic optimisers is usually much larger than that required by calculus based optimisers. For smooth, unimodal and continuous functions, stochastic methods are very much inferior to calculus based methods.

¹⁰The penalty function approach to handle constraints is discussed in Appendix H.

Stochastic methods are very useful if there is little or no prior knowledge of the behaviour of the objective function. They can be employed in situations where deterministic methods usually fail, such as non-differentiable or highly discontinuous functions, or functions with a mix of integer, continuous and discrete variables.

A comparative evaluation of 5 different gradient based & stochastic optimisation methods for combat aircraft parametric design was carried out at Lockheed Aeronautical Systems [82]. The objective function was formulated in terms of 8 aircraft related variables, and 24 different optimisation runs of each method were carried out, with the same upper limit on maximum permissible evaluations of the objective function in each run. The comparison included a statistical test to determine the probability of achieving good results just *by chance*¹¹. The study concluded that the best results were obtained with SA method, followed by the modified GA method.

3.6 Selection of suitable optimisation method

There is no optimisation method which is universally good for all applications, hence a suitable method is to be selected keeping in mind the nature of the objective function. Wolpert & Mcready [91] have proposed the “No Free Lunch” theorem of optimisation, according to which any (optimisation) algorithm performs only as well as the knowledge concerning the cost (objective) function is put into use in the cost (objective) evaluation procedure. Further, they have concluded that on an average, all optimisation methods are equally effective, and have suggested that an optimisation method should be tailored to suit the problem at hand, using the information about the function. Hence, the relative strengths & weaknesses of deterministic & stochastic methods must be utilised in selection of the appropriate method. To achieve this, many hybrid methods have been developed, which incorporate the useful characteristics of both types of methods. One such method is SIGH¹², which uses SA or GA to quickly examine the search space to identify likely zones of interest, and then initiate local searches in these zones using gradient based methods [82]. The use of a similar hybrid optimisation method has recently been reported by Bos [92] for multidisciplinary design optimisation of a supersonic transport aircraft.

¹¹Such a test is essential while comparing the *goodness* of results obtained by stochastic & deterministic methods, due to the presence of an element of randomness in the former.

¹²Stochastic Iterated Genetic Hill-climbing.

Chapter 4

Details of SA & GA method

As discussed in Chapter 3, stochastic optimisation techniques have been found to be suitable in arriving at the global optimum of complex, non-linear & multi-modal objective functions. SA & GA are two of the most popular stochastic optimisation techniques that have found wide application in engineering design problems. A brief description of these technique was provided in Chapter 3; this chapter provides further details and the algorithm of an SA & GA code that were used in the present work.

4.1 SIMANN SA Optimiser

In this section, the SIMANN SA algorithm developed by Goffe et al. [90], based on the methodology proposed by Corana et al. [88] for objective functions involving continuous variables is described. This optimiser was used in the exploratory case studies discussed in Chapter 6 & 8, as well as to obtain the final results.

4.1.1 Description of the algorithm

Let $\mathbf{x}$ be a vector with $(x_1, x_2, \dots, x_n)$ as its components. Let $f(\mathbf{x})$ be the function to be minimised¹ and let $l_1 \leq x_1 \leq u_1, \dots, l_n \leq x_n \leq u_n$ be its n variables. Though the design variable $\mathbf{x}_i$ need to be ranging in a finite continuous interval, f need not be continuous, but it must be bounded.

The algorithm starts from a user specified point $\mathbf{x}_o$, which may also be randomly

¹A maximisation problem can be usually be solved by minimising $-f(\mathbf{x})$.

generated. A step length vector $\mathbf{V}_o$, whose elements (v_n) are the initial step lengths in each variable direction. A series of points $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_i, \dots$ are generated, which approach the global minimum of f according to the following steps :

1. Generation of trial points

New points are generated around the current point $\mathbf{x}_i$, applying random moves, in turn, along each coordinate direction, using

$$\mathbf{x}_{i+1} = \mathbf{x}_i + r \cdot \mathbf{V}_i$$

where

$$\begin{aligned} r &= \text{uniformly distributed random number } r \in [-1, 1] \\ \mathbf{V}_i &= \text{step length vector for the } i^{\text{th}} \text{ trial point} \end{aligned}$$

If $\mathbf{x}_{i+1}$ falls outside the design domain of f , a new point is randomly generated until a point belonging to the definition domain is found.

2. Selection criteria

In a minimisation problem, if $f(\mathbf{x}_{i+1}) < f(\mathbf{x}_i)$, then $\mathbf{x}_{i+1}$ is accepted, and if this is the lowest value of f obtained so far, then $f_{opt} \leftarrow f(\mathbf{x}_{i+1})$, and $\mathbf{x}_{opt} \leftarrow \mathbf{x}_{i+1}$. If, however, $f(\mathbf{x}_{i+1}) \geq f(\mathbf{x}_i)$, it is not outrightly rejected (as in the case of gradient based optimisers), but accepted in accordance with the Metropolis criteria [86], i.e. if

$$\hat{p} < e^{\left[-\frac{\Delta f}{T_i}\right]}$$

where

$$\begin{aligned} \Delta f &= f(\mathbf{x}_{i+1}) - f(\mathbf{x}_i) \\ T_i &= \text{A parameter called } \textit{Annealing Temperature} \\ \hat{p} &= \text{A uniformly distributed random number } r \in [0, 1] \end{aligned}$$

The Metropolis criteria ensures that occasional uphill movement in the objective function value is allowed, hence the sequence $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_i, \dots$ does not necessarily correspond to monotonically decreasing f values. Two factors decrease the probability of uphill moves, lower T_i and larger Δf .² The algorithm starts with a high value of Annealing Temperature T_{init} , which is progressively reduced as iterations proceed, in accordance with an *Annealing Schedule*, as explained later. The algorithm is then looped back to step 1.

²However, if $\hat{p} \approx 0$, even cases with small T_i & large Δf may be accepted.

3. Step length adjustment

After N_S steps through all design variables, their step lengths $\mathbf{V}$ are adjusted, to ensure that roughly half of all the moves are accepted. The goal here is to sample the function widely ; very high acceptance rate implies that the function domain is not being fully explored, while a very low acceptance rate means that the new trial points are being generated too far away from the current optimum. Both of these imply that the algorithm is not progressing efficiently and involves wasting of computational effort. This is achieved using the following rule for step length adjustment suggested by Corana et al. [88]

$$v_{u_{new}} = \begin{cases} v_{u_{old}} \left(1 + c_u \frac{\frac{n_u}{N_S} - 0.6}{0.4} \right) & \text{if } n_u > 0.6N_S, \\ \frac{v_{u_{old}}}{1 + c_u \left(\frac{0.4 - \frac{n_u}{N_S}}{0.4} \right)} & \text{if } n_u < 0.4N_S \end{cases}$$

where

- u = specific design variable direction ($1 \leq u \leq n$)
- c_u = a varying criterion controlling step length in u direction
- N_S = number of cycles before $\mathbf{V}$ is adjusted
- n_u = number of accepted cases in last N_S evaluations

After adjusting the step lengths, the algorithm is looped back to step 1.

4. Annealing Temperature reduction

After carrying the above loop N_T times, the Annealing Temperature T is gradually reduced using a parameter R_T i.e. $T_{new} = R_T \cdot T_{old}$, where $0 < R_T < 1$. This is called as a geometric annealing schedule, but other schedules such as linear or logarithmic can also be used. The algorithm is then looped back to step 1, with $\mathbf{x}_o \leftarrow \mathbf{x}_{opt}$.

5. Convergence criteria

The iterations are repeated from step 1 till the reduction in f_{opt} in N_{eps} successive cycles is less than a small number eps , or if the total number of function evaluations exceed the user-specified value $maxevl$.

The pseudo code of SIMANN algorithm is shown in Table 4.1.

4.1.2 Tuning of SIMANN parameters

As with all general purpose optimisation methods, some control parameters in SA have to be “tuned” to suit the objective function, and to ensure that the optimiser performs efficiently. The eight such control parameters in SIMANN are :

```

READ  $T_{int}$ ,  $R_T$ ,  $N_T$ ,  $\mathbf{V}$ ,  $\mathbf{c}$ ,  $N_S$ ,  $max_{evl}$ ,  $N_{eps}$  &  $eps$ 
CALCULATE  $f_o = f(\mathbf{x}_o)$ 
 $\mathbf{x}_{opt} = \mathbf{x}_o$ 
 $f_{opt} = f(\mathbf{x}_o)$ 
DO UNTIL CONVERGENCE
DO  $N_T$  times
DO  $N_S$  times
DO  $i = 1, n$ 
GENERATE  $\mathbf{x}_n$ 
CALCULATE  $f_n = f(\mathbf{x}_n)$ 
IF  $f_n \geq f_o$ 
APPLY METROPOLIS CRITERIA
IF ACCEPTED:  $\mathbf{x}_o = \mathbf{x}_n$  &  $f_o = f_n$ 
ENDIF
IF  $f_n < f_o$ , THEN
 $\mathbf{x}_o = \mathbf{x}_n$  &  $f_o = f_n$ 
ENDIF
IF  $f_o > f_{opt}$ , THEN
 $\mathbf{x}_{opt} = \mathbf{x}_o$  &  $f_{opt} = f_o$ 
ENDIF
END DO
END DO
ADJUST  $\mathbf{V}$  SO THAT 50% OF ALL TRIALS ARE ACCEPTED
END DO
IF CHANGE IN  $f_{opt} < eps$  IN LAST  $N_{eps}$  ITERATIONS,
AND  $|f_n - f_o| < eps$ , OR  $max_{evl}$  EXCEEDED, THEN
REPORT  $\mathbf{x}_{opt}$ ,  $f_{opt}$  &  $\mathbf{V}$ 
STOP
ELSE
 $\mathbf{x}_o = \mathbf{x}_{opt}$ 
 $T = R_T \cdot T$ 
ENDIF
CONTINUE

```

Table 4.1: Pseudo algorithm of SIMANN for function minimisation

1. Initial Annealing Temperature (T_{int})
2. Temperature reduction factor (R_T)
3. Number of cycles before Annealing Temperature reduction (N_T)
4. Starting step sizes for n design variables ($\mathbf{V}$)
5. Step size reduction criterion ($\mathbf{c}$)
6. Number of cycles before step size reduction (N_S)
7. Number of cycles for checking convergence criteria (N_{eps})
8. Minimum reduction in f acceptable before termination (eps)

A bad choice for these parameters can make the algorithm extremely inefficient and may even result in failure to arrive at the global optimum³. Strictly speaking, the appropriate values for all these parameters are problem-dependent, but based on some test optimisation runs, the following values have been suggested by Corana et al. [88] for five of these parameters:

$$\begin{aligned}
R_T &= 0.85 \\
N_T &= \max(100, 5 \cdot n) \\
c_k &= 2, k = 1, \dots, n \\
N_S &= 20 \\
N_{eps} &= 4
\end{aligned}$$

The value of eps can be chosen based on the magnitude of the objective function and the minimum improvement in its value that may be considered significant. Since the step sizes of the design variables are continually adjusted as the algorithm proceeds, their starting values do not matter⁴. Further, Goffe et al. [90] have suggested a methodology for arriving at more appropriate values for N_T , R_T and T_{int} , by carrying out a few trial runs, as explained below.

Determination of T_{int} , R_T & N_T

T_{int} and R_T are the two most important optimisation parameters in SIMANN. If T_{int} is too low, then the algorithm is likely to converge to local minima.

To determine the suitable value of T_{int} , Goffe et al. have suggested to carry out a trial run with $T_{int} = 1$, and $R_T = 1.5$. This leads to a 50% increase in the

³This point is illustrated with examples in Chapter 6.

⁴A reasonable starting value for $\mathbf{V}$ can be assigned as $v_i = 0.5(u_i - l_i)$.

Annealing Temperature in each subsequent cycle. By examining the intermediate results, the Temperature T^* at which the $\mathbf{V}$ components cover the entire range of specific design variable i.e. at which $v_i = u_i - l_i$ can be located. Another method to determine appropriate T_{int} is to start the runs from very high T_{int} value. T^* is the temperature at which components of $\mathbf{V}$ start declining rapidly. T_{int} should be assigned a value slightly higher than T^* .

If a very low value for R_T (& N_T) is chosen, then the algorithm “quenches” to a local minimum, whereas too high a value for R_T results in a phenomenal increase in number of function evaluations. A few trial runs from various different starting points $\mathbf{x}_0$ should be carried out with progressively increasing R_T (& N_T) values. The highest value for these parameters at which the algorithm converges to the same (or very similar) optimum configuration as for the previous values could be considered appropriate. By carrying out such trial runs for a particular objective function, Goffe et al. [90] were able to reduce the number of function evaluations required to reach the global optimum by up to 99.6 % !. Hence, any time spent in carrying out these trial runs could be well worth the effort, in the long run⁵.

4.2 A simple GA Optimiser

In this section, a simple GA code developed by the author is described. This code is essentially the FORTRAN version of a similar code developed by Belegundu [93] in BASIC, with some modifications, as explained below. This code was used in one of exploratory case studies discussed in Chapter 6.

4.2.1 Description of the algorithm

Using similar terminology as in section 4.1 for the SIMANN method, let us assume that $f(\mathbf{x})$ is the function to be maximised⁶. The algorithm proceeds to arrive at the optimum solution in the following steps :

1. Encoding the variables of $\mathbf{x}$

Each element $x_1, x_2, \dots, x_n$ of the vector $\mathbf{x}$ is encoded as a binary string of length k_i that represents its real value. The value of each x_i can then (with a certain tolerance) be coded as a number between 0 & 2^{k_i-1} . Depending on the

⁵However, for another objective function, such trial runs did not lead to any reduction in the values for R_T (& N_T) suggested by Corana et al.

⁶In most GA implementations, maximisation of the function is assumed. Minimisation can be achieved by maximising $-f(\mathbf{x})$, or by maximising $\xi - f(\mathbf{x})$, where ξ is a very large number.

desired accuracy of representation of each x_i , the appropriate string length k_i is chosen⁷. The n such strings are then concatenated⁸ to form a *chromosome* of an individual that represents the vector $\mathbf{x}$ of total string length $l_{strt} = (\sum_{i=1}^n k_i)$.

2. Generation of the initial population of *maxpop* individuals

The initial population of *maxpop* individuals is randomly generated, by invoking a random number generator routine l_{strt} times for each individual. In each call to this routine, a random number $r \in [0, 1]$ is generated; the corresponding bit is assigned the value 1 if $r \geq 0.5$, or 0 otherwise.

3. Evaluation of fitness of each member of the population

Each member of the population represents a vector $\mathbf{x}$, which is a possible solution to the problem. The $f(\mathbf{x})$ of each of the *maxpop* individuals is calculated, and considered as its *fitness*. The individual $\mathbf{x}_{opt}$ with the highest fitness value is considered as the current optimum configuration, and its fitness value is stored as the current optimum value f_{opt} .

4. Marking of the biased *roulette wheel*

The members of the population are ranked in the order of decreasing fitness, and the average fitness f_{avg} is evaluated. To ensure that the probability of selection of fitter individuals for further reproduction is higher than that for the less fit ones, a methodology called biased *roulette wheel* marking is used [79]. In this methodology, each individual $\mathbf{x}$ of the population is allocated a portion of a roulette wheel in proportion to its fitness, relative to the total fitness of the population. Thus, the fraction of roulette wheel allocated to the i th of the *maxpop* individuals is :

$$m_i = \frac{f(\mathbf{x}_i)}{\sum_{j=1}^{maxpop} f(\mathbf{x}_j)} \quad (4.1)$$

The *maxpop* individuals are ranked in the order of fitness as $1, 2, \dots, j, j+1, \dots, maxpop$. The fraction of the roulette wheel to be allocated to the individual $\mathbf{x}_i$ with the rank j is calculated as :

$$m_j = 2 \frac{maxpop + 1 - i}{maxpop(maxpop + 1)} \quad (4.2)$$

The roulette wheel is then marked with cumulative value of m_j in the order of ranking of the various individuals.

5. Creation of new population by Selection, Crossover & Mutation

The random number generator is called twice, and two members of the population are selected, using the biased roulette wheel. These two “parents” are

⁷The original code by Belegundu assumed a constant string length for each x_i .

⁸placed one after another.

then “mated” with a probability p_{cross} , to produce two “children” i.e. new $\mathbf{x}$ are created by interchanging the bit strings of the two parents at randomly selected locations. This is schematically illustrated below for the creation of two children C & D from the two parents A & B by crossover at location X.

```

A = 0 1 0 0 0 1 1 1 0 1 1 0 0 1 0 1 1 0 0
      X
B = 1 0 1 1 0 1 1 0 0 0 0 1 0 1 0 1 1 0 0

C = 0 1 0 0 0 1 1 1 0 0 0 1 0 1 0 1 1 0 0
D = 1 0 1 1 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0

```

The operator mutation is then applied to each bit of the two child strings, in which the bits are flipped with a probability p_{mutat} . In this way, a new *generation* of the population is created.

6. Stopping Criterion⁹

The fitness of all members of the new generation is evaluated. The individual $\mathbf{x}_{new}$ with the best fitness is identified, and if $f(\mathbf{x}_{new}) > f_{opt}$, then $f_{opt} \leftarrow f(\mathbf{x}_{new})$, and $\mathbf{x}_{opt} \leftarrow \mathbf{x}_{new}$. The algorithm is terminated if the improvement in f_{opt} in N_{eps} successive generations is less than a small number eps , or if the total number of generations exceed $maxgen$.

The pseudo code of the above GA algorithm is shown in Table 4.2.

4.2.2 Tuning of GA parameters

There are seven parameters in the above GA code which affect its performance, and hence appropriate values have to be assigned to them before the code can be applied to the optimisation problem at hand. For some of these parameters, several trial runs may be needed to “tune” these parameters.

1. Length of the binary string (l_{strt})

The smallest possible size of individual string lengths k_i that result in the desired accuracy of representation of each individual component of the vector $\mathbf{x}$ should be used, to minimise l_{strt} . For instance, for variables that are “on-off” type, i.e. which have only two possible values, $k_i = 1$ is sufficient. Lower l_{strt} also results in lesser computer memory requirements.

⁹There was no stopping criterion in the original code by Belegundu.

```

READ  $maxpop$ ,  $l_{strt}$ ,  $p_{cross}$ ,  $p_{mutat}$ ,  $maxgen$ ,  $N_{eps}$  &  $eps$ 
  GENERATE INITIAL POPULATION OF  $maxpop$  INDIVIDUALS
  CALCULATE FITNESS OF EACH MEMBER
  IDENTIFY MEMBER  $\mathbf{x}_{old}$  WITH BEST FITNESS  $f(\mathbf{x}_{old})$ 
     $\mathbf{x}_{opt} = \mathbf{x}_{old}$ ,  $f_{opt} = f(\mathbf{x}_{old})$ 
DO UNTIL CONVERGENCE
  DO  $i = 1, maxpop$ 
    RANK ALL MEMBERS IN DECREASING ORDER OF FITNESS
    MARK THE ROULETTE WHEEL
    IF  $p_{cross} < \text{A RANDOM NUMBER } r \in [0,1]$ , THEN
      SELECT TWO INDIVIDUALS USING BIASED ROULETTE WHEEL
      SELECT CROSSOVER POINT USING A RANDOM NUMBER  $r \in [0,1]$ 
      GENERATE TWO CHILDREN FROM THE SELECTED INDIVIDUALS
    DO  $j=1, (maxpop \cdot l_{strt})$ 
      IF  $p_{mutat} < \text{A RANDOM NUMBER } r \in [0,1]$ , THEN
        FLIP THE INDIVIDUAL BIT
      ENDIF
    ENDDO
    IDENTIFY THE MEMBER  $\mathbf{x}_{new}$  WITH HIGHEST FITNESS  $f(\mathbf{x}_{new})$ 
  ENDIF
  ENDDO
  IF  $f(\mathbf{x}_{new}) > f(\mathbf{x}_{old})$ , THEN
     $\mathbf{x}_{opt} = \mathbf{x}_{new}$ ,  $f_{opt} = f(\mathbf{x}_{new})$ 
  ENDIF
  IF CHANGE IN  $f_{opt} < eps$  IN LAST  $N_{eps}$  GENERATIONS,
  OR  $maxgen$  IS EXCEEDED, THEN
    REPORT  $\mathbf{x}_{opt}$ ,  $f_{opt}$  &  $V$ 
    STOP
  ELSE
     $\mathbf{x}_{old} = \mathbf{x}_{opt}$ 
  ENDIF
CONTINUE

```

Table 4.2: Pseudo algorithm of GA code for function maximisation

2. Population size ($maxpop$)

Goldberg [94] has shown that the optimal value of $maxpop$ for binary coding increases exponentially with l_{strt} . Even for relatively small problems, this would lead to very high memory storage requirements. However, based on numerical experimentation, Alander [95] has shown that good results can be obtained with $l_{strt} \leq maxpop \leq 2(l_{strt})$.

3. Probability of Crossover (p_{cross}) & Mutation (p_{mutat})

p_{cross} between $0.60 \leq p_{cross} \leq 1.0$ is used in most GA implementations. Higher the value of p_{cross} , higher is the genetic re-combination as the algorithm proceeds, ensuring higher exploitation of genetic information. p_{mutat} is usually assigned a low value, between 1% to 5%, since it is only a secondary genetic operator. Mutation is needed to introduce some random diversity in the optimisation process. However, if p_{mutat} is too high, there is a danger of losing genetic information too quickly, and the optimisation process approaches a purely random search.

4. Maximum number of generations ($maxgen$)

The selection of $maxgen$ is governed by the limits to be imposed on the execution time and number of function evaluations, from practical considerations. In each generation, the objective function is calculated $maxpop$ times, (except in the first generation in which the fitness of the initial population is also calculated) and the various genetic operators are also applied several times as shown in Figure 4.2.

5. Minimum reduction in f for termination (eps)

As in SA, the selection of this parameter is problem dependent, and its appropriate value depends on how much improvement in f may be considered significant. In some problems it may also be desirable to vary the value of eps as the generations increase, since much larger improvements are usually obtained in the initial generations, compared to the final ones.

6. Number of cycles for checking convergence criteria (N_{eps})

The value of this parameter is determined by trial and error, and a value of 3 or 4 is usually quite sufficient. Larger values of N_{eps} increase the chances of converging to the global optimum, but at the cost of requiring more computational time.

Chapter 5

Description of CASTOR

5.1 Introduction

As discussed in Chapter 2 the review of literature revealed that the CASTOR code developed by Simos and Jenkinson at Loughborough University, U.K. was found to be suitable for application in the present work. This Chapter provides a brief description of the various modules of version 1B of this program, whose source code is listed in [47].

5.2 General description

CASTOR is computer program for integrated trajectory and configuration optimisation of commuter aircraft, and is aimed at combining the preliminary design process with flight profile analysis and mathematical optimisation algorithms. It is limited to twin-turboprop aircraft with wing mounted engines, but this indeed is the most common configuration employed world-wide for such aircraft.

The program utilises 24 optimisable variables, of which 12 are design or *configuration* variables, and 12 are flight profile or *trajectory* variables. 13 parameters are used as constraints, and their values or limits are to be specified by the user. While some of these are used to model the physical limitations and the environment within which the aircraft can be expected to operate, the remaining are actually derived parameters, whose values are usually obtained by iterations in conventional aircraft design algorithms. By specifying these parameters as equality constraints in CASTOR, the need for iterative loops in the design synthesis is eliminated. Further, there are 99 fixed parameters in CASTOR, whose values are assumed constant. A

brief description of the optimisable variables, and the constraints used in CASTOR is provided in Appendix H.

The aircraft is *flown* through a specified number of stages, which constitute the main mission, plus a diversion and a hold segment. The output from the program includes the final geometry, component mass breakdown, manoeuvre & gust load factors, centre of gravity (c.g.) positions, trimmed drag polar, optimum flight profiles for the main mission and diversion stages, field performance and the aircraft cost. There is a choice of 3 objective functions in CASTOR, namely minimum fuel (M_{fuel}), minimum take-off mass (M_{TO}) & minimum Direct Operating Cost (DOC).

CASTOR consists of two distinct modules, the Analysis module and the Optimisation module. In the Analysis module, the value of the user-defined Objective Function is determined for a specific set of design variables. The values of the constraint function are also obtained for all the imposed constraints. Unlike almost all other classical aircraft design algorithms, the analysis module in CASTOR is *single pass* i.e. there are no iterations within it to change the values of design variables to meet the constraints, if they are not met. This job is left to the Optimiser module, which runs through several combinations of design variables through the analysis module to determine the set that meets all constraints and has the lowest value of the Objective Function.

The RQPMIN gradient based optimiser was employed in CASTOR for optimisation. This method has been described in Chapter 3. Further details are given in [71].

5.3 Analysis module of CASTOR

The analysis module of CASTOR calculates the value of the objective function for a given set of design variables, along with the value of the constraint functions. It consists of the following submodules.

1. Geometry
2. Mass & Balance
3. Aerodynamics
4. Power-plant & Propeller
5. Airfield Performance
6. Mission Analysis

7. Cost Estimation

8. Noise

A brief description of each sub-module of the analysis module of CASTOR is given below.

5.3.1 Geometry

The first step in CASTOR is to fix the geometry of the wing, horizontal & vertical tails, fuselage and nacelles. Most of these components are sized based on assumed values of geometric parameters which are supplied as input. For instance, the wing geometry is decided based on the input values of aspect ratio, taper ratio, sweep-back angle and area. On the same lines, the vertical and horizontal tails are sized based on assumed values of aspect & taper ratios, and respective tail volumes. Flaps are assumed to start from the wing root, and their area is calculated assuming a specified flap chord to wing chord ratio and flap span to wing span ratio, both of which are specified as input. The fuselage is assumed to consist of three segments, the front fuselage, passenger cabin & the rear fuselage. While the length of the rear fuselage is optimised (as a ratio of the fuselage diameter), the length of the front fuselage and passenger cabin is specified as input, as well as the fuselage diameter itself. The wetted area of fuselage & nacelles is calculated using appropriate formulae listed in Appendix B of [14]. For the fuselage, a circular cross-section and elliptic plan-form for front and rear segments is assumed. Assuming the nacelle to be a fully streamlined body without cylindrical mid-section, the wetted area is calculated using its diameter, length and location of the maximum thickness from the nose, all of which are provided as input. It may be noted that the propeller diameter is also specified as an input in CASTOR, as well as the propeller RPMs at climb, cruise & descent phases.

5.3.2 Mass & Balance

Many formulae based on statistical co-relation of relevant aircraft parameters & component masses are available in aircraft design literature e.g. [12], [13], [14], [96] & [97]. In [98], five such formulae were compared, and the RMS error with the actual wing masses of a few existing twin-engined propeller driven aircraft was determined. The formula that resulted in the least RMS error (8.5%) was used in CASTOR for wing mass estimation. The fuselage mass was estimated as the average of that obtained by three different formulae from [14], [96] & [97]. Other component

masses such as empennage, landing gear, nacelles, surface controls, systems & furnishings were estimated from formulae listed in [14] and previous unpublished work at Loughborough University & Short Brothers plc.

These component masses were used to estimate the c.g. of the empty aircraft after making assumptions about their distribution. Forward & aft c.g. limits were determined assuming typical worst case loading scenarios in full fuel & zero fuel configurations. The most forward c.g. was determined by one of the following :-

- Empty aircraft
- Aircraft with full payload evenly distributed along the cabin
- The seats (and associated payload) next to windows and ahead of the neutral point only were occupied

On the same lines, the most aft c.g. was determined by one of the following :-

- Empty aircraft
- Aircraft with full payload, 80% of which is evenly distributed along the cabin, and the remaining 20% concentrated at the rear bulkhead
- Window seats aft of the neutral point occupied

The field performance evaluation is carried out at the most forward c.g. condition, whereas the stability calculations are made at the most aft c.g. configuration. By specifying an equality constraint on the static margin, it is ensured that the optimum configuration is reasonably stable.

5.3.3 Aerodynamics

This module is used to calculate the aerodynamic characteristics of the wing and flaps at any given operating condition. At a given aircraft lift coefficient, classical linearised trim equations are used to calculate the lift split between the tail-plane & *aircraft minus tail*, which is further apportioned to the wing, fuselage & the nacelle. Simplifications include use of linear lift slopes for wing/fuselage/nacelle and shallow climb angles. Vertical offsets between the c.g., aerodynamic centre & thrust-line are also neglected. Zero-lift drag of the various components is calculated on the basis of the flat-plate and axisymmetric body analogies, along with user-defined values for correction factors for surface finishes & shapes. In the estimation of the

induced drag of the wing, a theoretical factor based on wing taper & aspect ratio is considered. Tail-plane induced drag is modelled in a similar fashion to the wing, and nacelle/fuselage contributions to the total induced drag are assumed equal to the product of their lift coefficients and angle of attack. The induced interference drag between the wing and the tail-plane is calculated using Munk's theorem. Lift & drag due to flap deflection is modelled using the methodology listed in [14], based on thin aerofoil theory. Lift effectiveness and drag correction factors based on the flap deflection and flap type are included for four types of flaps viz. single or double slotted, with or without Fowler movement. The reduction in aircraft $C_{L_{max}}$ due to tail-plane down load is accounted for. It is possible for the user to override the program calculations by specifying the value of aerofoil maximum lift coefficient in the landing configuration.

5.3.4 Power-plant & Propeller

The characteristics of PW-120 aircraft were analysed and surface fitted, using the computer programs provided by the manufactures i.e. Pratt & Whitney of Canada. Take-off SHP at take-off, climb & cruise ratings were provided as functions of altitude & true airspeed, including the gear-box torque limitations. Fuel flow and the residual jet thrust was modelled as a function for power setting, altitude & true airspeed, at design conditions as well as during flight idle, since very low power settings are used in the descent segment of pressurised aircraft. Similar relationships for 4 other power-plants were also generated viz. General Electric CT-7, Pratt & Whitney PT6A-67R, Rolls Royce RB-550 & Rolls Royce RTM 322.

The characteristics for two propellers viz. 5 bladed Hartzell propeller (installed on Shorts SD330-200 aircraft) & 6 bladed Hamilton Standard 14 RF (installed on Shorts SD360-300 aircraft) & are modelled using Chebyshev Polynomial approximation [65], giving thrust coefficient as a function of power coefficient and advance ratio.

5.3.5 Airfield performance

The minimum acceptable performance from the aircraft is specified in terms of constraints on three calculated parameters viz. Balanced Field Length (BFL), Landing Field Length (LFL), & the second segment climb gradient. The first two of these represent limitations on the runway length and hence the airports from where the aircraft is expected to be operated. The third constraint is also referred to as the WAT constraint, which ensures that a climb gradient of at least 2.4% is available if one engine failed at the take-off safety speed (V_2), while operating under specified

values of aircraft takeoff mass (W), airport elevation (A) and ambient air temperature (T). The BFL was calculated at SL-ISA conditions and MTOW, using a closed form expression for given in [14]. This was done to minimise the computational time requirements during optimisation. Similarly, the factored LFL was also estimated using a formula from [46], after modifying it with known data for a few existing commuters.

5.3.6 Mission analysis

Flight profile analysis is conducted using methods similar to the ones developed in a previous study [15]. The climb, cruise & descent phases are split into a number of segments, and an average performance is calculated for each segment. However, climb & descent are divided into a number of equal height segments, as opposed to equal distance, since this lead to halving the number of equality constraints required. Results obtained in [15] revealed that constant rate of descent (ROD) profiles (such as the ones flown with un-pressurised aircraft) were associated with an approximately linear variation of throttle with altitude. This observation is used in CASTOR to model constant ROD profiles by optimising the throttle at the commencement & end of descent, and assuming it to be varying linearly in between. A constraint can be specified on the maximum permissible ROD at the start & descent of descent, in which case the initial & final throttles required to satisfy the constraint are calculated. For pressurised aircraft, the descent is usually at constant throttle setting (at or near the flight idle).

The 8 parameters related to these three phases that are optimised are the Indicated Airspeed (IAS) & throttle setting in climb, the True Airspeed (TAS), distance & altitude during cruise, and the Indicated airspeed and initial & final throttle setting during descent (Refer Table H.1 in Appendix H for details).

There is a provision in CASTOR for analysing commuter aircraft designed for multi-stage segments; this is done by analysing the first (main) stage and a *notional* stage similar to the last one. The notional stage is flown at a reduced Take-Off mass, and linear interpolation is then used to calculate the fuel burn of the intermediate stages. Because very little difference was observed in the fuel burn of the first and the last stages of the main mission, it is assumed that the first and notional stage can utilise the same values of airspeed & throttle settings. The diversion stage is assumed to have the same value of climb/descent control variables as the main & notional stages; this is because initial runs revealed that the optimum descent profiles tended to have the same climb/descent control settings for the descent & main stages. At the cost of a slightly over-optimum diversion fuel burn which is well within the accuracy of the overall mass estimation tolerances, this assumption leads to a large reduction in number of trajectory related design variables.

5.3.7 Cost estimation

The aircraft initial cost is estimated as the summation of the material cost, labour cost, developmental costs and the cost of power-plant. The DOC per flight is also broken down in terms of the standing charges, airframe & engine maintenance cost, crew cost, fuel cost & landing fees. Though not clearly mentioned in [47], these formulae appear to have been supplied by Short Brothers plc (who were associated with this project), since they contain many terms which are company specific such as work split between in-house and sub-contracted manufacture, and the associated material and labour costs.

5.3.8 Noise estimation

The far-field noise level due to the propeller was estimated using an empirical method outlined in [99]. Based on the power input to a four bladed propeller and the rotational & helical tip Mach numbers, the Equivalent Perceived Noise level (EPNdB) at a specified lateral distance from the runway centerline was estimated. The power input & propeller diameter were the two optimisable parameters that directly affect the noise level, since the propeller RPM was assumed to be a user-specified constant. The FAR-36 sideline noise level constraint (94 EPNdB at 450 m distance under sea-level ISA conditions) was applied. Though this constraint was rarely seen to be active during the parametric studies reported in [47], the situation might change if the FAR-36 regulations were tightened or higher propeller RPMs are used.

Chapter 6

Case studies with stochastic optimisers

6.1 Introduction

In this chapter, the application of two stochastic optimisation methods viz. Genetic Algorithms (GA) & Simulated Annealing (SA) in tackling multi-modal objective functions related to aircraft conceptual design are highlighted. The procedural details and results obtained in the two case studies that were carried out for this purpose are discussed below.

In the first study [100], SA & GA were applied to minimise the objective function $\mathcal{P}$ as discussed in Chapter 2. Optimum configurations of a twin-engined turboprop Air-Taxi aircraft were obtained, and compared with the ones reported in [50] & [45].

In the second study [101], SA & GA were coupled to the analysis module of the CASTOR code described in Chapter 5. Optimum configuration & profile of a 50 seater commuter aircraft were obtained for the three objective functions, and compared with those reported earlier in [47] & [102] for the same mission.

6.2 Application of SA & GA to minimise $\mathcal{P}$

As discussed in Chapter 2, a new objective function $\mathcal{P}$ was proposed in [50] & [45] for direct incorporation of cost and economic parameters in the aircraft conceptual design process. In the present case study, the algorithm for calculating $\mathcal{P}$ was coupled with SA & GA optimisers, and the optimum configurations of the Air-Taxi

aircraft so obtained for all the four cases were then compared with the ones reported in the previous with the MUV method. For ease in understanding, a brief description of the algorithm used and the various cases investigated in [50] & [45] is provided in the next section.

6.2.1 Brief description of the previous study

The aim of the study was to arrive at the optimum value of the following parameters that result in the minimum $\mathcal{P}$ for the passengers, for operation of an Air-Taxi aircraft over a specific network :

1. Passenger capacity N_{cap}
2. Cruising velocity V_{cr}
3. Cruising altitude H_{cr}
4. Max. lift coefficient $C_{L_{max}}$
5. Wing loading W/S
6. Wing aspect ratio $(AR)_w$
7. Wing thickness ratio $(t/c)_w$
8. Type of undercarriage $UCtype$ (fixed/retractable)

These parameters, which characterise the optimum configuration of the aircraft and the way in which its operated, were termed *design variables*. Except N_{cap} and $UCtype$, all design variables were continuous. N_{cap} had certain specific integer values due to the inevitable jumps in the number of passengers seated abreast with increase in capacity (to ensure a suitable fuselage slenderness ratio). $UCtype$ was either 0 or 1 (depending on whether the undercarriage was retractable type, or fixed type). Only two types of power plants viz., piston-prop and turboprop were considered, and twin-engined configurations of both these types were optimised, using *rubber-engine* sizing methods. The methodology was targeted at virgin networks, i.e. for those cities that are not already connected by air, hence it was applied over a hypothetical network. However, it can be readily modified to also apply to existing networks.

The generic expression for the cost function proposed in [50] & [45] is:

$$\mathcal{P} = \sum_{i=1}^n \left[F_i + \frac{t_i \cdot \mathcal{V}}{K_i} \right] \quad (6.1)$$

where,

- n = Number of segments in the travel plan
- F_i = Fare paid by the passenger for i th segment
- $\mathcal{V}$ = Average value of time for the passenger
- t_i = Time spent in i th segment
- K_i = Comfort factor for i th segment

K_i accounts for the perceived increase in comfort (or discomfort) during the various segments of travel, depending on how gainfully the time spent in a particular segment can be utilised by the passenger.

Combining the terms related to the costs associated with the flight phase, airport development and travel time, equation 6.1 can be re-written as

$$\mathcal{P} = \mathcal{F}_{flight} + \mathcal{F}_{airport} + \mathcal{F}_{time} \quad (6.2)$$

where

- $\mathcal{F}_{flight}$ = Flight related costs
- $\mathcal{F}_{airport}$ = Airport related costs
- $\mathcal{F}_{time}$ = Time related costs

Four cases arise, depending on which of the three cost terms of Equation 6.2 are considered, as shown in Table 6.1. An iterative methodology for aircraft synthesis

Case No.	$\mathcal{F}_{flight}$	$\mathcal{F}_{airport}$	$\mathcal{F}_{time}$
1	Considered	Ignored	Ignored
2	Considered	Considered	Ignored
3	Considered	Ignored	Considered
4	Considered	Considered	Considered

Table 6.1: The four cases investigated in [50] & [45]

was developed based on formulae listed in [13] & [14] for the estimation of mass breakdown, aerodynamic characteristics, field performance, mission performance, aircraft cost & DOC, in terms of the study parameters. The details of this methodology and the derivation of the formulae for the various terms are given in [50]. Due to the iterative nature of the algorithm, convergence is not guaranteed for all sets of design variables. In other words, for many sets of design variables, the algorithm does not converge; these cases are considered to be infeasible and a very high

value is artificially assigned to $\mathcal{P}$. Further, some design variable sets lead to violation of the constraints imposed and are rejected in a similar fashion. This feature of the algorithm makes $\mathcal{P}$ highly non-linear and discontinuous, hence conventional optimisation methods (both direct and gradient based) were considered unsuitable.

To overcome this limitation, an interactive optimisation method called *Modified Univariate Method* (MUV) was used, which was based on the Univariate Method explained in [103]. MUV is essentially an iterative, cyclic directional search in all the design variables, but one at a time. The main advantage of this method was that the step size, direction and extent of search could be altered in keeping with the trend of variation of $\mathcal{P}$, thus avoiding infeasible regions to a great extent. This led to a substantial reduction in the number of calculation cycles required, and also provided a feel for the function. The method, however, was quite cumbersome, since the values of the design variables were manually manipulated by the user. Further, there was no way to prove that the global minimum was reached.

6.2.2 Minimisation of $\mathcal{P}$ with SA

In this study, the SIMANN optimiser described in Chapter 4 was used. A description of the trial runs to obtain appropriate values of the suitable optimisation parameters follows.

6.2.3 Tuning of SIMANN parameters

The 8 optimiser related parameters in SIMANN and the values assigned to them in this study are listed in Table 6.2. Table 6.3 provides the details of some of the trial

Parameter	Symbol	Value	Basis	Ref.
Initial Temperature	T_{int}	10.0	Trial Runs	[90]
Temperature reduction parameter	R_T	0.3	trial Runs	[90]
Cycles before temperature reduction	N_T	2	Trial Runs	[90]
Initial step length	V	1.0	Recommendation	[88]
Step length parameter	c	2.0	Recommendation	[88]
Cycles before step change	N_S	10	Recommendation	[88]
Cycles for checking convergence	N_{eps}	4	Recommendation	[88]
Tolerance on $\mathcal{P}$ for termination	eps	0.001	Recommendation	[88]

Table 6.2: Values assigned to SIMANN Parameters [100]

runs carried out to determine suitable values for the first three parameters listed in

Table 6.2. The appropriate value of T_{init} was obtained using a methodology slightly

Case	T_{int}	R_T	N_T	T_*	T_{final}	N_{accep}	N_{eval}	$\mathcal{P}$	Optimum
1	10^6	0.80	4	—	3518	4981	5000	13.455	local
1	10^2	0.30	4	2.7	5.30E-04	2763	4161	13.247	local
1	10^1	0.30	2	3.0	5.90E-04	916	1761	12.992	global
2	10^5	0.25	4	6.0	2.30E-05	3859	5441	22.587	local
2	10^1	0.30	2	0.6	3.80E-05	1853	3201	22.267	global
3	10^4	0.30	4	24.0	5.90E-04	1857	3521	69.632	local
3	10^5	0.25	4	1.5	2.30E-05	3850	5441	68.752	global
3	10^1	0.30	2	0.9	5.90E-05	876	1761	68.758	global
4	10^2	0.40	4	9.0	1.60E-05	2219	4481	93.123	local
4	10^1	0.30	2	0.8	1.80E-05	861	1921	92.623	global

Table 6.3: Trial runs for tuning SIMANN Parameters [100]

different from the one discussed in Chapter 4. This methodology has been adopted by Goffe et al. in optimising a test function, as outlined in [90]. Several trial runs were carried out with high T_{init} values, to determine the temperature T^* at which the step lengths begin to decline sharply. Reduction in T_{init} leads to a reduction in total number of evaluations required (N_{eval}). However, there is a danger of getting stuck in local minima if one starts with a very low T_{init} value. The best way to overcome this problem is to ensure that T_{init} is slightly higher than T^* determined by initial runs, as shown for case 2 and 4. A very high R_T can lead to rapid quenching, as was observed in the first run for case 1 ; values between 0.25 to 0.4 were seen to give the best results. A reduction in N_T also leads to much lower N_{eval} (especially when coupled with low T_{init}) as can be seen by comparing the two global minima results for case 3 ; its appropriate value has to be decided by trial-and-error method.

Table 6.3 also demonstrates the effect of improper choices of these parameters on the performance of the optimiser. For instance, the first run for case 1 ended in a local minima due to a high value of R_T viz. 0.80. The algorithm can be said to have *quenched* in this case. Because of the very high T_{int} value, most of the function evaluations were accepted, and the run ended at a very high temperature (3518). In the second run for this case, both T_{int} & R_T were reduced, but since the value of N_T was high, large number of function evaluation (N_{eval}) were needed and the optimiser ended in a local minimum again. The third run, however, ended in the global minimum with nearly 50% of the total function evaluations accepted i.e. $\frac{N_{accep}}{N_{eval}} \approx 0.5$ as desired, since appropriate values for T_{int} , R_T & N_T were used.

The first run for case 2 ended in a local minimum since inappropriately high T_{int} and N_T values were used. Note the very high value of $\frac{N_{accep}}{N_{eval}}$, and large N_{eval} for this

case. The global minimum was reached in the second run for this case when the appropriate values for the these parameters were used, with far lower N_{eval} .

Due to a high T_{int} value, the first run for case 3 ended in local minimum. The second run demonstrated the peculiarity of stochastic optimisation, since it ended in a near-global minimum even with high T_{int} value and lower than appropriate R_T value. The objective function value in this case is very near to the global optimum obtained in the third run, in which appropriate values for the optimisation parameters were used. It may be noted, however, that the third run for this case required much lower N_{eval} , and $\frac{N_{accep}}{N_{eval}} \approx 0.5$.

Finally, the two runs for case 4 re-confirmed that global optimum is reached with low N_{eval} , when appropriate values are assigned for the three optimisation parameters.

Based on these trial runs, the values of $T_{init} = 10$, $R_T = 0.3$, and $N_T = 2$ were assigned for all the optimisation cycles. Note that the ratio $\frac{N_{accep}}{N_{eval}} \approx 0.5$ for most of the runs ending in global minima.

6.2.4 Minimisation of $\mathcal{P}$ with GA

The details of the GA code used in this study have been provided in Chapter 4, hence only problem specific issues and the tuning of GA parameters will be discussed here.

The selection of appropriate length for each string was the first major task. To ensure a suitable fuselage slenderness ratio, the variable N_{pax} could have only 21 specific integer values, due to the jumps in the number of passengers seated abreast with increase in capacity. This was taken care in the algorithm by choosing a 5 bit string for N_{pax} (which could cater to $2^5 = 32$ different values), assigning the 21 specific values and collating the extra 11 values to the lower limit of N_{pax} , as suggested in [75]. The clustering of the values at the lower limit was done because it was known from previous runs that it corresponded to the optimum value of N_{pax} for two out of the four cases. Trial runs showed that clustering in this fashion did not cause any problem with the runs for the other two cases also. One bit was sufficient to take care of the two discrete values that $LGTtype$ could take. For the other design variables, string lengths of 3, 5 or 7 are chosen depending on the extent of accuracy desired in the solution, resulting in a total string length l_{strt} of 40 bits for each of the 8 design variables.

Since this GA code was developed for maximisation of an objective function, it was used in the present minimisation problem by maximising $-\mathcal{P}$. The algorithm was terminated when improvement in the maximum fitness in N_{eps} consecutive gen-

erations was below a tolerance governed by two parameters T_{rel} and T_{abs} , rather than a constant eps value as discussed in Chapter 4. T_{abs} represents the absolute tolerance on the value of $\mathcal{P}$, while T_{rel} represents a relative tolerance w.r.t the current best $\mathcal{P}$ value.

6.2.5 Tuning of GA parameters

The GA parameters to be tuned were p_{cross} , p_{mutat} , $maxpop$, $maxgen$, N_{eps} , T_{rel} and T_{abs} . A p_{cross} of 100% was chosen to promote maximum genetic re-combination, and p_{mutat} was set to a low value of 3.33%, to introduce a small amount of random diversity in the population. An increase in $maxpop$ and $maxgen$ leads to larger computational effort. To obtain their appropriate values, several runs were carried out for all cases with $maxpop$ values ranging between 10 and 100, and $maxgen$ between 200 & 500. The lowest value of $maxpop$ and the generation number N_{gen} at which the minimum $\mathcal{P}$ value was obtained is shown in Table 6.4. T_{rel} , T_{abs} &

Case	$maxpop$	$maxgen$	N_{gen}
1	50	500	94
2	50	200	147
3	40	300	207
4	80	200	116

Table 6.4: Results of trial runs for tuning of GA Parameters

N_{eps} were heuristically assigned the values of 5.0E-5, 5.0E-3 & 3, respectively. In some GA implementations, the best individual of the population is retained in the next generation ; this is termed as *élitism* which was first proposed by De Jong [104]. However, in a few trial runs for case 1, *élitism* was seen to lead to premature convergence to a local minimum, hence it was not used in further runs.

6.2.6 Optimum configurations obtained by the three methods

A comparison of the results obtained by all the methods for the four cases is given in Table 6.5. For all cases, configurations having a lower $\mathcal{P}$ were obtained using GA and SA, compared to the ones obtained by the MUV method. It must be noted that while the MUV method got stuck in the local minima for case 1, GA & SA were able to climb out of this local minimum. For case 2, the optimum configurations obtained by GA & MUV have a retractable Landing Gear, while SA converges to a

Case	N_{pax}	V_{cr} kmph	$C_{L_{max}}$	W/S kg/sqm	AR	H_{cr} km	$LGtype$	t/c	$\mathcal{P}$ \$/pax/trip	N_{eval}	Method
	39	388.98	1.52	306.56	6.24	0.47	FIX	0.20	12.992	1761	SA
1	39	372.71	1.39	266.31	6.61	0.49	FIX	0.20	13.230	4750	GA
	24	396.00	1.80	262.31	6.40	0.46	FIX	0.18	13.450	281	MUV
	24	360.86	2.99	138.46	5.04	0.47	FIX	0.20	22.267	3201	SA
2	24	365.44	3.00	140.56	5.00	0.47	RET	0.17	22.500	7400	GA
	24	400.86	3.00	148.96	5.00	0.46	RET	0.16	22.660	320	MUV
	6	556.34	1.45	713.04	7.56	0.48	RET	0.10	68.752	5441	SA
3	6	545.04	1.59	683.73	7.58	0.46	RET	0.11	69.080	8280	GA
	6	550.80	2.40	669.08	7.30	0.46	RET	0.10	69.320	153	MUV
	6	487.01	3.00	154.62	5.00	0.47	RET	0.11	92.623	1921	SA
4	6	485.17	3.00	156.72	5.00	0.46	RET	0.10	92.915	9280	GA
	6	486.00	3.00	153.84	5.00	0.46	RET	0.10	92.970	115	MUV

Table 6.5: Comparison of results obtained by SA, GA & MUV for all four cases [100]

configuration with fixed Landing Gear, and lower $\mathcal{P}$. For case 3 also, SA was able to identify a configuration with the lowest $\mathcal{P}$. The optimum configurations obtained by the three methods for case 4 do not radically differ from each other.

Though the MUV method required very low number of function evaluations, the total time needed to arrive at the optimum solution was more than that needed by the standalone SA and GA methods, due to its interactive nature¹. The GA needed the largest number of function evaluations among all the three methods, but lesser overall time than the MUV method. For all the cases, the best results were obtained with SA, in the least overall time. Hence, the efficacy of the two stochastic optimisation methods in tackling this objective function was well established.

6.2.7 Iteration history of case 1 with SIMANN

Figure 6.1 shows the iteration history of various parameters and $\mathcal{P}$ for case 1, when minimised using SIMANN. Large fluctuations are seen in the variable values and corresponding $\mathcal{P}$ value in the first 5 iterations, after which they remain almost constant upto the 10th iteration. A change in the values of all variables occurs between the 10th & 11th iteration, especially for the two discrete variables viz. N_{pax} & $LGtype$, whose values remain unchanged thereafter. Though the value of $\mathcal{P}$ at the end of 10th & 11th iteration is quite similar, they correspond to totally different configurations, which shows that more than one “good” solution exists in different regions of the design space. This information can be very useful for the designer, who can select one of these design points based on some other considerations. It can also be seen that after the 11th iteration, the fluctuations in the values of all the variables (except H_{cruise}) reduce rapidly, and their values are virtually constant after the 14th iteration, till the convergence criteria is met in the 16th iteration. It can be concluded from this observation that $\mathcal{P}$ is virtually insensitive to variations in H_{cr} .

6.3 Application of SA & GA to CASTOR

In the second case study, SA & GA methods were coupled with the analysis module of the CASTOR code. The SA code in this study was the same as in the one in the previous study i.e. SIMANN SA code. For GA, a code called GOOD developed by Kalker-Kalkman ([105] & [76]) and described below was used. A brief description

¹In MUV method, trial configurations were manually supplied as input by the user, hence it was very tedious & time consuming. The process could be automated, but at the cost of lack of insight into the function behaviour, which was one of the strong points of this method.

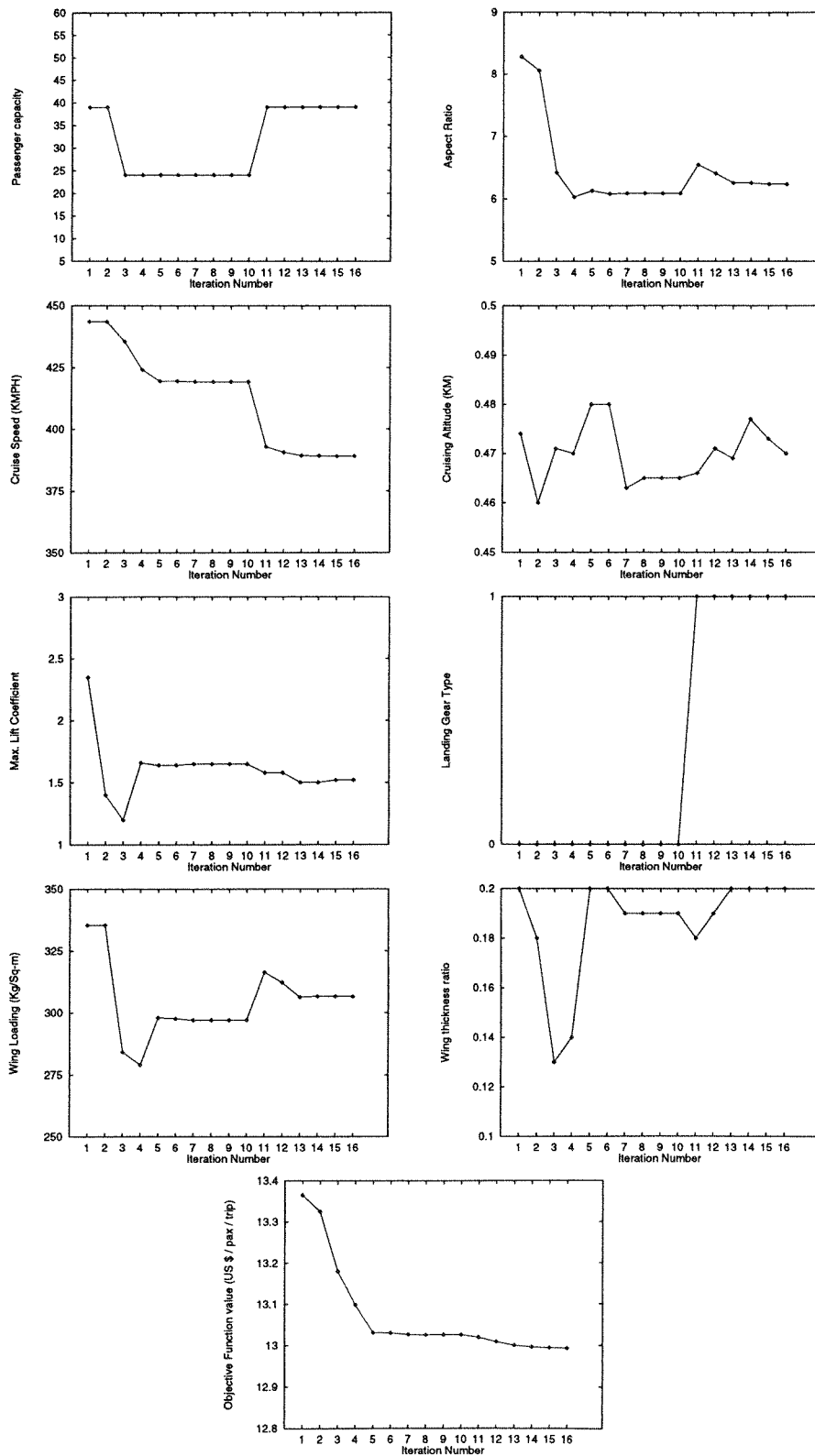


Figure 6.1: Iteration history of case 1 with SIMANN

f this study, and the results obtained follows.

In [47], CASTOR was coupled to the gradient based optimisation method RQPMIN described earlier in Chapter 3. Optimum configurations & profiles of commuter aircraft that minimize any one of the three objective functions viz. Mission Fuel Weight (M_{fuel}), Maximum Take-Off Weight (M_{TO}), & the Direct Operating Cost (DOC) were obtained for arbitrarily defined missions. Case studies for a 50 seater commuter aircraft capable of doing 5 trips over a range of 185 KM (without reuelling) are discussed in [47] & [102]. In this study, the optimum configurations obtained by SIMANN and GOOD corresponding to the minimum value of DOC , M_{TO} & M_{fuel} were compared with those reported in [47] using RQPMIN method.

3.3.1 CASTOR coupled with RQPMIN optimiser

As discussed in Chapter 3, gradient based optimisers like RQPMIN are prone to getting stuck in the local minima in a multi-modal problem. For this reason, multiple runs from various different starting points are required to ensure that the entire design space has been explored. RQPMIN consists of 40 intrinsic control parameters called *assignment variables*, which are used to tune its performance [71]. While the default values of these parameters should result in reasonable performance and accuracy, appropriate values for them have to be obtained by numerical experimentation if performance and accuracy have to be improved. Many internal calculations are carried out during the optimisation run, which have been estimated to consume nearly 50% of the total calculation time [106]. Further, it is quite difficult to comment on the overall convergence of the RQPMIN optimiser, since it depends a great deal on how well the constraint scale factors had been adjusted in each case, needing several trial runs [47].

Seigers [70] has highlighted the following three drawbacks of RQPMIN based on his experience of applying it for optimisation of combat aircraft configurations:

- It requires smooth functions with smooth derivative information, and any discontinuity may cause it to fail.
- Finite differences are used for generating derivative information, which is time consuming and their accuracy can seriously influence optimisation results.
- It is not a global optimisation procedure because it can search only a limited portion of function definition space, and it has no means of distinguishing between a local & global optimum.

6.3.2 CASTOR coupled with SIMANN optimiser

The first step in coupling CASTOR with SIMANN was to determine the suitable value of the three optimisation parameters, viz. T_{int} , R_T & N_T . For this, a slightly different approach was used in this study compared to that outlined earlier in section 6.2.3. For T_{int} determination, a trial run was commenced with T_{int} set to unity, and R_T to 1.5. This lead to a 50% increase in the temperature in each subsequent iteration. The step lengths of the various variables in the intermediate results were closely examined. It was found that at a temperature of 438, the step lengths components covered the entire range of the respective variables. This temperature corresponds to T^* discussed in section 6.2.3. Hence T_{int} of 500 was chosen for all subsequent runs.

As regards appropriate R_T & N_T values, few trial runs were carried out from various starting points with a progressive increase in the values of these parameters. The highest value for R_T & N_T at which the algorithm converged to the same (or very similar) optimum configuration as in the previous run was considered appropriate. Based on these trial runs, the suitable values for R_T & N_T were found to be 0.85 & 100, respectively.

This approach for determining appropriate T_{int} , R_T & N_T values was also recommended by Goffe et al. in [90]. It was adopted for all further applications of SIMANN, since it was more systematic and can be uniformly applied to all problems.

6.3.3 CASTOR coupled with GOOD GA Optimiser

In this study, a GA code developed by Kalker-Kalkman called GOOD (Generator Of Optimal Designs) was employed [105]. This code is coupled with a graphical interface, to enable on-line manipulation of optimisation related parameters. GOOD employs *elitism*, and the best member of the population is considered as the current optimum. The values of all design variables and the objective function of the current optimum are displayed on the screen, and subsequent such points are connected by lines. Thus, the user can get a graphical feedback of how the optimisation is proceeding & the trend of change in values of the design variables. It is also possible for the user to intervene in the optimisation process at any stage, and to change the parameters based on the visual feedback. For instance, it is possible to specify new search intervals for one or more design variables, change the population size or mutation rate, proceed with the present population set for a specific computational time or number of evaluations, or even to start again from scratch. The details of this method and application to other problems in previous work are given in [105].

For the present case, the algorithm was initiated with a population size of 10,

which was slowly increased to 70. The optimum configurations obtained² by modifying the search intervals and the scaling of the fitness function were quite similar to the ones obtained by the SIMANN & RQPMIN method, as discussed in the next section.

6.3.4 Comparison of optimum configurations by the 3 methods

In [47], a detailed output of the minimum *DOC* configuration has been provided, hence it was possible to compare the optimum configurations obtained for this objective function by all the three methods. The geometry & the flight profiles for the main mission of the optimum aircraft obtained by the three methods for minimum *DOC* are superimposed in Figure 6.2. It can be seen that the optimum configu-

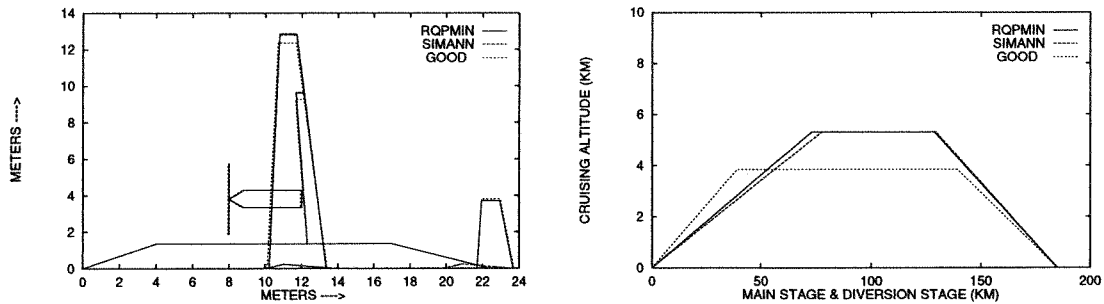


Figure 6.2: Minimum *DOC* configurations & mission profiles by the three methods [101]

rations & mission profile obtained by RQPMIN & SIMANN are quite similar. The comparison also brings out the multi-modal nature of the objective function, since even though the three objective function values differ from each other only within 0.5%, the optimum flight profile obtained by GOOD is quite different.

Figure 6.3 shows the optimum configuration & main mission profiles obtained by three different runs of SIMANN. It can be seen that the optimum configurations & mission profiles for these three runs are quite similar, and difference in the *DOC* values are less than 0.3%. For these three cases, the seeds that were used to generate the random number series were not the same, hence the path that these three runs took to arrive at the optimum solution were totally different. For the minimum M_{TO} and minimum M_{fuel} case, the values of only 4 wing related design variables (from the optimum set of 22) were listed in [47] & [102], hence a limited comparison could

²All runs of CASTOR coupled with GOOD were carried out by Dr Kalker-Kalkman of Department of Mechanical Engineering, Delft University of Technology, Delft, The Netherlands, since the code was not available to the author at Cranfield University.

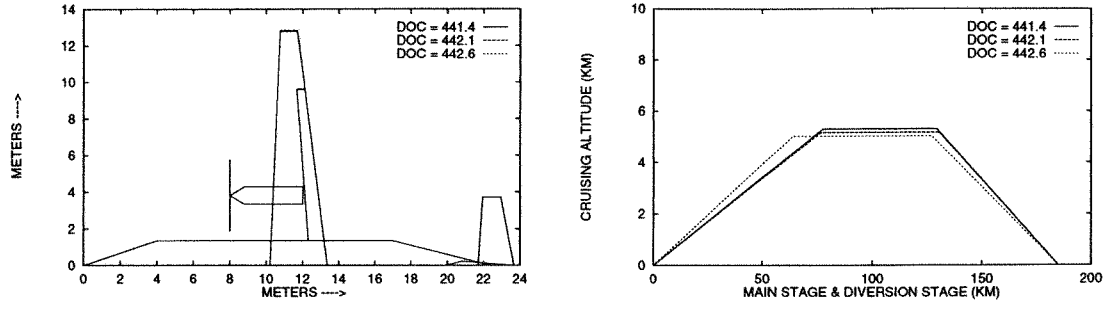


Figure 6.3: Minimum DOC configurations & mission profiles for 3 runs of SIMANN [101]

be made. These parameters are the Aspect Ratio AR , gross area S_w , taper ratio τ & the thickness-to-chord ratio t/c of the wing. Table 6.6 compares the values of these parameters of the optimum configurations obtained by the three methods for the two objective functions, along with the number of function evaluations required for each run N_{eval} . It may be noted that in [47], N_{eval} was listed only for the minimum DOC case. It can be seen that all the optimum configurations obtained by SIMANN

Method	DOC	M_{fuel}	M_{TO}	AR	S_w	τ	t/c	N_{eval}
Units	US\$/trip	Kg	Kg		m^2			
Minimum DOC Configurations								
RQPMIN	441.9	1010	16245	12.62	52.40	0.3	0.21	2275
SIMANN	441.4	1013	16253	12.49	52.42	0.3	0.21	5232001
GOOD	443.8	1061	16157	11.54	52.92	0.3	0.21	134035
Minimum M_{fuel} Configurations								
RQPMIN	460.9	942	16413	13.00	52.86	0.3	0.18	NA
SIMANN	466.9	931	16522	13.00	53.52	0.3	0.17	4176001
GOOD	465.3	937	16342	12.92	53.41	0.3	0.19	6029680
Minimum M_{TO} Configurations								
RQPMIN	459.9	974	16030	12.28	51.84	0.3	0.21	NA
SIMANN	465.1	976	16023	11.83	52.74	0.3	0.21	3888001
GOOD	464.1	972	16104	11.86	53.18	0.3	0.21	63667

Table 6.6: Comparison of optimum configurations by the three methods [101]

have better objective function values compared to those obtained by RQPMIN. For the minimum M_{fuel} case, GOOD also comes up with better configurations compared to the RQPMIN method. The number of function evaluations per run by RQPMIN were very small compared to SIMANN or GOOD, but the total number of such runs that were required by RQPMIN to reach the global minimum was not reported in [47], hence it is not possible to make a comparison of overall computational time. The computational time needed for one run of SIMANN was approx. 3 hours while

running on a network of SUNSPARC workstations. For GOOD, the computational time required on a Pentium 100 MHz machine was also reported to be of the same order.

6.3.5 Conclusions of this case study

The two stochastic methods viz. SA (SIMANN) & GA (GOOD) were found to be quite robust in arriving at the global optimum of the three multi-modal objective functions related to commuter aircraft configuration & trajectory optimization. The number of optimizer related parameters (that have to be tuned by the user) were far less in the case of SIMANN & GOOD, compared to RQPMIN. However, the number of function evaluations for one run of SIMANN & GOOD were much larger compared to the RQPMIN method.

Chapter 7

Airport layout & cost estimation module

7.1 Introduction

This module was developed to arrive at the layout and cost of setting-up and running an airport in a developing country (such as India), based on the geometric details and the frequency of operation of the most critical aircraft that shall be operating from it. Though it is mainly developed for sizing & cost estimation of small regional airports (suitable for operation of a particular twin-turboprop commuter & regional aircraft), the airside sizing & land area estimation can also be carried out for airports designed for operation of larger aircraft.

An implicit assumption while developing this module was that the airport is to be sized to enable operations of a particular aircraft, and that most (if not all) commercial flight operations from the airport will be with this aircraft. The costs of developing and running the airport are also assumed to be influenced by (and recovered from, either in whole or in part) these flight operations. In real life, the airport sizing is carried out with the operation of many different aircraft types (with many different airlines) in mind, all of which might exert their influence on various aspects of the airport. For example, special strong rooms and freight storage areas may be required if mail & cargo operations are also expected. Furthermore, the operation of a specific aircraft type may lead to the requirement of special ground handling equipment (tugs, pneumatic trolleys, cranes, passenger steps etc), which may not be needed by many other aircraft operating from that airport. The development of a new airport usually leads to a progressive increase in General Aviation activity. At times, this influences the level and extent of facilities that need to be provided at the airport, and may greatly contribute to the operating

costs (and revenues) of the airport. It is also assumed that sufficient and suitable land is available at the airport site and that no restrictions are imposed due to the presence of any obstacles (man made or natural) in its vicinity. In other words, the effect of other factors that usually influence the airport layout, sizing and costing are not considered.

While not very common, a few airports have been designed with the operation of only one specific aircraft in mind. A recent example of this is the London City Airport, which was designed primarily for the operation of the De Havilland Dash-7, with a declared distance of 742 m.¹ The only two other aircraft that were licensed to operate on this airport were the Dornier Do-228 & DHC 6 Twin-Otter. To overcome this severe restriction of aircraft types that could operate from this airport, the runway length was later extended to 1199 m. This enabled newer regional turboprop aircraft such as Dash-8-100 & -300, ATR-42-320, Fokker-50 and Saab 340-B and the regional turbofan BAe 146-100 & -200 to be operated from this airport [60]. The presence of obstacles (both actual & proposed) in the vicinity of the airport, however, lead to a need for a larger than normal approach angle of 5.5 degrees.

This module provides a means to establish a direct coupling between the aircraft & the airport, in the sense that any change in the aircraft configuration (e.g. increase in bwing, M_{TO} or BFL) or in the operational parameters (e.g. increase in frequency or change in the flight schedules) directly affects the airport related costs. While the module was developed with data and guidelines applicable to Indian airports, an attempt has been made to keep it fairly generic in nature, so that it may be applied to any country if relevant cost data and regulatory guidelines are made available.

7.1.1 Sub-modules of the Airport module

The airport module consists of the following sub-modules, which are explained below:

- Airport configuration and layout
- Geometric design of the airfield
- Airport classification under three levels
- Estimation of airport setting-up costs

¹Though the airport had two overlapping runways of total length of 1050 m, there were many obstacles in the approach surface at both ends. An unusually high approach angle of 7.5 degrees and displaced thresholds at both ends of the runway were required for obstacle clearance. Hence, the runway had a declared distance of 742 m. [60]

- Estimation of annual staffing & recurring costs

7.2 Airport configuration and layout

The term *airport configuration* represents the number and orientation of runways, and the location of the passenger terminal area relative to the runways. It is strongly driven by the volume of traffic and the meteorological conditions under which the flight operations are permissible (VMC or IMC)². The runway orientation depends to a large extent on the direction of the prevailing wind patterns in the area, the size and shape of the land area available for airport development, and the land use or airspace restrictions in the vicinity of the airport. However, it is always prudent to choose a configuration that does not restrict further growth and expansion of the airport, should the need arise in the future. A single runway layout has been shown to be sufficient for 50-100 operations per hour under VMC conditions and 50-70 operations per hour under IMC conditions, depending on the composition of the aircraft mix and the navigational aids available [5]. Since this is far in excess of the expected traffic from a small regional airport, this layout was chosen for the present module.

7.3 Geometric design of the airfield

The geometrical dimensions of the airport pavements i.e. the length and width of the runway(s), taxiway(s) and apron(s) are mainly governed by the performance and dimensions of the most critical aircraft. The frequency and type of aircraft movements and the aircraft mix also affect certain aspects of the airport layout such as the taxiway contours and sizing of aprons. Detailed guidelines for airport layout and configuration design have been laid out by International Civil Aviation Organization (ICAO) [3] and Federal Aviation Authority (FAA) [4]. The aim of these guidelines is to provide assistance to the airport designers, and to ensure a reasonable amount of uniformity in the design of airport facilities for aircraft operations. While the FAA design criteria provide for uniformity at airports in the USA; ICAO aims at uniformity & safety at a global level, and its standards are applicable to all member nations of the Convention on International Civil Aviation. ICAO classifies airport using a two-element code, consisting of an *aerodrome code number* (based on the reference field length) and *aerodrome code letter* (based on

²VMC stands for Visual Meteorological conditions i.e. when the weather conditions are such that the aircraft can maintain safe operation by visual means. Instrument Meteorological conditions (IMC) are said to exist when the visibility or the height of the dominant cloud base falls below that prescribed under VMC conditions [5].

the wing span & outer main gear wheel span). The Reference Field Length is the actual runway take-off length (including the stop-way & clear-way, when provided) converted to an equal length at mean sea-level, 15 deg. C & 0 % gradient. FAA also uses a two part airport reference code; the *aircraft approach category* (based on the aircraft approach speed in the landing configuration at max. landing weight), and *airplane design group* (based on the wing span). These two classifications are shown in Table 7.1 & Table 7.2.

Aerodrome Code number	Reference Field Length (m)	Aerodrome Code Letter	Wingspan (m)	Outer MLG span (m)
1	< 800	A	< 15	< 4.5
2	800 - < 1200	B	15 - < 24	4.5 - < 6
3	1200 - < 1800	C	24 - < 36	6 - < 9
4	$\geq$ 1800	D	36 - < 52	9 - < 14
		E	52 - < 65	9 - < 14

Table 7.1: ICAO Aerodrome Reference Code [3]

Aircraft Approach Category	Approach Speed (kt)	Airplane Design Group	Aircraft Wingspan (ft)
A	< 91	I	< 49
B	91 - < 121	II	49 - < 79
C	121 - < 141	III	79 - < 118
D	141 - < 166	IV	118 - < 171
E	$\geq$ 166	V	171 - < 214
		VI	214 - < 262

Table 7.2: FAA Airport Reference Code [4]

7.3.1 Geometric specifications of the runway system

The runway system at an airport consists of the following main constituents :-

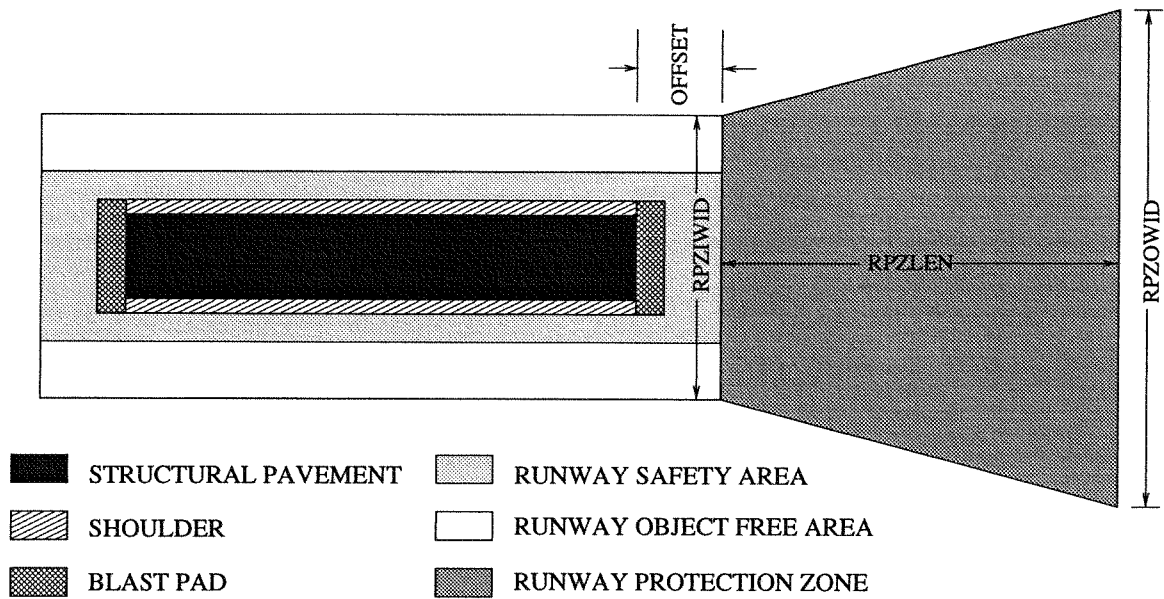
- Structural Pavement This is the surface on which the take-off, landing & taxi operations are performed i.e the runway & the taxiway. It supports the aircraft w.r.t structural load, control, maneuverability, stability and other operational & dimensional criteria.

- Pavement Shoulder This surface adjacent to the structural accommodates emergency & maintenance equipment, and resists the erosion due to the jet blast or propeller.
- Blast Pad Prior to commencing the take-off, the aircraft is usually positioned near the end of the runway with the brakes on and the engine setting at the take-off power. Hence a blast pad is usually provided, which is the area designated to prevent erosion of the surfaces adjacent to the runway ends due to jet blast or propeller wash.
- Runway Safety Area FAA regulations stipulate suitable strengthening of an area in the immediate vicinity of all sides of the runway, to reduce the risk of damage to the aircraft in the event of accidental excursion from the runway e.g. undershooting or overshooting, which is called the Runway Safety Area. It includes the Structural Pavement, Shoulders, Blast Pad(s), and Stop-way, if provided, and should be able to support emergency & maintenance equipment, apart from being able to support the aircraft. ICAO regulations also refer to an area similar to the Runway Safety Area as the Runway Strip & the Runway End Safety Area.
- Object Free Area & Obstacle Free Zone FAA defines Object Free Area as a two-dimensional ground area surrounding the runway which must be clear of parked aircraft and objects other than those whose location is fixed by function. The Obstacle Free Zone is defined as the volume of airspace entered above the runway, whose elevation is same as that of the nearest point on the runway centerline, & extending 200 ft beyond each end of the runway. This zone supports the transition between ground & airborne operations.
- Runway Protection Zone This consists of the area on the ground used to enhance the protection of the people & the objects in the vicinity of runway approach. A similar area is designated as the Runway Clear Zone under the ICAO regulations. This area should preferably be under the direct control of the airport authority, to avoid the presence of any obstacles in the future which might pose severe restrictions on the aircraft operations.

The above components of the runway system (except the Object Free Area & the Obstacle free zone) are illustrated schematically in Figure 7.1. In the present module, the airport is classified under the FAA regulations or ICAO regulations and the geometrical dimensions of the runway system are determined, using the relevant recommendations. For e.g., Table 7.3 lists the ICAO recommendations for the dimensions of the runway pavement and strip, and the separation between the runway and taxiway. Since no clear-cut specifications for the dimensions of the runway clear zone were available in the ICAO recommendations [3], FAA guidelines for the runway protection zone applicable to similar category of airports were used,

Runway pavement width (m)					
IACN	IACL				
	A	B	C	D	E
1	18	18	23	-	-
2	23	23	30	-	-
3	23	30	30	45	-
4	-	-	45	45	45
Runway pavement & shoulder width (m)					
	-	-	60	60	60
Runway strip width (m)					
IACN	1	2	3	4	
PI & NPI	150	150	300	300	
V	60	80	150	150	
Clear and Graded area width (m)					
IACN	1	2	3	4	
PI & NPI	80	80	150	150	
V	60	80	150	150	
Runway-taxiway separation criteria (m)					
V & NPI					
IACL	A	B	C	D	E
1	37.5	42.0	-	-	-
2	47.5	52.0	-	-	-
3	-	-	93.0	101.0	-
4	-	-	-	101.0	107.5
PI					
1	82.5	87.0	-	-	-
2	82.5	87.0	-	-	-
3	-	-	168.0	176.0	-
4	-	-	-	176.0	182.5
NOTES					
IACL	ICAO Aerodrome Code Letter				
IACN	ICAO Aerodrome Code Number				
PI	Precision Instrumented				
NPI	Non-Precision Instrumented				
V	Visual Flight Rules				

Table 7.3: ICAO runway dimensional standards & runway-taxiway separations [5]



$$RPZOWID = RPZIWID + 2 * DIVERG + RPZLEN$$

Figure 7.1: Schematic diagram of runway system components

		ICAO Aerodrome Code Number			
	Parameters	1	2	3	4
Visual runways					
Length	RPZLEN	300	300	300	300
Inner Width	RPZIWID	75	75	150	150
Divergence	DIVERG	0.10	0.10	0.10	0.10
Offset	OFFSET	30	60	60	60
Non-Precision Instrumented runways					
Length	RPZLEN	300	300	520	520
Inner Width	RPZIWID	150	150	150	150
Divergence	DIVERG	0.15	0.15	0.15	0.15
Offset	OFFSET	30	60	60	60
Precision Instrumented runways					
Length	RPZLEN	760	760	760	760
Inner Width	RPZIWID	300	300	300	300
Divergence	DIVERG	0.15	0.15	0.15	0.15
Offset	OFFSET	60	60	60	60
Refer Figure 7.1 for description of parameters					

Table 7.4: Runway Protection Zone dimensions [5]

as shown in Table 7.4 Taxiways are defined paths on the airfield surface which are established for the taxiing of aircraft and are intended to provide a linkage between one part of airfield and another, while a taxilane is a portion of the aircraft parking area used for access between taxiways and the aircraft parking positions [5]. Minimum separation between the centerlines of taxiways, centerlines of taxiways and taxilanes, and between the centerlines of taxiways/taxilanes and objects are recommended for safe manoeuvring of aircraft on the airport. Table 7.5 lists the

	ICAO Aerodrome Code Letter				
	A	B	C	D	E
Taxiway Width	7.5	10.5	15.0	18.0	23.0
Edge safety margin	1.5	2.3	3.0	4.5	4.5
Shoulder width	7.5	10.5	25.0	38.0	44.0
Taxiway strip width	27.0	39.0	57.0	85.0	93.0
Graded strip width	22.0	25.0	25.0	38.0	44.0
Inter-taxiway separation	21.0	31.5	46.5	68.5	81.5
Object-taxiway separation	13.5	19.5	28.5	42.5	49.0
Object-taxilane separation	12.0	16.5	24.5	36.0	42.5
NOTES					
For IACL C; taxiway width = 18 m if aircraft wheelbase $\geq$ 18 m					
For IACL D; taxiway width = 23 m if outer mlg wheelspan $\geq$ 9 m					
For IACL C; edge-safety-margin = 4.5 m; if aircraft wheelbase $\geq$ 18m					

Table 7.5: Taxiway dimensions and separation criteria [5]

taxiway dimensions and minimum recommended taxiway related separations as per ICAO separation. These were used to size the taxiways and to arrive at the distance between the centrelines of the runway and taxiway(s), and separation between the taxiway(s) & the apron(s). The separation between the apron(s) and the terminal building was assumed to be the minimum recommended separation between an *aircraft stand taxilane*³ and a fixed or moving object.

As a validation check, the module was applied to size a PI⁴ airport for operation of Boeing 767-200 aircraft, the output so obtained is shown in Table 7.6. The resulting dimensions of the runway system & taxiway layout matched exactly with those obtained using the FAA airport sizing program AIRPORT DESIGN 3.2, and quoted in [5].

It may be noted that though only ICAO recommendations have been listed and discussed above, the FAA recommendations for the airport geometry and sizing have

³ICAO defines an aircraft stand taxilane as a portion of the apron intended to provide access to only the aircraft stands.

⁴PI = *Precision Instrumented*

also been incorporated in the airport layout and sizing sub-module.

7.4 Airport classification under three levels

While the FAA & ICAO recommendations are quite adequate for geometric sizing of the airfield, they are not sufficient for determining the number of taxiways and aprons required and for sizing of the passenger terminal building, which is governed by the number and frequency of aircraft operations. Hence, there is a need to further classify the airports in increasing level of complexity and investment in the infrastructure, both in terms of the land-side and air-side development as well as the provision of aeronautical equipment. The aeronautical equipment fit at any airport is a strong function of the type, extent and frequency of aircraft movements and the level of operational reliability and aerodrome availability that is desired. It is frequently constrained by the limits on capital investment. It is also strongly influenced by local factors such as weather conditions, presence of natural and man-made obstacles in the vicinity of the airport, and the extent of air traffic already prevalent in the airspace. Furthermore, there may be a minimum fit recommended by the local Civil Aviation Agency as a pre-requisite for obtaining the licence to operate commercial services. In the absence of any specific information, the minimum equipment fit can be obtained from a study of the existing airports with similar operating environment.

7.4.1 Generic layout of a regional airport in India

To arrive at an idea of the equipment and facilities available at small airports in India, a database of airports with ICAO Aerodrome Code number ≤ 3 (runway length ≤ 1800 m) was prepared, using the information supplied by National Airport Authority of India [107] & [108]. The details of this database are listed in Appendix B. From this database, a Control Tower with one VHF (Very High Frequency) radio & a Non Directional Beacon (NDB) could be considered as the minimum equipment fit at regional airports in India. A flexible runway pavement of Asphalt or Tarmac can also be considered sufficient. To take this into account, the airports were classified under three different levels as shown in Table 7.7, in the increasing order of the extent of flight operations. The provision of aeronautical equipment at each level of the airport is commensurate with the type and extent of flight operations from it. Costs related to setting up and running the airport increase with the level of the airport. Figure 7.2 shows the generic layout of the three levels of the regional airports. The boundary of the aerodrome land directly under control of the airport management is shown in the dashed line.

AIRPORT SIZING FOR B767-200 AIRCRAFT : INPUT DATA			
Wingspan (m)	47.55	Wheelbase (m)	19.68
Outermost wheeltrack (m)	9.5	Approach speed (m/s)	70
M_{TO} (Kg)	142920	Airport Type	PI
Airport elevation (m AMSL)	304.8	Minimum visibility (m)	600
AIRPORT GEOMETRY SIZING AS PER FAA REGULATIONS			
Approach category	C	Design group	IV
Runway design criteria		Taxiway design criteria	
All dimensions in feet			
Runway pavement :		Taxiway Pavement :	
length	8130	width	75
width	150	Edge Safety Margin	15
Shoulder width	250	Shoulder Width	25
Blast pad :		Safety Area Width	171
width	200	Object-free area width	259
length	200	Wing tip clearance	44
Safety area :		Taxilane	
width	500	Object-free area width	225
length	1000	Wing tip clearance	27
Object-free area :		Runway centerline to :	
width	800	Taxiway/lane centerline	40
length	1000	Edge of aircraft parking	50
Obstacle-free zone :		aircraft hold line	250
width	400	Taxiway centerline to :	
length	200	Taxiway/lane centerline	215
		Fixed or moveable object	129.5
AIRPORT GEOMETRY SIZING AS PER ICAO REGULATIONS			
Aerodrome Reference Code Number 4		Aerodrome Reference Code Letter D	
Runway design criteria		Taxiway design criteria	
All dimensions in meters			
Runway pavement:		Taxiway pavement:	
width	45	width	23
Shoulder width	15	Shoulder Width	15
Runway strip		Runway centerline to :	
total width	300	taxiway/lane centerline	176
of which graded width	210	Taxiway centerline to :	
and strengthened width	150	taxiway/lane centerline	68
Runway End Safety Area		fixed or moveable object	42.5
width	90	Taxilane centerline to :	
length	90	fixed or moveable object	36

Table 7.6: Runway & taxiway sizing for Boeing 767-200 aircraft

Airport Level	1	2	3
Investment	Low	Medium	High
Navigational Aids	Tower + NDB + Transmitter	+ V/UHF Radio + Beacon	+ Approach + Runway Lights
ATC service	AIS only	Tower Control	Tower + Approach Control
Operations	Daytime VFR	Daytime VFR	VFR + IFR
Hours Open	As Required	8 Hours	12 Hours

Table 7.7: Classification of Indian regional airports

Level 1 airport is considered as a start-up airport, which requires the least possible infrastructural investment and administrative support. The minimum equipment fit could be considered sufficient for this airport, since it is expected to have very few aircraft movements in VMC conditions only. An Aeronautical Information Service (AIS) can be made available during the time period when the airport is operational, in which the local weather information is relayed on a tape through a radio transmitter. The airport need be operational only a few hours before and after the scheduled flights, since no local G.A. or other activity is assumed.

Level 2 airport represents a busier airport, with up to 3 return flights a day and some G.A. activity. With the increase in number of movements (including cloudy weather during daytime), local area ATC is provided, along with an Aerodrome Beacon to assist the pilots in locating the airfield. However, the airport is still assumed to be operational only during daytime (single shift of 8 hours).

Level 3 airport represents a busy regional airport, with up to 7 return flights a day. As regional airports get busier, peaking of flights usually occurs during the early morning and late evening hours, hence this airport is equipped with approach & runway lights. With further increase in number of movements (both total & peak-time), many of which would possibly be under low levels of visibility (due to fading light), an additional approach controller with his own V/UHF radio is also provided. The airport is assumed to be open for 12 hours a day, hence provision of an additional evening shift in the airport staffing is also made.

The final level of sophistication for regional airports (keeping in mind the constraints on investment) could be to install a VDF⁵ and ILS/DME⁶ equipment at one or both ends of the runway. But these equipments are considered to be too costly to be provided unless specific requirements exist. It was assumed that only

⁵VDF = VHF Direction Finder, which is installed at the airport and transmits at a pre-set frequency. It enables the Air-Traffic Controller to determine the True or Magnetic bearing of the aircraft, and advice the pilot of the same. It can also be used to provide approach control.

⁶ILS/DME = Instrument Landing System & Distance Measuring Equipment.

one taxiway at an end of the runway leading to an apron would be sufficient for the Level-1 airport, since only one aircraft could be expected to be operating from the airport at any given time. For the Level-2 & 3 airports, two & three taxiways & aprons, respectively, were assumed to be required, in keeping with the increase in traffic.

7.4.2 Estimation of total land area requirement

The dimensions & distances between runway, apron, terminal building and approach surface areas are calculated from the ICAO or FAA specifications, as discussed above. Figure 7.3 demonstrates the methodology adopted for estimating the length and width (hence area) of a Level-1 airport, which is applicable to all the three levels. The distance of the airport boundary fence from the runway on the far side

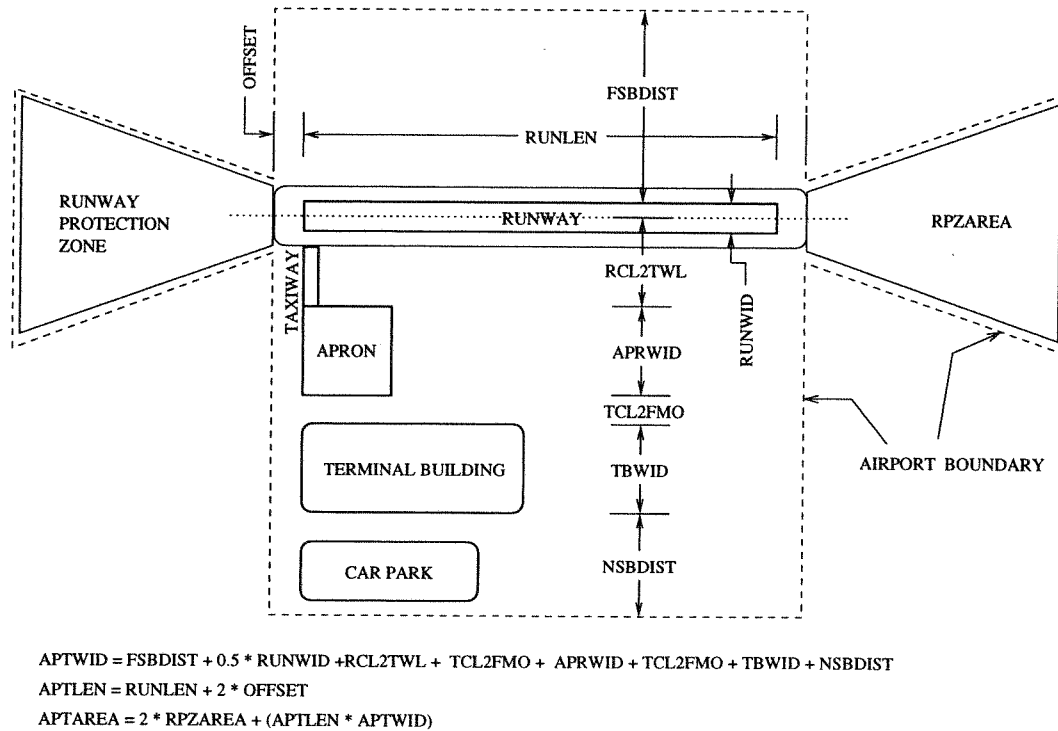


Figure 7.3: Example of estimation of airport land area requirements

(FSBDIST in Figure 7.3) is assumed as 320 m (1:7 slope to clear 150 ft obstacle). On the other hand, the distance between the airport boundary and terminal building (NSBDIST in Figure 7.3) is assumed to be 15 m. The car park is sized assuming 28 m² of area per person in the terminal building, and NSBDIST is increased, if need be. Other dimensions shown in Figure 7.3 are determined using FAA or ICAO guidelines, as discussed above. The funnel-shaped areas at the two ends of the

runway are the Runway Protection Zones (RPZ), as defined by FAA [4]. It is not absolutely essential for the airport authorities to acquire the land located below the RPZ (RPZAREA); it is sufficient to have restrictions imposed on the height of obstacles present in these zones to ensure that they are below the approach surface. This could be achieved by adoption of zoning ordinances or agreements with the parties that own that portion of the land. However, as discussed in Chapter 1, in a field as dynamic as Aviation, it is necessary to acquire land in advance or to be able to acquire sufficient real estate in the future for expanding the physical plant of the airport. With this in mind, it was decided to acquire the land below the Runway Protection Zone right from the inception of the airport. For a level-3 airports, this area would anyway be required for installation of the approach lighting system.

7.5 Estimation of airport setting-up costs

The total area under the jurisdiction of an airport may be classified under two categories, the airside area and the landside area. The airside area is provided for (and is sized by) the operation of the aircraft viz. runway(s), taxiway(s) and apron(s). The landside area consists of all facilities provided for (and sized by) the passengers and the other personnel at the airport such as the terminal building, car-parks etc. To arrive at the total cost related with setting up the airport, estimates for the cost of the airside and landside construction have to be made, apart from the cost of installing requisite aeronautical equipment at the airport and the costs associated with setting up an establishment to provide suitable fire and rescue service. The cost of procuring and preparing the land area required by the airport can greatly vary with its location and size. In some cases, it constitutes the largest proportion of the total airport setting up costs, especially if the airport is to be located very near the city (or cities) it serves. Hence it is not very uncommon for the the land to be provided to the airport authorities free of charge or at a nominal rate by the local government, to encourage development of new airports⁷. The nearer the airport from the city, lesser is the access cost & time for the passengers, but greater is the demand for land too. In the present module, an average land cost is assumed for an airport located 20 Km or more from the city, and as the airport location is moved nearer to the city, the land cost is assumed to increase. For an airported located within 10 Km of the city, an exceptionally high land cost is assumed.

⁷An example of this is the regional airport developed at Salem, in India, for which 130 acres of land was developed and released by the Tamil Nadu state government at no charge [107].

7.5.1 Cost of construction of the airside area

Having arrived at the geometrical dimensions of the runway(s), taxiway(s) and apron(s), it is necessary to determine their pavement thickness in order to estimate the cost of constructing them. These costs would depend to a large extent on the type of material locally available (or available nearby, to minimize transportation costs) and the split between material costs & labour costs. Both these vary from country to country and vary with the local sub-soil conditions. Estimates for the cost of preparing a runway with flexible pavement of a particular thickness can be obtained from various contractors to arrive at a cost of laying a cubic meter, which could be then used for costing any runway, given the length, width & thickness.

Determination of Pavement thickness

The thickness of the aerodrome pavements depends on the aircraft landing mass, tire pressure and main landing gear (MLG) layout and type and strength of the sub-grade below the pavement. These parameters differ for various aircraft and airport location, hence a generic methodology had to be developed to associate aircraft mass with pavement thickness for twin-turboprop regional aircraft. A methodology for determining the Aerodrome Classification Number (ACN) and the pavement thickness for flexible pavements as a function of the aircraft landing mass, MLG layout, tire-pressures and the sub-grade CBR ⁸ is outlined in [109], along with the listing of a computer program ACNFLEX. It was decided to obtain a co-relation between pavement thickness and aircraft M_{TO} , using this computer program.

A survey of such aircraft currently available in the market revealed that most of them have a simple dual under-carriage MLG layout. Data related to their MLG tires was obtained from [110]. Using this data, it was assumed that a particular tire (with associated pressure) could be selected for a range of aircraft M_{TO} , assuming 46.25% of the mass acting on each MLG leg, as shown in Table 7.8. Another parameter that affects the pavement thickness is the lateral gap between the two MLG legs (x_{gap}). A study of the MLG layout of 7 regional aircraft reported in [109] revealed that x_{gap} varies almost linearly with the load carried by each MLG leg (W_{leg}). The co-relation between the two was obtained as $x_{gap}(cm) = 18.536 + 0.003 \cdot W_{leg}$, as shown in Figure 7.4. ACNFLEX was then used to determine the pavement thickness for standard sub-grade CBR values for various M_{TO} values between 3500 kg & 30000 kg, as shown in Figure 7.5. A co-relation formula for average pavement thickness T as a function of M_{TO} was obtained from these results as $T = 0.1369 \cdot M_{TO}^{0.566}$, as shown in Figure 7.5. Having determined the average pavement thickness, a methodology for estimating the cost of their construction was developed, based on the

⁸CBR = California Bearing Ratio, which is a measure of sub-grade strength.

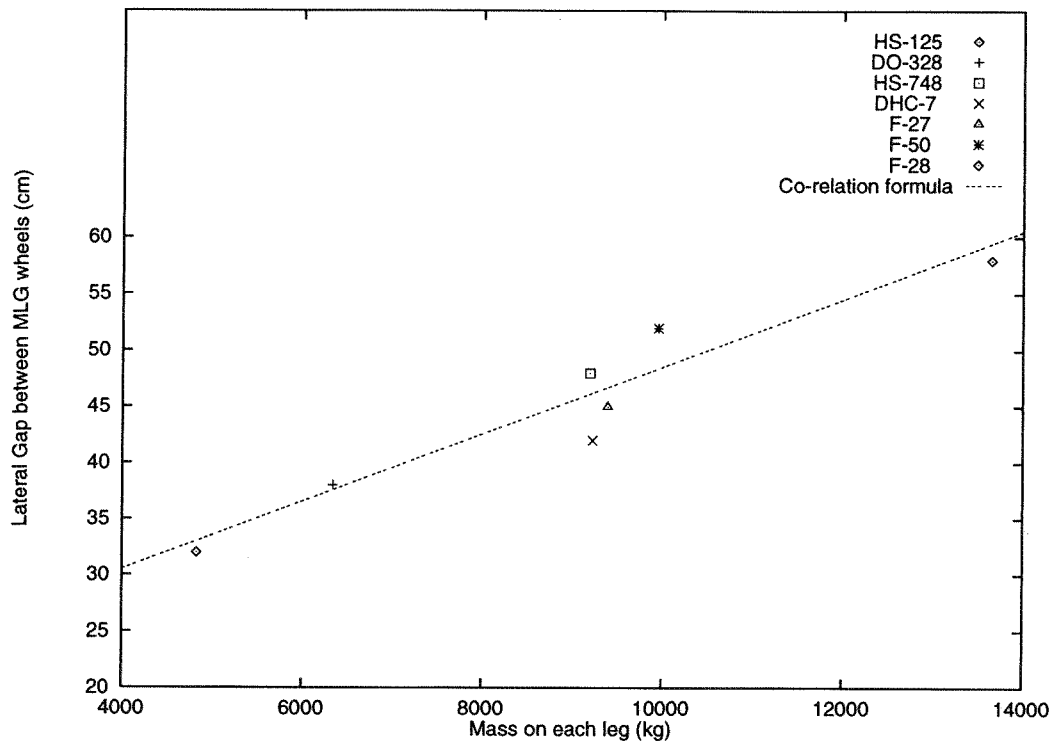


Figure 7.4: Co-relation between lateral gap v/s M_{TO}

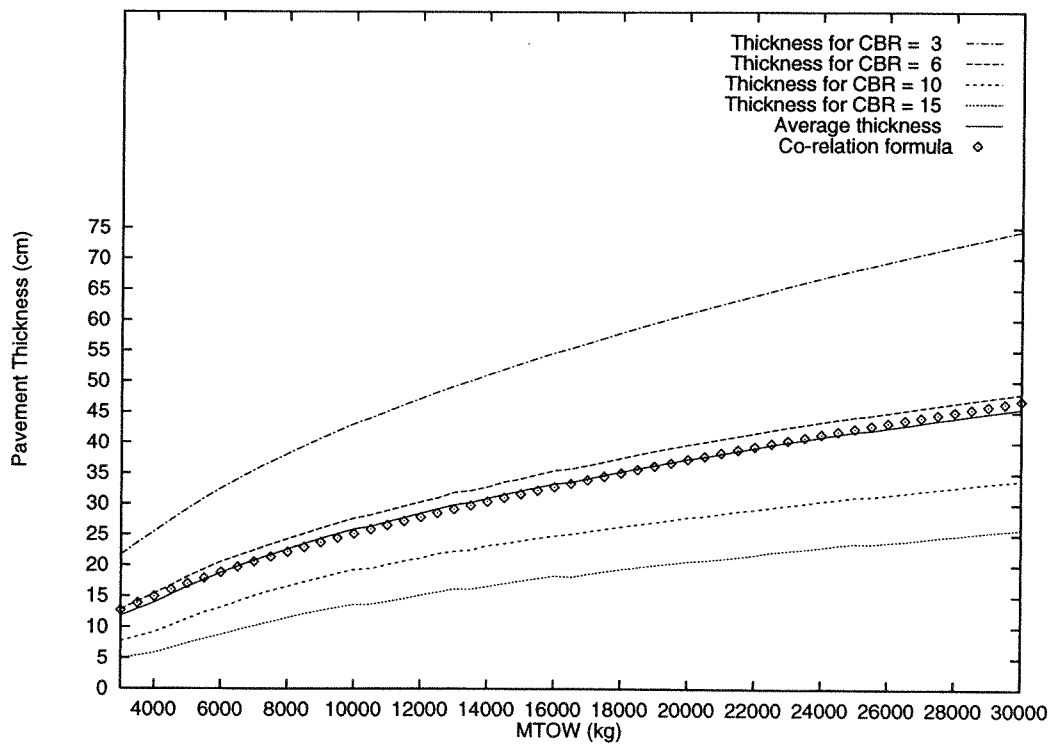


Figure 7.5: Pavement thickness v/s M_{TO} for various sub-grade CBR values

budgetary cost estimates for extension of 150 ft wide runway by 1500 ft at 2 Indian airports [107]. Both these airports have a runway with LCN 40, with flexible pavements suitable for operation of B-737-200 aircraft. Using LCN charts and B737-200 tyre pressure data, LCN 40 was converted to PCN 23 [111]. The average thickness of flexible material required for various sub-grade CBR values were evaluated using ACFLEX, as described above, which turned out to be 56 cm. Assuming a cost split of 73% for material & 27% for labour in India [107], the cost of construction of a flexible pavement was estimated as Rs. 3098.92 per cubic meter⁹.

As per the FAA regulations, the pavement thickness on the runways, taxiways & aprons have to be the same, but up to 30% reduction in thickness is allowed in the outboard portions of the runway & taxiways, due to lower probability of loading there [56]. This can lead to some savings in construction costs, depending on what fraction of the pavement is made with lower thickness. However, to allow for future growth of the airport and to keep the method of construction simple, it was assumed that the entire pavement width is of the total thickness.

7.5.2 Cost of construction of the landside area

The main constituent of landside area costs is the Passenger Terminal Building. The size of the terminal building is dependent on the maximum number of people expected to use the building at any given time (*peak hour load*), which itself is a function of the size of the aircraft(s) operating from the airport and their frequency. There should be sufficient space in the building to accommodate the passengers, airport staff and *meeters & greeters*¹⁰, and to allow their easy movement. The terminal building is assumed to be constructed in blocks, each suitable for accom-

⁹Unless otherwise stated, all cost terms in this chapter are in million Indian Rupees (Rs). The currency conversion rate is assumed to be 1 £ Sterling = 50 Rs.

¹⁰The people who come to see-off or pick up the passengers, which includes relatives, taxi-drivers, hotel reception staff, porters etc.

M_{TO} (kg)	Tire Size	Pressure (psi)	Typical Aircraft
7000 - 10000	22x6.8-10	90	B-1900, JS-41
10001 - 13000	24x7.7-10	100	Do-328, SAAB-340A
13001 - 16000	28x9.0-12	110	CN235-100
16001 - 20000	31x9.8-13	120	DHC D-8 series
20001- 23000	32x11.5-15	130	ATR-42 series
23001 - 26000	34x12.0-14	140	BAe-ATP

Table 7.8: MLG tire size & pressure data for regional turboprops [110]

modating 50 passengers. To arrive at the number of such blocks required at a particular airport, a concept of airport busy factor was used. This factor is defined as $ABF = \min(1, \frac{N_{daily}}{2})$, where N_{daily} is the number of aircraft movements per day. The total number of people in the terminal building during the peak hour for airports with low number of movements ($ABF = 1$) was assumed to be 1.5 times the aircraft capacity. For busier airports, this number was multiplied by ABF , and the terminal building was sized accordingly.

To estimate the cost of construction of the terminal building, a methodology was developed to scale down the costs associated with building one such terminal for an Indian airport [107]. The total cost of construction of a specified number & type of residential accommodation and transit hostel was also available for this airport. It was considered a good idea to provide *on-campus* accommodation for the key airport personnel, especially due to the fact that the airport is likely to be located in the outskirts of the city. The benefits of this are twofold. Firstly, the close proximity of these personnel would reduce the response time during out of operational hour needs and emergencies. Further, by careful planning, the residential area could be located in the land under the operational jurisdiction of the airport, and the investment on developing it could be recovered as a part of the rent over a period of time. The details of the methodology of scaling down the costs of terminal building and residential accommodation are given in Appendix C.

7.5.3 Cost of Fire & Rescue service

Each licensed airport has to have a rescue and fire-fighting service, the prime task of which is to save lives in the case of any accident or mishap. The most important factors bearing on effective rescue in a survivable aircraft accident are : the training received, the effectiveness of the equipment and the speed with which personnel and equipment designated for fire fighting purposes can be put to use [3]. ICAO categorises the aerodrome for rescue & fire-fighting capability on the basis of overall length of the longest aeroplane normally using the aerodrome and its maximum fuselage width. The minimum number of fire-fighting vehicles to be provided at each aerodrome category are also listed, as shown in Table 7.9. Recommendations for the minimum usable amounts of extinguishing agents for each aerodrome category are listed in [3]. Further guidelines on the rescue equipment to be provided at an aerodrome, minimum characteristics of the fire-fighting vehicles, physical properties and fire-extinguishing performance criteria for the foam etc are provided in [112]. There are no specific guidelines in [3] for determining the number of personnel to be provided at the fire-station, except that they should be adequate to meet the needs.

As can be seen from the various Tables in Appendix A, all existing regional turboprop aircraft (except DHC D8-400) have their overall length smaller than 28

Aerodrome Category	Aircraft overall length (m)	Fuselage max. width (m)	No. of Fire Tenders
1	0 - < 9	2	1
2	9 - < 12	2	1
3	12 - < 18	3	1
4	18 - < 24	4	1
5	24 - < 28	4	1
6	28 - < 39	5	2
7	39 - < 49	5	2
8	49 - < 61	7	3
9	61 - < 76	7	3

Table 7.9: ICAO Rescue & Fire fighting Category [3]

meters and maximum width of fuselage smaller than 4 meters, hence their ICAO aerodrome fire & rescue category is 5 or below. Estimates for the cost of fire-fighting vehicles and the commensurate equipment for overhaul & maintenance, communication and other equipment at the fire-station, protective clothing & equipment provided to each fireman and the cost of chemicals & foam for setting up the the foam were obtained from various sources, for such airports. For aerodrome above Cat. 2, it is assumed that a Rapid Intervention Vehicle (RIV) would be provided apart from a fire-tender. The annual staffing costs for firemen employed at Indian regional airports can be assumed to be Rs. 55,000/-, which includes the annual training cost of Rs. 4600/- [107]. Table 7.10 lists the costs associated with providing the Fire/Rescue service as per ICAO categorization. ICAO regulations do not

ICAO Fire & Rescue category	1	2	3	4	5
No. of Fire & Rescue Vehicles	1	1	2	2	2
Number Of Firemen	3	5	7	9	11
Fire & rescue vehicle cost	1.000	1.000	1.500	1.500	1.500
Equipment for vehicle	0.100	0.100	0.150	0.150	0.150
Equipment at fire-station	0.100	0.150	0.175	0.200	0.250
Equipment for Firemen	0.075	0.125	0.175	0.225	0.275
Chemicals & foam set-up Cost	0.025	0.050	0.075	0.075	0.100
Total Set-up Cost	1.300	1.425	2.075	2.150	2.275
Annual Staffing Costs	0.165	0.275	0.385	0.495	0.605

Table 7.10: Costs related with Fire & Rescue service

preclude an off-aerodrome location of the fire-station, or provision of fire & rescue service by any other private or public organization (such as the town fire-brigade

service). However, the recommended response time¹¹ is too low to use this option, hence each aerodrome is assumed to have a fire-station on site.

7.5.4 Cost of aeronautical equipment at the airport

These costs can vary from country to country, hence local estimates have to be made. Estimates for cost of aeronautical equipment for installation at Indian airports were obtained from vendors of such equipment in the UK, discussion with airport managers and from sources at National Airport Authority of India [107]. Table 7.11 lists the cost details of equipment at the three levels of Indian airports.

Equipment	Cost	Level-1	Level-2	Level-3
Control Tower Equip.	0.05	0.05	0.05	0.05
Radio Transmitter	0.05	0.05	0.05	0.05
NDB	0.50	0.50	0.50	0.50
V/UHF Radio	0.10	NIL	0.10	0.10
Aerodrome Beacon	0.20	NIL	0.20	0.20
Approach Lighting	0.40	NIL	NIL	0.40
Runway Lighting	0.70	NIL	NIL	0.70
TOTAL		0.60	0.90	2.00

Table 7.11: Cost of Equipment & facilities at the 3 levels of Indian airports

7.6 Estimation of annual staffing & recurring costs

These costs are a strong function of the local economy, standard of living, and hence vary from country to country. Table 7.12 lists estimates for the number and type of personnel required, and their average annual salaries for the three levels of airports described above. These estimates were obtained from [107] based on the staffing levels and salaries at similar airports in India. All salaries are gross i.e. they

¹¹Response time is considered to be the time between the initial call to the rescue and the fire fighting service, and the time when the first responding vehicle in position to apply foam at a rate of at least 50% of the specified discharge rate applicable to the aerodrome category. A response time of 2 minutes and not exceeding 3 minutes to the end of each runway, as well as to any other part of the movement area is recommended, under optimum conditions of visibility and surface conditions [3].

include a 40% factor for bonuses, pensions and other indirect benefits. The staffing at Level 3 airport includes extra staff required due to the night-time operations, possibly leading to an additional shift. Table 7.13 lists the annual recurring costs

Level	Level 1		Level 2		Level 3		
Designation	No.	Salary	No.	Salary	No.	Salary	Monthly
Airport Manager	1	0.1092	1	0.1092	1	0.1092	Rs. 6500
Dy. Airport Manager	-	NIL	-	NIL	1	0.1008	Rs. 6000
ATC Controllers	-	NIL	1	0.0924	2	0.1848	Rs. 5500
Asst. ATC Controllers	1	0.0776	1	0.0776	1	0.0776	Rs. 5000
Tech. Maintenance Staff	-	NIL	1	0.0672	1	0.0672	Rs. 4000
Security Officers	1	0.0588	1	0.0588	1	0.0588	Rs. 3500
Admin & Security Staff	2	0.0672	4	0.1344	6	0.2016	Rs. 2000
Miscellaneous Costs		0.0072		0.0154		0.0200	
TOTAL	5	0.3200	9	0.5500	13	0.8200	

Table 7.12: Annual staffing costs at Indian regional airports

associated with the three levels of airport. These estimates for Indian airports were also obtained from [107].

Head	Items	Level 1	Level 2	Level 3
Maintenance	Telecom & Navaid	0.030	0.045	0.100
Consumables	Office Supplies	0.012	0.018	0.025
Miscellaneous	Other Expenses	0.008	0.012	0.025
TOTAL		0.050	0.075	0.150

Table 7.13: Annual recurring costs at Indian regional airports

7.7 Examples of airport sizing & costing

As an example of application of the above methodology, the sizing and costing of three airports is shown in Table 7.14. The first one is a small *start-up* airport for operation of one return flight a day of a small commuter aircraft (such as Do-228). The second one is a small regional airport with two return flights of a medium capacity commuter/regional aircraft such as Saab-340B. The third one is a busy regional airport, with 5 return flights a day, and catering to a large capacity regional aircraft such as ATR72-210. For a fair comparison, all these three airports are assumed to be located at a distance greater than 10 km, but less than & 15 km from the city centre, hence the cost of land per hectares is the same.

Aircraft Type	Do-228	S-340B	ATR-72
Passenger capacity	19	35	66
Airport Level	1	2	3
Number of flights per day	1	2	5
Airport busy factor	1	1	3
Max. no. of people in terminal	28	52	247
Terminal building capacity	50	100	250
No of flights per year	300	600	1500
Landing Fee per flight (Rs.)	256	1397	1326
Annual income from Landing Fee (Rs.)	76800	838037	198860
RUNWAY & TAXIWAY SIZING, ICAO SPECIFICATIONS			
Fuselage length (m)	16.56	21.43	27.17
Wingspan (m)	16.97	19.74	27.05
Aerodrome Reference Code Number	2	3	3
Aerodrome Reference Code Letter	B	B	C
Runway pavement length (m)	800	1290	1370
Runway pavement width (m)	23	30	30
Runway shoulder width (m)	0	0	30
Runway strip width (m)	80	150	300
of which graded width (m)	80	150	210
and strengthened width (m)	80	150	150
Runway end safety area width (m)	0	0	60
Runway end safety area length (m)	0	90	90
Taxiway width (m)	10.5	10.5	15.0
Runway centerline to :			
Taxiway/lane centerline (m)	52	52	93
Taxilane centerline to :			
Fixed or movable object (m)	16.5	16.5	24.5

AIRPORT LAYOUT & SETTING UP COST ESTIMATION			
Width of airport boundary (m)	446	461	527
Length of airport boundary (m)	920	1410	1490
Approach surface area (acres)	7.78	13.34	29.30
Total area of airport (acres)	117.06	187.24	252.62
Land cost (million Rs.)	35.53	56.83	76.67
Average pavement thickness (cm)	19.53	29.08	38.81
Runway construction cost (million Rs.)	10.47	32.78	46.46
No. of taxiways	1	2	3
Taxiway Length (total) (m)	52	104	279
Taxiway construction cost (million Rs.)	0.33	0.98	5.03
No. of aprons	1	2	3
Apron length (total) (m)	17	44	91
Apron width (m)	18	24	30
Apron construction cost (million Rs.)	0.19	0.95	3.28
TERMINAL BUILDING SIZE & COST			
Width (m)	13.23	18.71	29.58
Length (m)	52.92	74.83	118.32
Floor area (sq m)	700	1400	3500
Construction cost (million Rs.)	2.201	3.878	8.909
Aeronautical equipment cost (million Rs.)	0.55	0.80	2.20
FIRE & RESCUE SERVICE COST			
Aerodrome Fire/Rescue category	3	4	5
Total number of firemen reqd.	7	9	11
Fire-station setup cost (million Rs.)	2.08	2.15	2.28
AIRPORT SETTING UP COST (million Rs.)	51.34	98.37	144.83
ANNUAL AIRPORT OPERATING COST			
Airport admin. & terminal staff salary	0.32	0.55	0.82
Maintenance, Consumables, misc. items	0.10	0.20	0.30
Firemen salary & training costs	0.39	0.50	0.61
ANNUAL OPERATING COSTS (million Rs.)	0.81	1.25	1.73

Table 7.14: Example of sizing & costing of three levels of airports

7.7.1 Non-linear nature of the Airport module

The % breakdown of the various components of Airport setting-up costs for these three airports is shown in Figure 7.6. It can be seen that the Land & Runway costs together represent a major fraction of the Airport setting-up cost, followed by the Terminal building & the Fire-Station. The navigational equipment and the Taxiway & Apron costs are a very small fraction of the total set-up costs, except for the Level-3 airport, since it has three taxiways & aprons and approach & runway lighting systems. Figure 7.6 reveals that as the airport gets bigger and busier, the

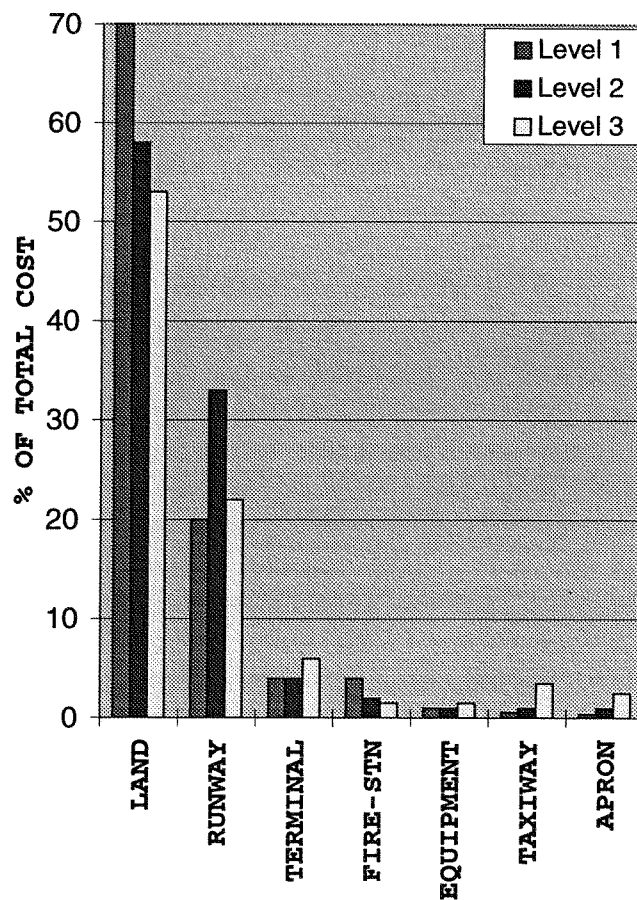


Figure 7.6: % breakdown of Setting up costs for the three airports

setting-up & operating costs increase. However, this increase may not always be linear, since some sizing parameters (e.g. the runway & taxiway widths, runway-to-taxiway separation & taxiway-to-apron separation) exhibit step jumps. This non-linearity is clearly brought out in Table 7.15, which lists the fractional increase (w.r.t Level-1 airport) in the dimensions & costs of some key components of the Level-2 & -3 airports. The setting-up costs of Level-2 airport are nearly twice that

All costs relative to Level-1		
Term	Level-2	Level-3
Airport Area	1.60	2.16
Pavement Thick.	1.49	1.99
Runway Length	1.61	1.71
Runway Cost	3.13	4.44
Taxiway Cost	2.97	15.24
Apron Cost	5.00	17.26
Terminal Size	2.00	5.00
Terminal Cost	1.76	4.05
Equipment Cost	1.45	4.00
Fire-Stn Cost	1.04	1.10
Setting-up Cost	1.92	2.82
Operating Cost	1.54	2.14

Table 7.15: Relative size & costs of the three levels of airports

of Level-1 airport, even though the total land area & the runway required are only about 60% higher. This is mainly due to the nearly 50% increase in the pavement thickness and 76% increase in the terminal costs, not to mention the other factors. The Level-3 airport occupies an area more than twice of the Level-1 airport, and needs twice the pavement thickness, but owing to a much larger passenger terminal and far larger taxiway & apron sizes, the overall setting-up costs are nearly three times as large. Even though the runway length is only 71% longer, its cost is more than four-fold, due to an increase in runway width. Table 7.15 also brings out the scale affect in sizing & costing of the terminal building ; though the terminal size increases by two times to five fold as the airport level increases, the costs do not increase in the same proportion. This is due to the fact that certain components of the terminal (e.g. the toilets & the area occupied by the control tower) do not scale up linearly as the terminal size increases. Further, the costs related to the Fire-Station for Level-2 & 3 airport increase only by 4% & 10%, respectively, since the major cost component in all the three fire-stations viz. the Fire-tender remains the same. Though the Taxiway & Apron costs increase by very large fractions, their increase in real terms is marginal, since they form a very small fraction of the total setting-up costs. Finally, it is interesting to note that the annual airport operating costs increase almost in proportion to the size of the airport, though there is no direct co-relation between them.

The module provides a means for obtaining the sensitivity of the airport related costs with change in the aircraft parameters such as Take-off mass, wingspan, Fuselage length & max. diameter, MLG layout & *BFL*, and operational parameters such as number of flights per day & the location of airport from city-center. In the

sizing & cost examples discussed above, the various cost terms are relevant to India, but the module is fairly generic and can be applied to widely differing scenarios given suitable values for the various cost terms, and can also incorporate any local regulatory restrictions or practices.

7.7.2 Limitations of the Airport module

In its present form, the module sizes the airport based on operation of only one aircraft type, and does not consider the effect of other factors on sizing & costs such as extent & duration of General Aviation and other aeronautical or commercial businesses that may be using the airport. But due to its modular structure and generic nature, the module could be easily modified to incorporate these features. Though the inherent non-linearity of the module is a reflection of the real-life phenomena, it can be a potential cause of difficulty for the optimizer, since the sensitivity of a parameter to the airport related costs will undergo sudden changes as its value varies. Some optimizers may be completely misled by such sudden changes, hence care has to be taken to use a suitable optimizer when this module is used.

Chapter 8

Case study with CASTOR

8.1 Introduction

This chapter discusses the salient features and the results obtained in a case study [113] that was carried out to develop a basic framework for integration of Generalised cost (C_{gen}) described in Chapter 1 in conceptual design and optimisation of civil aircraft. The aim of the study was to compare the C_{gen} of a few commuter/regional aircraft for short-haul business travel in India. For this study, the un-modified CASTOR code listed in [47] was used, without incorporating any of the modifications outlined in Chapter 9. Minimum *DOC* configurations of 15, 20, 30 & 60 seater twin-turboprop aircraft were determined using the CASTOR routine described in Chapter 5 coupled with the SIMANN optimiser described in Chapter 3, for operation over stage lengths of 100 nm. The airport model described in Chapter 7 was used to estimate the cost of setting up and operating a regional airport sized for operation of each of the above aircraft in India. All cost terms were calculated using relevant data for Indian conditions in 1996 from various sources, for e.g., the cost terms related to the airport model were obtained from [107]. Annual one-way demand of 18000 passenger trips was considered for the baseline case. The sensitivity of time costs & the various cost terms related to the airport infrastructure on C_{gen} was studied. Further, the sensitivity of C_{gen} of these configurations to changes in passenger demand levels was also determined.

8.2 Details of the case study

The case study was carried out for business air-travel in India between two cities located at distance of 100 nm (185 KM). India was chosen as a test market due to the

recent developments in the Indian domestic aviation sector, which has led to the creation of many regional airlines that operate commuter & regional aircraft. Appendix D discusses these recent developments and a model developed by the author for forecasting the demand for air-travel in India. Another reason was the availability of data related to the estimation of various components of Generalised cost. Such a short range may seem improper for air-travel, but presence of geographical barriers and lack of adequate infrastructure for surface transportation may make air-travel worthwhile. Many such potential city-pairs exist in North-Eastern & Western states of India¹. Since the market was new and untested, the expected travel demand was likely to be quite low, hence only twin-engined turboprop aircraft were considered. For the baseline case, the aircraft were scheduled to meet an expected demand of 18000 one-way trips annually. This translated into a need to transport 60 passengers per day, assuming that flights were scheduled on 300 days in an year. It was assumed that a well-equipped airport already existed at one end, and the costs related with setting up and operating a suitable airport at the end were to be recovered from the passengers, over a reasonable period of time. All aircraft were sized to be able to fly 5 stage lengths of 100 nm without refuelling, which is a desirable operational feature to reduce their turn-around time and the infrastructural requirements at the newly set-up airport.

It may be noted that BFL is set as one of the 12 constraints in CASTOR, as discussed in Chapter 5. In almost all minimum *DOC* cases investigated by the author (as well as those reported by Simos & Jenkinson in [47]), it was found that the constraint on BFL was always active, i.e. the optimum configurations were found to lie on the boundary of this constraint. Therefore, unrealistic configurations would have resulted if this constraint was set to the same value for all the aircraft. Hence it was decided to specify suitable values of *BFL* for all the four aircraft, based on the *BFL* of contemporary aircraft of similar capacities. The constraint on maximum *LFL* was also relaxed as the aircraft size increased, since all the aircraft are assumed to have conventional aerodynamics. Except the 60 seater, all aircraft were assumed to be un-pressurised, hence max. rate of descent was limited to 3.54 m/s (700 fpm), from the point of view of passenger comfort.

Some important parameters related to the minimum *DOC* configurations of 15, 20, 30 & 60 seater aircraft that resulted are shown in Table 8.1. In all the cases, the power-plant seemed to get sized to meet the *BFL* and OEI second-stage climb gradient constraints. The optimum 20 seater aircraft, in fact, needed lesser engine power than the 15 seater, and had lower cruising speed and total fuel requirement. Due to the short range and the upper limit on the rate of descent (except 60 seater aircraft), the optimum cruising altitude for all the aircraft was at the lower limit of 1500 m.

¹For e.g. Aizawl-Imphal, Dibrugarh-Itanagar, Kandla-Porbandar.

Parameter	Description	Units	15 seater	20 seater	30 seater	60 seater
BFL_{max}	Upper limit imposed on BFL	m	850	900	1100	1450
BFL_{act}	Actual value of BFL	m	850	900	1100	1450
LFL_{max}	Upper limit imposed on LFL	m	1000	1100	1250	1500
LFL_{act}	Actual value of LFL	m	861	835	985	1426
M_{TO}	Max. Take-off mass	kg	8481	9447	14265	23958
S_{ref}	Wing Area	sqm	48.36	57.34	68.02	76.89
W/S	Wing loading	kg/m^2	175.37	164.75	209.72	311.59
M_{empty}	Empty Mass	kg	5529	6111	9561	15350
$M_{fuel_{tot}}$	Total fuel mass	kg	1374	1297	1655	2087
$M_{fuel_{mis}}$	Mission fuel mass	kg	200	203	232	314
P_{TO}	Max. Take-off power	HP	1274	1137	1717	3000
P/W	Power loading	HP/kg	0.300	0.241	0.241	0.250
V_{cr}	Cruising speed	m/s	106	98	114	118
H_{cr}	Cruising altitude	m	1500	1500	1500	1500
L_{fus}	Fuselage Length	m	20.55	22.08	28.67	31.80
D_{fus}	Fuselage diameter	m	1.60	1.60	2.50	3.00
b_{wing}	Wing span	m	25.05	27.02	29.74	31.56
N_{abr}	No. of pax seated abreast	-	2	2	3	4

Table 8.1: Optimum configurations of the four aircraft [113]

8.3 Determination of Generalised cost

The general expression for C_{gen} per trip per passenger consists of the following four terms :

$$C_{gen} = C_{acc} + C_{time} + C_{flt} + C_{apt} \quad (8.1)$$

where,

$$\begin{aligned} C_{acc} &= \text{Access related cost} \\ C_{time} &= \text{Time related cost} \\ C_{flt} &= \text{Flight related cost} \\ C_{apt} &= \text{Airport related cost} \end{aligned}$$

To simplify the analysis, a constant C_{acc} of Rs 95 and corresponding Access time (T_{acc}) of 30 minutes was used in the study. A brief description of how the other three terms of Equation 8.1 were obtained is provided below. %subsection Estimation of Time cost C_{time} can further be expanded as :

$$C_{time} = \mathcal{V} \cdot (T_{acc} + T_{defer} + T_{blk}) \quad (8.2)$$

where,

$$\begin{aligned} T_{defer} &= \text{Defer Time} \\ T_{blk} &= \text{Block time for the flight} \\ &= \text{Trip Time} + 9 \text{ mins. for Take-off \& Landing} \end{aligned}$$

The concept of T_{defer} is discussed in Chapter 1, and its value is related to the number of flights available in a day and the duration of the time period during which demand for travel can be assumed to exist. Business trips on short stage lengths are usually attractive if travellers are able to return back to base the same day after completion of business, so there is hardly any need for scheduling flights between the hours of dusk and dawn. On this basis, the average duration of the time period for travel demand was considered as 12 hours in a day. Commuter & Regional aircraft schedules usually show a peak-time demand in the early hours of morning for onward journey in late evening hours for the return journey, but in this study, it was assumed that the flights were scheduled at equal intervals during the daytime, with a constant passenger load factor of 0.85. The number of flights to be scheduled per day ($N_{flt_{day}}$) was determined as the ratio of total number of passengers to be carried per day (i.e. 60) and the seating capacity of the aircraft. Thus, $N_{flt_{day}}$ for 15, 20, 30 & 60 seater aircraft was 4, 3, 2 & 1, respectively.

The *Value of Time* ($\mathcal{V}$) of passengers was considered as Rs 100 per hour. This figure, though quite arbitrary, was obtained assuming $\mathcal{V}$ to be $\approx 85\%$ of the hourly earnings², as suggested by [51] for domestic business travel.

8.3.1 Estimation of Flight cost

The aircraft acquisition cost (C_{acq}) and the Direct Operating Cost per seat-nm (DOC_{snm}) of the four aircraft were estimated using the Cost Estimation Module outlined in Appendix F, for an assumed fleet size of 350. If the C_{acq} estimates so obtained for these low capacity aircraft exceeded the industry estimates, an upper limit of US \$ 200,000 per seat was employed, to make them realistic. The DOC_{snm} was calculated to reflect realistic annual fleet utilization (N_{util}), assuming that the aircraft would be employed to other routes, if N_{util} on this route was low. Assuming “no frills” operation, a low value of 1.2 was considered for the IOC factor F_{IOC} . C_{flt} was, thus, the Total Operating Cost TOC per seat-nm.

8.3.2 Estimation of Airport cost

The methodology outlined in Chapter 7 was followed for estimation of C_{apt} , which involves the following steps :

- Classification of the airport under one of the three “Levels”
- Geometric sizing and layout of the airport as per ICAO regulations
- Estimation of the one-time cost related to setting-up the airport (C_{setup})
- Estimation of the annual cost related to the operation of the airport (C_{oper})

It was assumed that for C_{setup} , capital was borrowed at an interest rate R_{int} of 8%. The only source of income for the airport was assumed to be through the Landing Fee (L_{fee}) for each of the $N_{tripann}$ annual trips to meet the total annual demand of N_{pazann} . The shortfall between the annual expenditure and income of the airport (including the yearly repayment towards C_{setup}) was assumed to be recovered in full from all the passengers utilizing it over its depreciation period AP_{depr} of 20 years in the form of C_{apt} . The following expression was thus obtained for C_{apt} in terms of

²Assuming monthly earnings of Rs 24000 per month, and working for 8 hours a day for 300 days in a year.

the above parameters :

$$C_{apt} = \frac{C_{oper} + C_{setup} \left[\frac{1}{AP_{depr}} + \frac{R_{int}}{2} \right] - L_{fee} \cdot N_{trip_{ann}}}{N_{pax_{ann}}} \quad (8.3)$$

Determining the “Level” of the airport

As discussed in Chapter 7, a typical regional airport in India can be classified under one of the three levels based on the extent and duration of flight operations from it. Since 4 flights of the 15 seater aircraft were to be scheduled over a 12 hour period, the airport associated with it was assigned the level 3. This was because such an airport is expected to have runway & approach lighting to cater for operations during early morning or evening. On the other hand, since only one flight per day was scheduled for the 60 seater aircraft, the airport associated with it was assigned the level 1. For the 20 & 30 seater aircraft, level 2 airport was considered.

Geometric sizing of the airport

Table 8.2 gives the details of the geometrical sizing of the airports associated with the four aircraft, as per ICAO regulations [3].

Estimation of Airport Setting-up cost

As discussed in Chapter 7, the components of C_{setup} are:

- Cost of the aeronautical equipment (C_{equip})
- Cost of land acquisition and site preparation (C_{land})
- Cost of constructing the runway (C_{rway})
- Cost of constructing the taxiway(s) (C_{tway})
- Cost of constructing the apron(s) (C_{aprn})
- Cost of constructing the pax. terminal building (C_{tbld})
- Cost of setting-up the rescue & fire-fighting station (C_{rfset})

Aircraft capacity	15	20	30	60
Note: All dimensions in meters, unless stated otherwise				
Airport Level	3	2	2	1
Fuselage length	20.55	22.08	28.67	31.8
Wing Span	25.05	27.02	29.74	31.56
AERODROME CLASSIFICATION				
ICAO Code Letter	C	C	C	C
ICAO Code No	2	2	2	3
Fire Category	4	4	5	5
SEPARATION CRITERIA				
Runway-Taxiway	54.0	54.0	54.0	93.0
Taxiway-Apron	24.5	24.5	24.5	24.5
RUNWAY SIZING DETAILS				
Length	850	900	1100	1450
Width	23	23	23	30
Shoulder Width	37	37	37	30
Strip Width	80	80	80	150
Pavement Thk. (cm)	23.45	25.04	31.25	40.84
TAXIWAY SIZING DETAILS				
No. of Taxiways	3	2	2	1
Total Length	156	104	104	93
Width	15	15	15	15
APRON SIZING DETAILS				
No. of Aprons	3	2	2	1
Total length	85.15	59.04	64.48	31.56
Width	22.61	24.29	31.54	34.98
PASSENGER TERMINAL DETAILS				
Passenger Capacity	50	50	50	100
Width	13.23	13.23	13.23	18.71
Length	52.92	52.92	52.92	74.83
AIRPORT LAND AREA REQUIREMENTS				
Airport Width	458.83	460.52	467.76	521.12
Airport Length	970	1020	1220	1570
Runway Clear Zone (acres)	14.46	7.784	7.784	13.35
Total Airport area (acres)	138.90	131.64	156.59	228.89

Table 8.2: Geometrical Sizing of the airports for the four aircraft [113]

The minimum fit of the aeronautical equipment at an airport was determined in accordance with its level, as discussed in Chapter 7, hence C_{equip} could be readily estimated. Since land prices show a large variation, a representative value of Rs 50 per sq. m. was chosen for C_{land} [107]. For the level 3 airport, 50% higher C_{land} was assumed, to take into consideration the much larger site preparation costs involved with installing the runway & approach lighting system, and also due to provision of extra facilities for longer hours of operation and larger number of movements. Once the geometrical sizing of the runway, taxiway(s) & apron(s) and the pavement thickness was carried out, the costs related to their construction were estimated assuming a standard rate of construction per volume. Estimation of C_{tbl} was carried out according to the methodology explained in Appendix C. After determining the ICAO rescue & fire-fighting category [3] of the airport (based on the max. fuselage diameter and length), C_{rfset} was estimated as discussed in Chapter 7.

Estimation of airport annual operating cost

Based on the data related to staffing requirements and current salary levels of various categories of airport staff in Indian airports [107], the annual staffing costs (C_{staff}) & recurring costs (C_{recur}) for the three levels of airports were estimated. The recurring costs associated with the rescue & fire-fighting station (C_{rfrec}) were also estimated based on the ICAO rescue & fire-fighting category of the airport. Details of these estimates are provided in Chapter 7.

The breakdown of C_{setup} & C_{oper} for the four aircraft is given in Table 8.3. The single largest cost element is seen to be C_{land} , varying from 64% of C_{setup} for 15 seater aircraft to 43% for the 60 seater aircraft. The C_{setup} for the 15 seater & 30 seater aircraft are quite similar, this is because the higher C_{rway} for the 30 seater is almost offset by the higher C_{land} for the 15 seater aircraft. In fact, the C_{land} of the airport for the 15 seater and the 60 seater aircraft are quite similar, even though much larger area is needed by the airport for the 60 seater aircraft, as shown in Table 8.2. The annual gap between income and expenditure of the airports is seen to decrease as the aircraft capacity increases.

8.3.3 Comparison of Generalised cost of the various aircraft

Table 8.4 compares the C_{gen} of the four aircraft-airport combinations to meet the baseline annual passenger demand of 18000. It can be seen that the C_{acq} for all except the 60 seater aircraft had to be corrected to match industry expectations. DOC_{snm} is seen to reduce with increase in aircraft size, as expected. C_{apt} for the 60 seater aircraft was seen to be almost equal to C_{flt} , due to very high values of T_{defer} .

Aircraft size		15 seater	20 seater	30 seater	60 seater
Airport Level		3	2	2	1
Note:- All cost terms in million Rupees, unless stated					
Breakdown of C_{setup}					
Land cost	C_{land}	42.15	26.63	31.68	46.51
Runway cost	C_{rway}	13.35	15.10	23.03	51.75
Taxiway cost	C_{tway}	1.70	1.21	1.51	1.77
Apron	C_{aprn}	1.27	1.01	1.80	1.27
Term. Blg. cost	C_{tbld}	2.20	2.20	2.20	3.88
Eqpt. cost	C_{equip}	2.20	0.80	0.80	0.55
Fire-Stn. cost	C_{rfset}	2.70	2.70	2.90	2.90
Airport set-up cost	C_{setup}	65.57	49.65	63.92	108.63
Breakdown of C_{oper}					
Staffing cost	C_{staff}	0.82	0.65	0.65	0.32
Recurring cost	C_{recur}	0.30	0.20	0.20	0.10
No. of Firemen	-	9	9	11	11
Fire-Stn	C_{rfrec}	0.50	0.50	0.61	0.61
Operating cost	C_{oper}	1.62	1.35	1.46	1.03
Calculation of C_{apt}					
Annual flights	$N_{tripann}$	1200	900	600	300
Landing Fee	L_{fee} (Rs)	339.25	377.89	1208.60	1668.10
Annual Income	-	0.41	0.34	0.73	0.50
Annual Shortfall	-	1.19	1.00	0.72	0.62
Airport cost	C_{apt} (Rs)	393.91	303.57	359.57	576.30

Table 8.3: Breakdown of Airport cost terms for the various aircraft [113]

Aircraft Size	Units	15 seater	20 seater	30 seater	60 seater
C_{AUC}	10^6 US \$	3.00	4.00	6.00	11.06
N_{util}	hours	2076	2120	2054	1987
$N_{trip_{ann}}$	–	3049	2960	3092	3226
DOC_{snm}	US cents	14.48	12.78	10.87	9.97
T_{flt}	minutes	41	43	40	37
$N_{flt_{day}}$	–	4	3	2	1
T_{defer}	minutes	45	60	90	180
C_{acc}	Rupees	95.00	95.00	95.00	95.00
C_{time}	Rupees	193.08	221.64	266.42	411.58
C_{flt}	Rupees	703.41	621.06	527.88	403.54
C_{apt}	Rupees	393.91	303.57	359.57	576.30
C_{gen}	Rupees	1385.41	1241.27	1248.87	1486.21

Table 8.4: Generalised cost of the four aircraft for the baseline case [113]

The 20 seater aircraft had the lowest C_{apt} & C_{gen} , but only marginally lower than that for the 30 seater. The 70 seater aircraft was found to have the highest C_{gen} , followed by the 15 seater.

8.4 Sensitivity of Generalised cost to various cost components

Having ranked the aircraft based on C_{gen} with all cost terms included, the sensitivity of C_{gen} to change in values of some of the cost terms was investigated. As discussed earlier, the major component of C_{apt} in all cases was C_{land} . In some cases, it may be possible to develop a new airport with the land provided at discounted rate (or even free of charge) by the local government or council.³ Further, in situations where the airport is already existing or when the policy of recovering C_{setup} from the passengers is not in force, C_{apt} consists only of C_{oper} .⁴

Table 8.5 lists the main results of this sensitivity analysis. The effect of ignoring various cost terms on the C_{gen} of the four aircraft is also indicated by ranking them in the increasing order of C_{gen} . It is seen that if C_{land} is ignored, C_{apt} reduces by $\approx 40\%$ to 54% from its baseline value (i.e. with all cost terms included). However,

³ An example of this is the Salem airport in south India, for which 130 acres of land was provided by the Government of Tamil Nadu free of cost [107].

⁴ In most cases, a part or whole of this amount is recovered from the passengers in the form of the airport-tax or from the airlines in terms of the passenger-handling charge.

if C_{setup} is altogether ignored, the percentage reduction is between $\approx 82\%$ to 94% ! Thus, the true costs of setting-up a new airport are seen to be quite high.

As the various terms related to C_{apt} are progressively excluded from C_{gen} , the ranking of 30 & 60 seater aircraft start improving. The 30 seater aircraft has the lowest C_{gen} as long as C_{land} is not considered, in which case the 20 seater has the lowest C_{gen} . When C_{time} is progressively reduced (by reducing $\mathcal{V}$ to 50 & then ignoring it altogether), the 30 seater aircraft scores over the 20 seater. Only in the case where C_{acc} & C_{flt} alone are considered (i.e. C_{time} & C_{apt} are ignored) the 60 seater aircraft has the lowest C_{gen} ; the 30 seater is second-best even in this case.

For all the cases listed in Table 8.5, the 30 seater aircraft has either the first or second ranking. Based on this sensitivity analysis, it was concluded that the 30 seater aircraft was the best overall compromise solution for this scenario.

8.5 Sensitivity of Generalised cost to change in Annual Passenger Demand

It is fairly obvious that as the number of passengers that use the air-network increase, C_{apt} per passenger would reduce, since more people would share these costs. C_{time} would also come down, since more frequent flights would have to be scheduled to meet the increased demand. But how it would affect the C_{gen} of various aircraft capacities is not immediately apparent, since it depends on the relative values of its constituents. The sensitivity of the various terms of C_{gen} to changes in $N_{pax_{ann}}$ was carried out by studying the effect of doubling, tripling, halving, and quartering the annual passenger load, as shown in Figure 8.1.

With $N_{pax_{ann}}$ of 36000, the 30 seater aircraft is seen to have the lowest C_{gen} , with 60 seater not very far behind. For the 60 seater aircraft, the increase in C_{apt} and C_{time} is slightly offset by the decrease in C_{flt} .

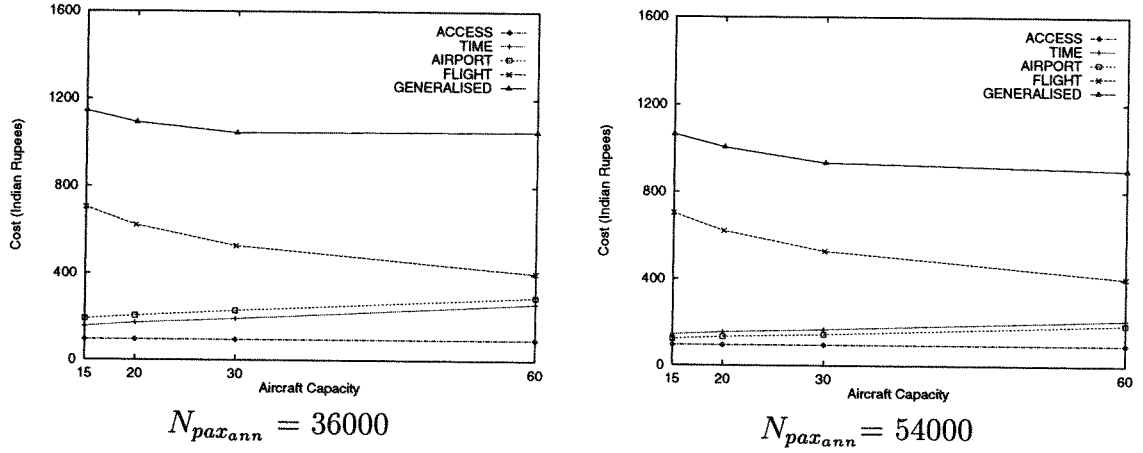
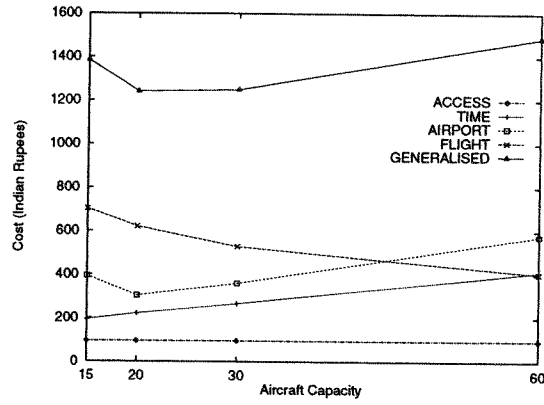
For $N_{pax_{ann}}$ of 54000, however, the 60 seater has the lowest C_{gen} , because C_{apt} & C_{time} are now much smaller components of C_{gen} , which thus follows the same trend as C_{flt} . The difference in the C_{gen} between 30 & 60 seater aircraft is still quite less, as in the previous case. Thus, as the number of passengers is increased, larger aircraft seem to have a lower C_{gen} . This trend may not be the same for ever increasing aircraft sizes, because beyond a certain point, the airport requirements may increase much more than what a level 3 airport provides, hence C_{apt} may increase drastically, altering the whole picture.

The situation is completely reversed for lower $N_{pax_{ann}}$. For instance, with $N_{pax_{ann}}$

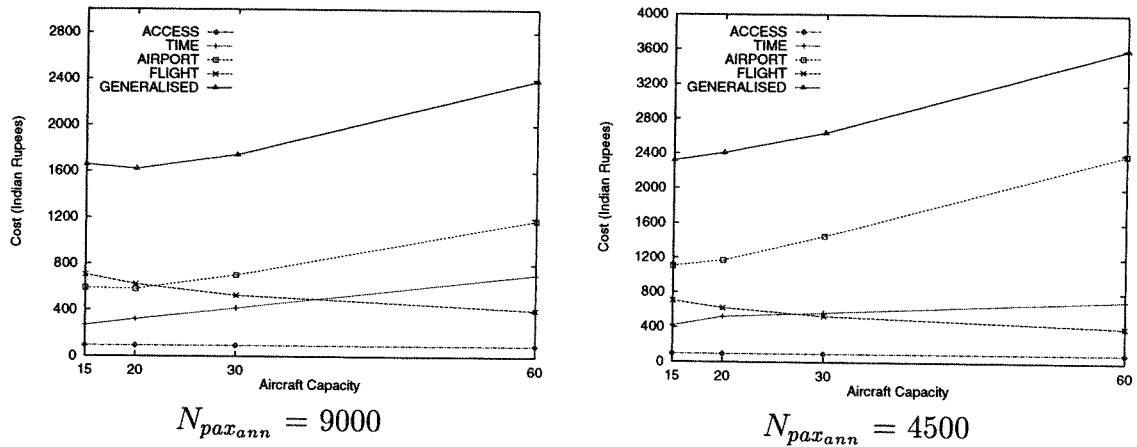
Aircraft Size	15 seater	20 seater	30 seater	60 seater
Effect of neglecting C_{land} & C_{setup} on C_{apt}				
C_{apt} (baseline) Rupees	393.91	303.57	359.57	576.30
C_{apt} (ignoring C_{land}) Rupees	183.14	170.39	201.15	344.73
% reduction in C_{apt} (ignoring C_{land})	53.4	43.9	44.1	40.2
C_{apt} (ignoring C_{setup}) Rupees	65.99	55.27	39.99	34.14
% reduction in C_{apt} (ignoring C_{setup})	83.2	81.8	88.9	94.1
Effect of varying C_{apt} terms on C_{gen}				
C_{gen} (baseline)	1385.41	1241.27	1248.87	1486.21
Ranking as per above C_{gen}	3	1	2	4
C_{gen} (ignoring C_{land})	1174.63	1108.09	1090.45	1254.65
Ranking as per above C_{gen}	3	2	1	4
C_{gen} (ignoring C_{setup})	1057.49	992.97	929.29	944.06
Ranking as per above C_{gen}	4	3	1	2
C_{gen} (ignoring C_{apt})	991.50	937.7	889.30	909.92
Ranking as per above C_{gen}	4	3	1	2
Effect of varying $\mathcal{V}$ on C_{gen}				
C_{gen} ($\mathcal{V} = 100$)	1385.41	1241.27	1248.87	1486.21
Ranking as per above C_{gen}	3	1	2	4
C_{gen} ($\mathcal{V} = 50$)	1288.88	1130.43	1115.65	1280.43
Ranking as per above C_{gen}	4	2	1	3
C_{gen} ($\mathcal{V} = 0$)	1192.31	1019.67	982.47	1074.61
Ranking as per above C_{gen}	4	2	1	3
Effect of neglecting C_{time} & C_{apt} on C_{gen}				
C_{gen} (ignoring C_{time} & C_{apt})	798.41	716.06	622.77	498.34
Ranking as per above C_{gen}	4	3	2	1

Table 8.5: Sensitivity analysis of Generalised cost terms [113]

EFFECT OF HIGH $N_{pax_{ann}}$



BASELINE CASE WITH $N_{pax_{ann}} = 18000$



EFFECT OF LOW $N_{pax_{ann}}$

Figure 8.1: Sensitivity of Generalised cost to annual passenger demand

of 9000, the decrease in C_{flt} is overcome by increase in C_{time} itself, hence C_{gen} follows the trend of C_{apt} itself. The 20 seater aircraft has the lowest C_{gen} for this case, closely followed by the 15 seater. For the 60 seater aircraft, C_{apt} and C_{time} are seen to be even larger than C_{flt} !

When $N_{passann}$ is further reduced to 4500, C_{gen} is seen to be dominated by C_{apt} which is excessively high for 30 and 60 seater aircraft. The 15 seater aircraft is the clear winner in this case, but the magnitude of C_{gen} itself is quite high. It may be noted that though C_{acc} is constant in all cases shown in Figure 8.1, it has been included to provide a quick visual comparison of the magnitude of C_{gen} for each case.

8.6 Conclusions of the case study

The case study revealed that for low passenger loads, C_{time} and C_{apt} are the most dominant terms in C_{gen} , hence low capacity aircraft were seen to have low C_{gen} . The situation was reversed for higher passenger loads. The overall compromise solution for the baseline case was the 30 seater aircraft, while the 20 seater aircraft had the least average C_{gen} for all the passenger loads. Within the limitations of the case study, it was concluded that small to medium capacity aircraft are more suitable for short-haul travel in India when C_{gen} is considered as a figure of merit, and that the inherently lower seat-mile costs of larger aircraft are more than offset by the increase in their costs related to time and the airport infrastructure.

8.7 Limitations of the case study

The three major limitations of this case study were :

- The C_{gen} of the four aircraft were calculated *after* their optimum *DOC* configurations were obtained. In other words, the configurations investigated were not the minimum C_{gen} configurations, but the minimum *DOC* configurations, and that too as per the un-modified *DOC* module of CASTOR⁵.
- The value of main parameter affecting C_{apt} , viz. *BFL* had to be specified as a constraint in CASTOR; its optimum value for minimum C_{gen} was not determined.

⁵It may be noted that after these optimum configurations were obtained, their C_{AUC} & DOC_{snm} was recalculated as per the Acquisition and operating cost estimation module outlined in Appendix F.

- Many modules of CASTOR were found to be outdated since this routine was nearly a decade old.

However, the study did serve a very useful purpose of highlighting the interplay of the various components of C_{gen} and its strong dependence on $N_{pax_{ann}}$.

This exploratory case study paved the way for the next, more elaborate study, in which the above limitations of the present study were progressively removed. A critical analysis of the existing modules of CASTOR was carried out, and a need was felt to modify and update most of them, as well develop new ones to improve the routine. These modifications and improvements are discussed in Chapter 9.

Chapter 9

Description of modified & new modules of CRAGER

9.1 Introduction

This chapter provides a brief overview of the modifications carried out to the various submodules of CASTOR and the new modules added to it, to make it suitable for application in the present work. The validation of some of these modules with data related to present day commuter & regional aircraft is also discussed. Further details of the major modifications are given in Appendix E, F & G. The modified program was renamed as CRAGER i.e. *Commuter & Regional Aircraft Generalised cost Estimation Routine*. The description of the various modules of CRAGER along with a flowchart is given in Appendix H.

9.2 Geometry module

The geometry module of CASTOR seemed to be tailored for sizing the aircraft with a specific engine and propeller combination, since the propeller diameter, RPMs at various mission segments and the nacelle geometry were specified as inputs. Rather than using fixed values for nacelle geometry and propeller diameter, it was decided to arrive at their appropriate values based on P_{TO} , which is an optimisable parameter. Further, it was also decided to relate the front fuselage length (L_{fus_f}) to the fuselage diameter D_{fus} .

9.2.1 Nacelle parameters

The three nacelle parameters that are given as input in CASTOR are its equivalent diameter (D_{nac}), total length (L_{nac}), and the *overhang* (L_{hang}) i.e. the distance between the nacelle leading edge and the wing leading edge at nacelle mounting point. These parameters related to some existing aircraft were obtained from the aircraft performance manuals and specification booklets viz. [114], [115], [116], [117], [118], & [119] and various editions of *Jane's All the World's Aircraft* e.g. [110] and are listed in Table 9.1. A linear correlation between D_{nac} and P_{TO} was obtained, as shown in Figure 9.1. Further, L_{hang} was seen to be nearly equal to the local wing chord for many aircraft. The main exceptions were DASA Do-228-212, IPTN CN235-100 & CASA212-300 which were seen to have very small L_{hang} , and Dash8-100, which has an unusually large L_{hang} . Since most nacelles are extended till the trailing edge of the wing at the nacelle mounting point (from aerodynamic considerations), a good approximation to L_{nac} was considered as twice the local chord.

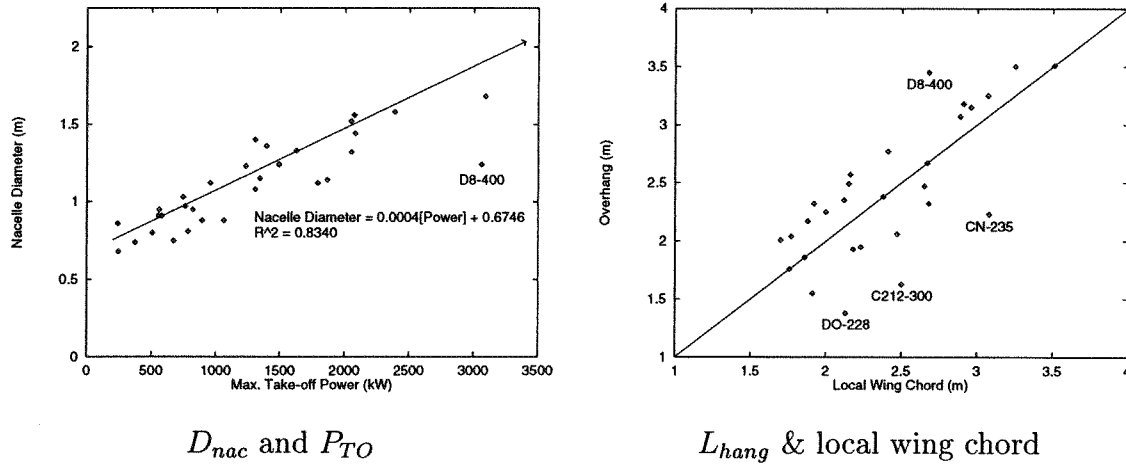


Figure 9.1: Correlation for Nacelle diameter and length

9.2.2 Propeller diameter selection

According to Torenbeek [14], D_{prop} is the most important design parameter of the propeller and in a sense comparable to the wing-span, albeit with definite limitations. The selection of D_{prop} is governed by many factors such as performance i.e. efficiency under varying conditions, tip speed in connection with propeller efficiency and noise considerations and practical limits such as ground clearance and the clearance between the tips and the aircraft structure.

NAME	L_{fus_f}	D_{fus}	D_{nac}	L_{hang}	$Chord$	L_{nac}	D_{prop}	P_{TO}	N_b
Units	m	m	m	m	m	m	m	kW	-
BN-2T	2.50	1.18	0.86	0.91	2.00	2.91	2.03	239	3
AP-68TP	3.19	1.24	0.68	0.99	1.49	2.84	2.03	245	3
SKA-350	3.40	1.54	0.81	2.49	2.15	4.19	2.67	783	4
F406	4.00	1.49	0.74	2.04	1.77	4.46	2.36	373	3
HAMC Y-12-II	3.90	1.80	0.80	1.86	1.86	3.72	2.49	507	3
AN28-PT	3.84	1.80	0.95	1.93	2.18	3.47	2.82	820	5
B1900D	4.85	1.87	1.12	1.95	2.23	3.88	2.78	954	4
DO-228-212	4.14	1.99	0.91	1.38	2.13	1.51	2.69	579	4
EMB110	4.03	1.88	0.91	2.25	2.00	4.50	2.36	555	3
FC METRO	5.04	1.80	1.03	2.17	1.88	3.75	2.69	746	4
L-410	4.33	2.15	0.95	1.55	1.91	3.10	2.30	559	5
JS - S31	4.52	1.98	0.97	1.76	1.76	3.22	2.69	760	4
C212-300	4.54	2.25	0.75	1.63	2.50	4.26	2.79	671	4
SD330-200	5.29	2.54	0.88	2.01	1.70	3.82	2.82	893	5
DO328	5.11	2.42	1.33	2.35	2.12	4.23	3.50	1625	6
EMB120	5.10	2.30	1.15	2.57	2.16	5.41	3.20	1342	4
JS-41	5.45	2.08	1.23	2.32	1.92	4.64	2.90	1230	5
S340B	5.51	2.31	1.36	2.77	2.41	5.53	3.35	1394	4
D-8-100A	5.90	2.70	1.24	2.32	2.68	6.81	3.96	1491	4
SD360-300	5.49	2.54	0.88	2.01	1.70	3.82	2.74	1062	6
AN-26	4.53	2.09	1.56	2.38	2.38	5.96	3.90	2074	4
L-610 G	5.51	2.70	1.08	2.06	2.47	3.30	3.50	1305	4
CN235-100	5.91	2.90	1.40	2.23	3.08	3.94	3.35	1305	4
ATR42-300	5.60	2.81	1.24	2.67	2.67	4.45	3.96	1492	4
SAAB 2000	5.51	2.31	1.68	3.50	3.25	6.75	3.81	3090	6
Y7-100A	6.18	2.74	1.44	3.51	3.51	5.85	3.90	2080	4
F-50	5.90	2.90	1.14	3.25	3.07	6.14	3.66	1864	6
IPTN-N250	5.80	2.65	1.58	3.07	2.89	5.96	3.81	2386	6
F-60	6.90	2.72	1.52	3.18	2.91	8.35	3.66	2050	6
ATR72-200	5.65	2.82	1.12	2.47	2.65	5.12	3.96	1790	4
ATP	6.11	2.76	1.32	3.15	2.96	6.11	4.19	2051	6
D-8-400	5.52	2.68	1.24	3.45	2.68	9.19	4.11	3062	6

Table 9.1: Fuselage, nacelle & propeller related data for commuter & regional aircraft

In the initial versions of CASTOR, D_{prop} was a design constant, but it was shifted to the list of design variables in the final version. Trial runs with CASTOR revealed that if D_{prop} , P_{TO} and forward speeds were used as design variables with propeller RPMs for the various phases as a design constant, then a very large fraction (in some cases as high as 50%) of the total configurations investigated during an optimisation run were infeasible only due to inappropriate combinations of these three parameters. This is because many values of propeller Advance Ratio J ($= \frac{V}{ND_{prop}}$) or the Power Coefficient C_P ($= \frac{P_{TO}}{\rho \cdot N^3 D_{prop}^5}$) were out of the range of the characteristics of the two propellers that were used to obtain the Thrust Coefficient C_T .

For estimating the suitable value of propeller diameter (D_{prop}), a correlation between P_{TO} & the parameter $n_{blade} D_{prop}^2$ was obtained, as suggested in [120]. This is due to the fact that the power loading of the propeller i.e. the ratio of P_{TO} and the propeller disk-area ($\frac{\pi D_{prop}^2}{4}$) is proportional to P_{TO} . The correlation obtained using the data listed in Table 9.1 is shown in Figure 9.2. The D_{prop} so obtained was increased if it resulted in a tip-Mach number higher than 0.85. Upper & lower limits on J & C_P were imposed, to ensure that they were always within the range of the propeller characteristics, resulting in reliable estimates of C_T . The correlation

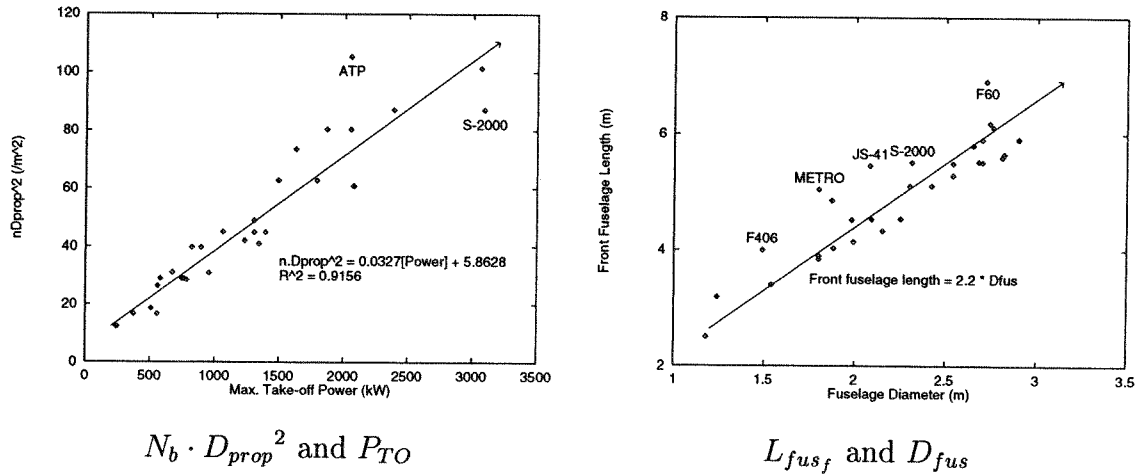


Figure 9.2: Correlation for Propeller diameter and Front Fuselage length

between the front fuselage length (L_{fus_f}) and D_{fus} for the aircraft listed in Table 9.1 is shown in Figure 9.2. Except for the aircraft having a large front cargo hold (such as F406 & FC-METRO) and the stretch aircraft (such as JS-41, S-2000 & F-60), L_{fus_f} is seen to be roughly 2.2 times D_{fus} , as represented by the trend-line in Figure 9.2.

9.3 Mass & Balance

A critical look at the formulae used in CASTOR for the estimation of the mass of various components of the aircraft revealed that many of these were outdated, while some others used gross simplifications. For instance, the mass of the furnishings was assumed as 35% of the payload, and the mass of systems as 7.5% of the MTOW. No clearcut definition of crew mass was provided, and it was considered as a part of payload. Hence it was decided to use better formulae and to validate them with the data related to modern commuter & regional aircraft. New formulae for estimating component masses were developed (except the mass of Landing Gear), the details of which are given in Appendix E.

Component mass breakdown of four commuter & regional aircraft were obtained from the manufacturers [121] and other sources [122]. Table 9.2 lists the component mass breakdown of these aircraft, along with their estimates using the new formulae and the ones used in CASTOR. While the empty mass predicted by both the methodologies is within 3% of the quoted values, the new formulae provide better estimates for some components such as mass of furnishings and the various systems. The seemingly large mismatch between quoted & computed masses of some components is misleading; it is attributable to the absence of any clearcut and universally acceptable definition of what each component exactly constitutes of [123]. The sizing and layout of the Empennage to meet the stability requirements is largely a matter of detail design. In CASTOR, the c.g. location is estimated using several assumptions related to the distribution of the mass of various components and various scenarios of cabin loading. The calculation of Empennage sizes is based on user-specified values of geometry and tail volumes for vertical & horizontal surfaces. While retaining this procedure, a provision was also made to bypass the calculation of the most forward and most rear c.g. positions, in which case user-defined (or default) values (as a % of Mean Aerodynamic Chord MAC) could be used. The default values for these were specified as 17% & 40% of MAC, based on data related to two contemporary aircraft from [114] & [116]. The default value for the location of the c.g. of the empty aircraft & loaded aircraft were also assumed to be 30% & 25% of MAC, respectively, unless over-ridden by calculation.

9.4 Power-plant & Propeller

In CASTOR, the choice of power-plant is restricted to one of the two types for which data is provided, viz. PW120 & CT7¹. The aircraft can also be optimised for

¹In the later versions of CASTOR, data related to 3 other engines has been added viz. Pratt & Whitney PT6-67AR, Rolls -Royce RB-550 & RTM322

Component	18 seater			29 seater			30 seater			35 seater		
	Data	New	Old	Data	New	Old	Data	New	Old	Data	New	Old
Wing	709	466	529	1007	906	859	1078	1118	1573	1149	1238	1621
Fuselage	744	749	694	1268	972	1056	1784	1541	1328	2115	1980	1666
Empennage	215	226	197	267	313	278	270	203	178	391	237	210
Nacelle	61	118	147	153	186	245	219	105	183	232	105	216
Engine	314	367			598			453			532	
Propeller	142	114			190			142			168	
Power-plant	516	860	684	1043	1388	1140	1054	1056	851	1126	1238	1009
Landing Gear	255	199	199	415	365	365	371	468	468	447	553	553
Surface Contrl.	90	85	108	105	134	161	212	134	161	230	152	180
Fuel Syst.	54	50		55	82			82			93	
Hydr. Syst.	66	58		109	94		59	94		61	108	
Elect. Syst.	327	246		410	369		230	368		348	412	
Env. C. Syst.	81	90		97	145		154	150		208	180	
De-Icing Syst.	25	7		38	51		32	51		69	68	
Instruments	57	75		0	75		65	75		63	75	
Avionics	110	50		249	125		125	125		217	225	
Fire Protn. Syst.	17	11		22	21		10	21		11	25	
Ext. Paint	20	25		34	33			42			42	
Systems	757	612	425	1014	995	782	675	1008	779	977	1228	922
Furnishings	311	263	643	667	643	1035	741	677	1071	874	885	1285
Empty Mass	3658	3578	3626	5939	5902	5921	6404	6310	6592	7541	7616	7662
% Error		2.2	0.9		0.6	0.3		1.5	-2.9		-1	-1.6
Misc. Items	22			178			44			56		
Crew	186	186		186	186		223	186		223	186	
Fluids	0	50		62	50		56	50		88	50	
Payload	1552	1584	1836	2500	2552	2958	2654	2640	3060	3185	3168	3672
Zero Fuel Mass	5418	5400	5463	8865	8691	8879	9381	9187	9649	11093	11019	11332
Fuel	254	254	254	1043	1043	1043	1054	1054	1054	1239	1239	1239
MTOW	5672	5655	5716	9908	9736	9922	10435	10244	10700	12332	12259	12569
% Error		0.3	-0.8		1.7	-0.1		1.8	-2.5		0.6	-1.9

Table 9.2: Component mass breakdown using new & old (CASTOR) formulae

scaled versions of these power-plants, but only with respect to the sea-level static thermodynamic rating. Since the data related to these power-plants was proprietary in nature, it could not be used in the present work². Further, it was felt necessary to overcome the limitation on the scaling of engines in CASTOR, i.e. to be able to scale the power-plant based on any other operating condition apart from the sea-level static rating. For example, it might be necessary to size the engine to meet a specific power output requirement at cruise rating at a specific altitude, to meet an aircraft performance requirement on maximum cruise speed.

9.4.1 Generic turboprop engine module

To overcome the above limitations, a generic turboprop engine model (GENENG) was developed by the author to estimate the performance of turboprop engines suitable for Commuter & Regional transport aircraft, based on data from open literature. At present, it consists of data related to the following 7 engines with the sea-level static SHP at max. Takeoff rating varying between 550 & 2000 :

- PT6A-25 of Pratt & Whitney Canada Inc. from [124]
- PT6A-27 of Pratt & Whitney Canada Inc. from [125]
- PT6A-41 of Pratt & Whitney Canada Inc. from [12]
- TPE-331-15 of Allied Signal Garrett Engines. from [12]
- T5321A of Avco Lycoming. from [44]
- PW-120 of Pratt & Whitney Canada Inc. from [126]
- RTM-322-06 of Rolls Royce PLC. from [127]

This database consists of the values of the SHP available, Fuel-flow, and Jet Thrust produced by the engines at specific altitudes between sea-level & 35000 ft and forward speeds between 0 & 350 knots (TAS), at max. Take-off, max. Climb & max. Cruise ratings. GENENG can then be used to obtain realistic estimates of any of these three parameters for a generic engine that lies within this database at any operating condition, i.e. altitude, forward speed, and engine rating. The user has to specify a *ball-parking* criterion, i.e. the desired value of any one of the three parameters at a specific operating condition. The generic engine is positioned in the database by identifying the nearest two engines at the ball-parking criterion.

²The engine manufacturers were approached to provide same or similar data, but no positive response was received.

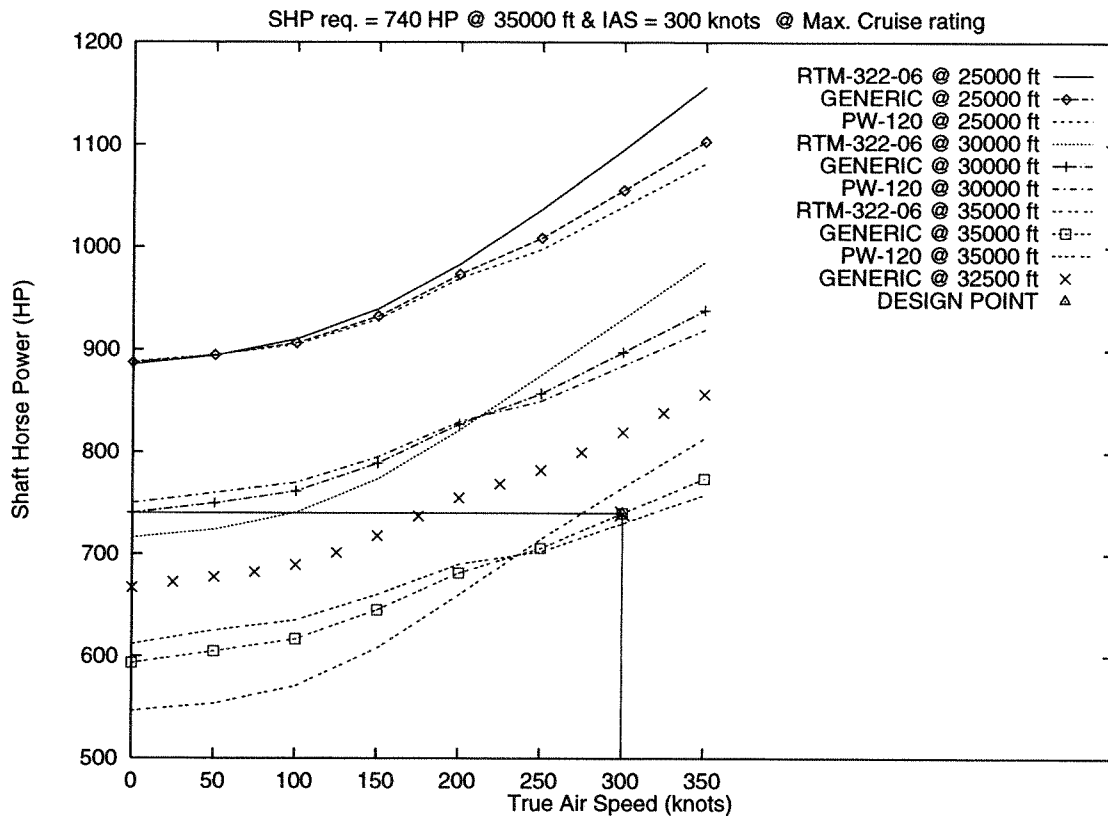


Figure 9.3: A generic engine ball-parked using cruise requirements [128]

The fractional ratio of the location of the generic engine from these two engines is then calculated. Assuming that the same fractional ratio would also apply at all the other data points, the values of all the parameters at all engine ratings are then generated at specific combinations of forward speed and altitude. Using Bicubic Spline interpolation routines [65], the value of any of the three parameters at any forward velocity and altitude can then be obtained.

As an example of the application of GENENG, Figure 9.3 shows a generic engine *ball-parked* by cruise considerations. The engine is required to develop 740 SHP while operating at max. Cruise rating, at 35000 ft & an IAS of 300 knots. Using this criteria to position the engine in the database, the performance characteristics at any other operating conditions can be obtained. For e.g., the trend in variation of SHP with forward speed for such a generic engine at 32500 ft are shown in Figure 9.3. This engine falls between PW-120 & RTM-322-06 engines. It can be seen that the SHP variation for the generic engine follows the trend in-between these two aircraft at all the altitudes shown in Figure 9.3. Further details of GENENG are given in [128].

9.4.2 Propeller module

The characteristics of two propellers viz. 5 bladed Hamilton Standard 14 RF propeller & 6 bladed Hartzell propeller were modelled in CASTOR. Using Chebyshev polynomials, a formula was developed to obtain the Thrust coefficient (C_T) as a function of Power Coefficient (C_P) and Advance Ratio (J). The characteristics of these two propellers were obtained by the author from Shorts [129], and were checked with the formulae used in CASTOR. Large mismatches between the quoted & fitted value were observed for both the propellers at low advance ratios i.e below 0.4. The errors were quite large for the Hartzell propeller at all advance ratios.

An alternative approach was developed using cubic spline interpolation routines [65] to surface fit the characteristics of these two propellers, which lead to much better fits. Figure 9.4 compares the fits obtained using the formulae listed in CASTOR & the spline fits used in the present work for the two propellers. At low C_P values and $J > 0.4$, the Hartzell propeller developed negative C_T values. Hence it was decided not to use the characteristics of this propeller in the present work. Such behaviour was also observed in the Hamilton Standard propeller, but only at very low C_P values. The characteristics of this propeller were available only upto J of 2.4 & C_P of 0.75. It was decided to extrapolate these curves for J of 3.0 & C_P of 1.0, to enable their use at appropriate operating conditions, as shown in Figure 9.4.

9.5 Airfield performance

In CASTOR, the Landing Field length is estimated as a function of wing loading & Lift coefficient in the landing configuration, using the following formula:-

$$LFL = \left(5.612 \frac{M_{land}}{S_{wing} C_{L_{land}}} + 108.0 \right) \cdot FLF \quad (9.1)$$

Where

- LFL = Landing Field length (m)
- M_{land} = Max. Landing mass (kg)
- S_{wing} = Wing area (m^2)
- $C_{L_{land}}$ = Aircraft max. Lift Coefficient at landing configuration
- FLF = Field length factor

For aircraft with $M_{land} \geq 5700kg$, FLF is specified as 1.67 under FAR-25, -135, & -121 regulations [130], and 1.0 under FAR-23 regulations [126].

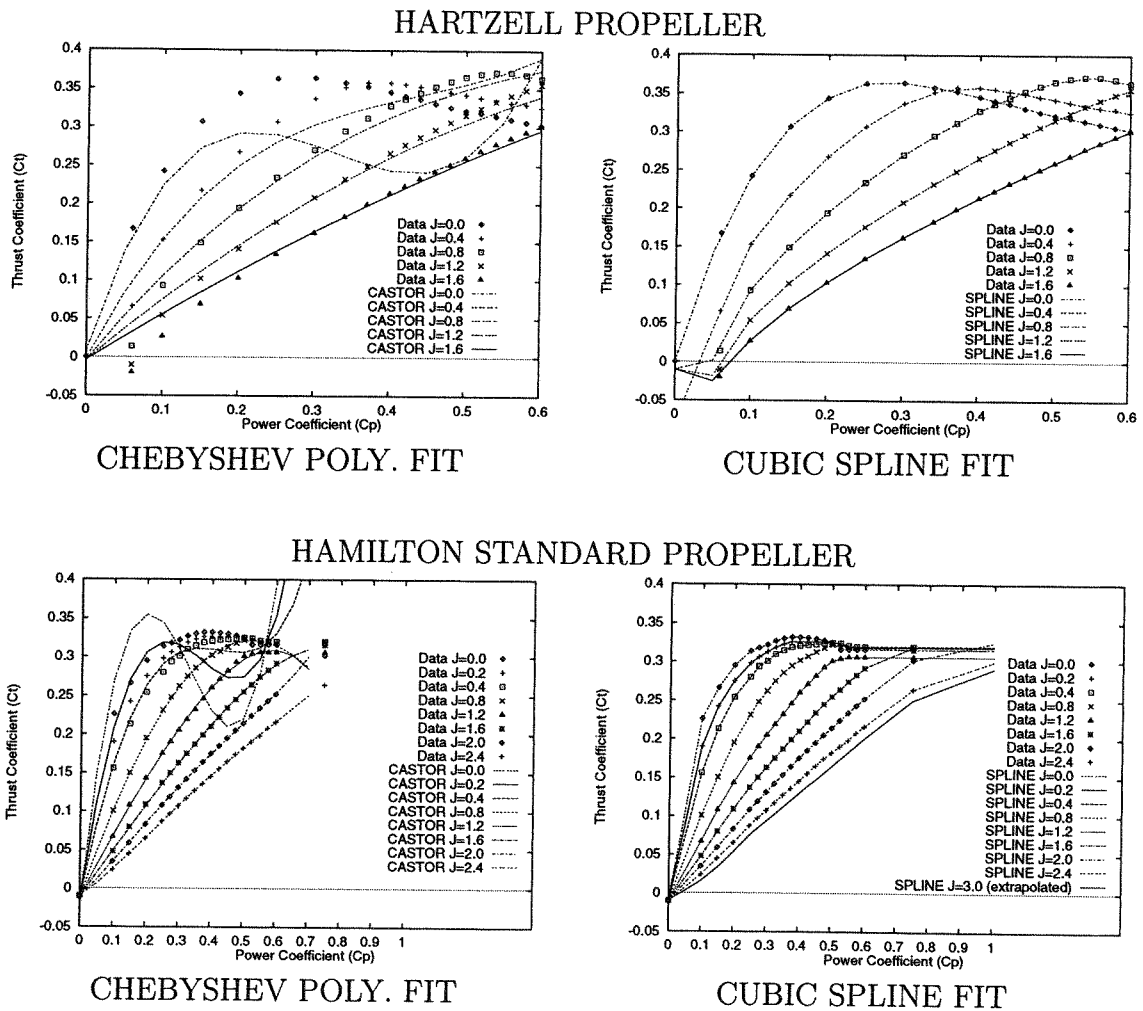


Figure 9.4: Comparison of Chebyshev & Cubic Spline fits for propeller characteristics

The approach speed and the landing distance of a few twin-turboprop commuter & regional aircraft were obtained from various sources, and their LFL was estimated using Equation 9.1. For most aircraft, the calculated values were within $\pm 5\%$ of the quoted ones, as shown in Table 9.3 & Figure 9.5. For some aircraft, the stalling speed in the landing configuration was quoted, hence an appropriate factor (1.3 for aircraft certified under FAR-25 & 1.5 for aircraft certified under FAR-23) was applied to estimate the approach speed. The LET 410 & LET 610G aircraft were certified under Russian civil regulations, about which no details were available, hence a FLF of 1.0 & 1.67 were assumed, based on whether Landing Run or Landing Distance was quoted. For the SHORTS SD330-200 & SD360-300 aircraft, the stalling speeds were estimated assuming a $C_{L_{max}}$ value of 2.0, which is typical for aircraft of this type. A graphical procedure for determining first approximations to LFL of civil transport aircraft (turboprop & turbojet-fan) is presented in [130]. The un-factored LFL is plotted against the square of approach speed for typical values of mean deceleration achieved during braking, and upper and lower limits for turboprop aircraft currently in production are provided. The un-factored LFL using Equation 9.1 for all the aircraft listed in Table 9.3 was plotted against V_{app}^2 found to be within this band, as shown in Figure 9.5. The Balanced Field Length (BFL) is defined as

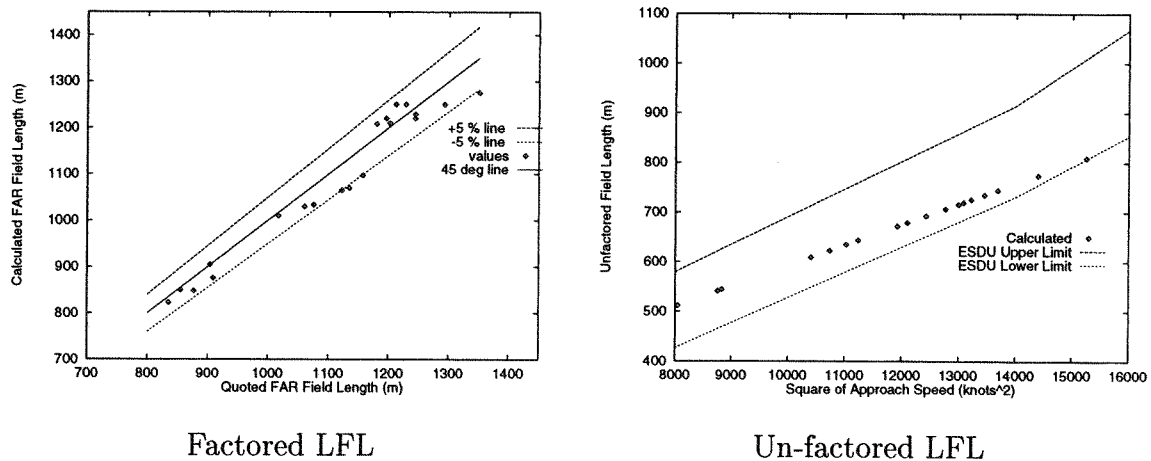


Figure 9.5: Correlation for Factored & Un-factored Landing Field Length

the one where the distance to continue the takeoff following the recognition of an engine failure at a specific speed (called critical engine failure speed V_1) is equal to the distance required to stop if the takeoff is aborted [126]. Thus the estimation of BFL involves determining the speed V_1 at which the accelerate-stop distance (ASD) with one engine inoperative is the same as the accelerate-go distance (AGD) when the takeoff is continued at the same condition. Numerical procedures for estimation of BFL are outlined in [18] & [135]. In [18], ASD & AGD are calculated assuming $V_1 = 90\%$, 95% & 100% of the lift-off speed using numerical integration. A parabolic fit is then used to determine the value of V_1 & the associated BFL . In [135], an iterative procedure is used in which the ASD & AGD are determined for various

Aircraft	N_{paz}	Spec.	M_{land}	V_{stall}	V_{thr}	FLF	$LF L_{calc}$	$LF L_{quot}$	% error	Ref.
Units			kg	kt	kt		m	m		
REIMS-F406	14	SFAR41	4468	57	74	1.67	679	674	0.72	[110]
Bae JS-31	18	SFAR41A	6600	90	117	1.67	1244	1229	1.17	[110]
EMB-110	19	SFAR41	5900	69	90	1.67	855	850	0.57	[110]
DASA Do228	19	FAR23	6100		75	1.00	412	402	2.49	[114]
Bae JS-S31	19	SFAR41C	7080		114	1.67	1196	1220	-2.02	[115]
Metro-23	19	FAR23	7110		130	1.00	877	848	3.43	[110]
BEECH 1900D	19	FAR23	7303	84	109	1.00	819	823	-0.47	[110]
CBA-123	19	FAR25	9250	88	114	1.67	1202	1210	-0.65	[110]
L-410 UVP-E	21	NLGS-2	6200	66	79	1.67	733	720	1.73	[110]
CASA C212-300	26	FAR25	7450		94	1.67	909	876	3.66	[131]
Bae JS-41	29	FAR25	10115		116	1.67	1228	1250	-1.83	[132]
SD330-200	30	FAR25	10250	86	111	1.67	1157	1097	5.16	[129]
EMB-120	30	FAR25	11250		115	1.67	1212	1250	-3.17	[131]
DASA Do328	30	FAR25	13230		102	1.67	1017	1010	0.72	[116]
SAAB 340B	37	FAR25	12700	82	107	1.67	1083	1065	1.70	[117]
DHC D8-200	39	FAR25	15377	72	94	1.67	904	905	-0.10	[133]
SD360-300	39	FAR25	12020	90	117	1.67	1244	1220	1.90	[129]
LET L-610G	43	ENLG-S	14200	74	96	1.00	562	587	-4.30	[110]
IPTN CN235	50	FAR25	14900	95	124	1.67	1351	1275	5.64	[118]
ATR42-300	50	FAR25	16400		106	1.67	1075	1034	3.78	[131]
ATR42-320	50	FAR25	16400		96	1.67	935	940	-0.49	[134]
ATR42-500	50	FAR25	18300		110	1.67	1134	1070	5.65	[131]
SAAB 2000	54	FAR25	22000		120	1.67	1293	1250	3.29	[119]
ATR72-200	66	FAR25	21350		113	1.67	1180	1208	-2.35	[131]
Bae JS-61	74	FAR25	23133		105	1.67	1060	1030	2.84	[131]

Table 9.3: Quoted & calculated LFL of some commuter & regional aircraft

assumed values of V_1 , till they are equal within a specified tolerance. Both these procedures involve a lot of calculation and computational time, hence they were not considered to be suitable for the present work. The following formula for estimating BFL is listed in [47], which is based on an empirical expression derived in [14]:

$$BFL = \frac{0.704}{1 + 2.3(\gamma - 0.024)} \left[\frac{M_{TO}}{S_{wing} C_{L_{V_2}}} + 14 \right] \left[\frac{1}{1.12 \frac{n_{eng} P_{TO}}{M_{TO}}} + 2.7 \right] + 200 \quad (9.2)$$

Where,

- BFL = Balanced Field Length (m),
- γ = Second stage climb gradient with one engine inoperative,
- M_{TO} = Max. Takeoff mass (kg),
- S_{wing} = Wing area (m^2),
- $C_{L_{V_2}}$ = Lift coefficient at takeoff climb speed (V_2),
- P_{TO} = Power available at max. takeoff rating (HP)
- n_{eng} = Number of engines (= 2)

The calculation of BFL requires knowledge of γ , which is available only in the detailed performance manuals supplied by the manufacturers. The values of BFL and V_2 are also not readily available in open literature. The BFL of some contemporary twin-engined turboprop aircraft for which the performance manuals were available were determined using Equation 9.2, and compared with the quoted values of BFL or ASD. Since the calculated values matched with the quoted ones within 5%, as shown in Table 9.4, Equation 9.2 was used in the present work. The sensitivity of the

Name	N_{pax}	M_{TO}	S_{wing}	P_{TO}	V_2	γ	$C_{L_{V_2}}$	BFL_c	BFL_q	% error	Ref.
Units		Kg	m^2	HP	kt			m	m		
DASA Do228	19	6400	32.00	776	69	.028	2.52	775	750	-3.33	[114]
BAe JS-S31	21	6800	25.20	1020	112	.036	1.30	1331	1300	-2.37	[115]
DASA Do328	30	13990	40.00	2180	94	.037	2.39	995	975	-2.05	[116]
BAE JS-41	32	10936	32.59	1650	113	.024	1.59	1376	1371	-0.36	[132]
SAAB 340B	35	13155	41.81	1870	114	.024	1.46	1261	1290	2.26	[117]
LET L-610G	43	14500	56.00	1750	89	.039	1.99	1073	1035	-3.67	[110]
IPTN CN235	44	15800	59.10	1750	114	.036	1.24	1377	1341	-2.69	[118]
SAAB 2000	50	22000	55.70	3738	130	.042	1.42	1314	1360	3.41	[119]
ATR72-210	66	21500	61.00	2750	112	.036	1.70	1223	1210	-1.07	[136]

Table 9.4: Quoted & calculated BFL for some commuter & regional aircraft

BFL to changes in wing-loading and power-loading was determined using Equation 9.2. For this, a hypothetical aircraft with $\gamma = 0.010$ and $C_{L_{V_2}} = 2.0$ was considered, and its BFL was estimated for various values of wing-loading between 150 & 400 kg/sqm and power-loading between 0.16 to 0.40 kW/kg. The results so obtained are shown in Figure 9.6, which indicate that the BFL is more sensitive to changes in

wing-loading compared to power-loading. It can also be seen that at a given power-loading, the *BFL* reduces linearly with reduction in wing-loading, however the rate of change of the *BFL* with wing-loading is higher at lower power-loadings. Further, at a given wing-loading, the *BFL* is seen to reduce quadratically with increase in power-loading, and the rate of change of the *BFL* with power-loading is higher at high wing-loadings. This analysis shows that much larger reduction in the *BFL* can be obtained by reduction in wing-loading compared to increase in power-loading. From practical considerations, however, an increase in power-loading is perhaps easier to achieve compared to a reduction in wing-loading. Higher power loading also improves γ especially under “Hot & High” conditions, which leads to a reduction in *BFL*.

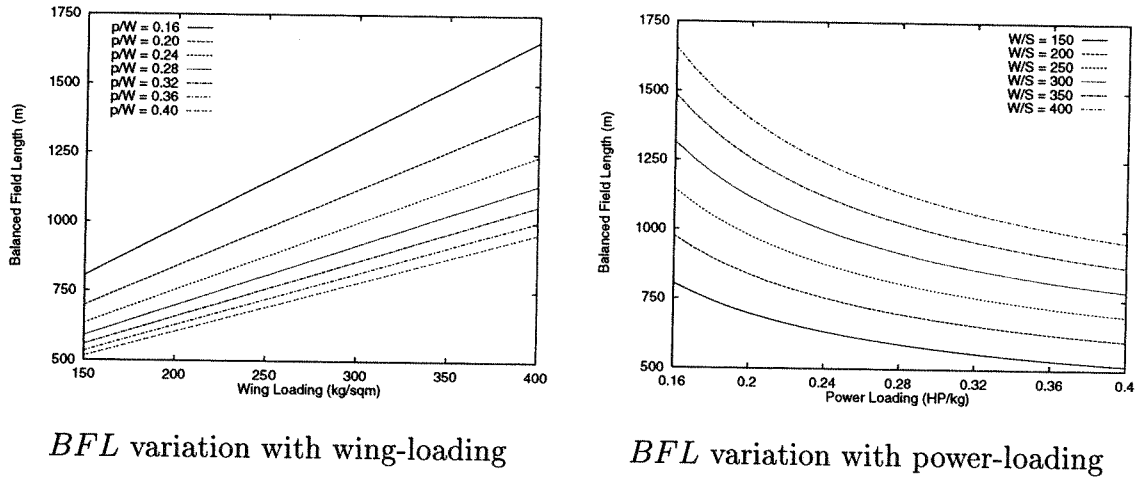


Figure 9.6: Sensitivity of *BFL* to wing-loading & power-loading

9.6 Mission analysis

In CASTOR, upper & lower limits for the possible cruise IAS and cruising altitude is specified are input, and these parameters and their optimal values are sought. Many combinations of these two parameters were found to result in unacceptably high or low Mach number values, beyond lower than acceptable values or above the usual limits applicable to commuter & regional aircraft. It was decided to use cruise Mach number as an optimisable variable, and obtain the associated speeds for the specific altitude. The three parameters related to the cruise stage of the diversion mission viz., the distance, speed & altitude are also optimised in CASTOR, while the climb and descent related variables are assumed the same as that of the main stage. The only parameter from the diversion stage that is used in the synthesis is the fuel consumed. However, even that is not included in the calculation of the fuel related objective function i.e. M_{fuel} , but carried as a “dead mass” during the

main mission [47]. Since the code was intended for short range missions, it was decided to remove these three parameters from the list of optimisable variables. The diversion fuel is estimated assuming one more main mission stage is flown for a user-specified diversion distance, after the main stage parameters were optimised. Some trial runs demonstrated that the inaccuracy in estimating the diversion fuel mass by this procedure is well within the overall tolerances on mass estimation.

In CASTOR, the Holding fuel is estimated assuming the same fuel flow as during the (optimised) diversion cruise segment. Since the diversion stage was not to be optimised in the modified module, the Holding fuel was estimated assuming it is conducted at 10,000 ft at the minimum drag speed and 50% throttle, based on operational experience [137]. Further, the manoeuvre allowance³ is ignored in CASTOR, which can be a large proportion of mission fuel for short range multi-stage missions. A rough approximation for the manoeuvre allowance was found to be 0.0125 kg per HP per engine, based on the data provided in the performance and specification manual of some existing commuter & regional aircraft viz., [114], [115], [116], [117], [132], [133] & [136].

9.7 Cost estimation

The methodology used in CASTOR for the estimation of aircraft acquisition cost (C_{acq}) and the *DOC* was considered to be unsuitable for the present work, since it was based on very simplistic procedures and old data. It used some specific terms related to in-house company information (such as the fraction of airframe manufactured in-house and the associated man-hour rate) and also some gross simplifications. For instance, it assumed a constant developmental cost of £100 million at 1985 rates for all aircraft, irrespective of the size and the values of various design parameters. A more generic and detailed methodology was developed for estimation of C_{acq} & *DOC*, which is explained in detail in Appendix F. The C_{acq} & *DOC* breakdown of 9 contemporary commuter & regional aircraft using this methodology are also discussed in Appendix F.

9.8 Noise estimation

The noise estimation module in CASTOR could cater for only a four-bladed propeller. In the present work, a more detailed noise estimation module was developed, which can be used for estimating the Far-field noise generated by a propeller having any

³Fuel consumed in Take-off, Taxi & Approach phases in each stage of the mission.

number of blades (N_b) between 2 to 8. This method is also based on the same empirical procedure outlined in [99] as in CASTOR. The details of the new noise estimation module are given in Appendix G. Table 9.5 compares the Sideline Noise Levels (SNL) as per FAR Part-36, Stage-3 regulations calculated by this model with the quoted values (from various references) for some commuter & regional aircraft. In all cases, the noise level is predicted within $\pm 3\%$ of the quoted value. The most important parameter that affects SNL is seen to be the Propeller RPM at Take-off (RPM_{TO}), followed by D_{prop} & P_{TO} .

Name	D_{prop}	RPM_{TO}	P_{TO}	V_2	N_b	SNL_{cal}	SNL_{quo}	% error	Ref.
Units	m		HP	kt		EPNdB	EPNdB		
DHC D8-100	3.96	1050	2150	94	4	81.82	81.00	1.02	[110]
JS-S31	2.69	1591	1020	112	4	83.28	83.30	-0.02	[115]
DASA-F-50	3.66	1200	2250	103	6	83.46	85.00	-1.81	[110]
DASA Do328	3.50	1300	1851	94	4	86.13	84.00	2.54	[116]
ATR42-320	3.96	1180	1950	106	4	85.40	83.70	2.03	[134]
SAAB 2000	3.81	1100	3738	130	6	85.33	84.00	1.58	[119]
DHC D8-200	3.96	1200	1950	103	4	85.85	85.00	1.00	[133]
DHC D8-300	3.96	1200	2142	133	4	86.50	84.30	2.61	[138]
IPTN CN235	3.35	1384	1870	114	4	87.36	87.00	0.41	[118]
SAAB 340B	3.35	1384	1870	114	6	84.75	85.90	-1.34	[117]

Table 9.5: Quoted & calculated Sideline Noise levels for some commuter & regional aircraft

9.9 Airport module

A new module for estimation of setting-up and operating costs of regional airports was developed, as discussed in Chapter 7. In this module, the layout and sizing of a minimum-configuration airport for operation of a specific aircraft is carried out, based on ICAO & FAA recommendations. The main inputs to this module are the passenger capacity, number of flights per day, max. Take-off mass, fuselage dimensions, wing-span and BFL of the aircraft. The “level” of the airport is decided based on number of flights per day, which also decides the minimum fit of aeronautical equipment at the airport. The airport is classified as per the ICAO or FAA specifications. The geometric layout and sizing of the runway, taxiway, aprons is carried out and the minimum separation between runway-taxiway, taxiway-apron, apron-terminal-building is determined. Using this information and the BFL , the length and width of the airport is determined, and the total airport area is calculated, which includes the area of the runway protection zones at both ends of the runway. The pavement thickness is estimated using a correlation with the max.

Take-off mass of the aircraft. The airport set-up cost is estimated, which includes the cost of construction of runway, taxiway(s), apron(s) and the terminal building, cost of aeronautical equipment installed at the airport, and the cost of setting-up a suitable fire & rescue station. Finally, the annual operating cost of running the airport is determined. In the present version of the airport module, cost data related to regional airports in India was used, but relevant cost data for other countries can easily be substituted, when available.

9.10 Output module

In CASTOR, the output is available only in numerical form. To obtain a visual feel of what the optimum solution represents, a simple geometry output module was developed. In this module, the data related to the plan view of the configuration and its mission profile is written in output files in a particular sequence, which can then be plotted using GNUPLOT⁴. With slight modifications, the same files can also be used by other proprietary packages such as EXCEL⁵. When the data related to different optimum solutions is written sequentially in these files, a direct visual comparison of the various configurations & mission profiles is possible.

⁴A public domain interactive plotting program developed by T. Willams & C. Kelley. UNIX or WINDOWS versions of this software can be down-loaded from several sites on the WEB, such as *src.doc.ic.ac.uk*.

⁵©Microsoft Corpn.

Chapter 10

Summary of case studies with CRAGER

10.1 Introduction

This chapter describes the various case studies that were carried out for short range business travel in India using CRAGER. Though these studies were broadly on the same lines as the one described in Chapter 8, there were some important differences, which are discussed below.

The aim of these studies was to demonstrate the following two major applications of CRAGER :

1. CRAGER as a system cost analysis tool. For this, optimum configurations & flight profiles of four different commuter & regional aircraft of passenger capacities of 19, 30, 50 & 70 seats aircraft were obtained by minimising their Generalised cost (C_{gen}) for operation over three stage different lengths viz. 100, 200 & 400 nm, to meet the same annual demand of 18000 one-way passenger-trips.
2. CRAGER as an aircraft evaluation tool. For this, a comparison of C_{gen} of the optimum 50 seater aircraft determined by CRAGER for the three stage lengths and five contemporary regional transport aircraft was carried out.

Detailed results of the case studies are presented in Appendix I. Only the salient features of the studies and main results are discussed here. For ease in understanding and to avoid repetition, the various aircraft are referred to as “CC-FFFF-SSS”, where “CC” stands for the passenger seating capacity of the aircraft (19, 30, 50

or 70) and “FFFF” is a code used to specify the objective function used while optimisation, which are explained in each section. “SSS” stands for the stage length for which the aircraft has been optimised (100, 200 or 400 nm). For e.g., “70-OG-400” represents the 70 seater aircraft that has been optimised for minimum C_{gen} for operation over a stage length of 400 nm.

10.2 CRAGER as system cost analysis tool

One of the main application of CRAGER is for comparison and analysis of C_{gen} of an air-transportation system with the aircraft and associated airport as the two main elements, and aircraft size and stage length as the two varying parameters.

In Chapter 8, the effect of changes in passenger demand on the C_{gen} of four aircraft optimised for minimum DOC were investigated. As noted, these aircraft were designed for a specific BFL , which was supplied as a design constraint in CASTOR. In CRAGER, BFL is a design variable, hence its optimum value for minimum C_{gen} can be obtained. On the same lines as in the study discussed in Chapter 8, a comparative analysis was carried out for 19, 30, 50 & 70 seater aircraft for operation in India over stage lengths of 100, 200 & 400 nm. Minimum C_{gen} configurations of these aircraft were obtained, and are referred to as “CC-OG-SSS”. The main differences in the input parameters of these aircraft were in the fuselage dimension & layout and the type of flap employed, and are listed in Table I.1 of Appendix I. All aircraft optimised for 100 nm stage lengths were assumed to have a capability of doing 5 hops without refuelling, while those optimised for a stage length of 200 nm were expected to do 2 such hops. The aircraft optimised for 400 nm, however, were expected to perform only one trip before refuelling.

As discussed in Appendix H, CRAGER consists of 20 optimisable Design Variables and 12 Design Constraints. In the present study, all the aircraft were assumed to have pressurised cabins, hence the Design Constraint on max. rate of descent was removed, and zero throttle descents were assumed, as suggested in [15], [47] & [102]. Trial runs for 19 & 30 seater aircraft revealed that the optimum configurations always had the Take-off flap deflection ($\delta_{f_{TO}}$) at the specified upper limit, hence this Design Variable was not optimised but assigned a fixed value of 20 degrees. In the 50 & 70 seater aircraft, however, the constraint on second-stage climb gradient was sometimes not fulfilled with a fixed $\delta_{f_{TO}}$ value due to the use of Fowler flaps, hence it was retained in the list of Design Variables. The values assigned to the Design Constants and Design Constraints are listed in Table I.2 & I.3, respectively, of Appendix I.

Since all the aircraft are expected to meet the same annual travel demand, the

number of annual trips required decreases with increase in aircraft capacity. A direct consequence of this is the increase in Defer time (T_{defer}) with increasing aircraft capacity, which directly affects Time costs (C_{time}). BFL also increases with increases in aircraft size, hence, in general, Airport cost (C_{apt}) increases. On the other hand, it is a well-known fact that for the kind of aircraft being analysed, Flight cost (C_{flt}) decreases with increase in aircraft capacity. Thus, as the aircraft size increases, parameters that directly affect C_{time} & C_{apt} start becoming more and more important.

The detailed comparison of the optimised design variables and the configurations & flight profiles is given in Appendix I; Table I.5 & I.6 and Figure I.1 for the 19 & 30 seat commuter aircraft and Table I.7 & I.8 and Figure I.2 for the 50 & 70 seat regional aircraft. A graphical comparison of the two important design parameters of the various aircraft viz. the wing loading and power loading is provided in Figure 10.1. All commuter & regional aircraft that are listed in Appendix A are also superimposed on this chart for comparison. It can be seen in Figure 10.1 that

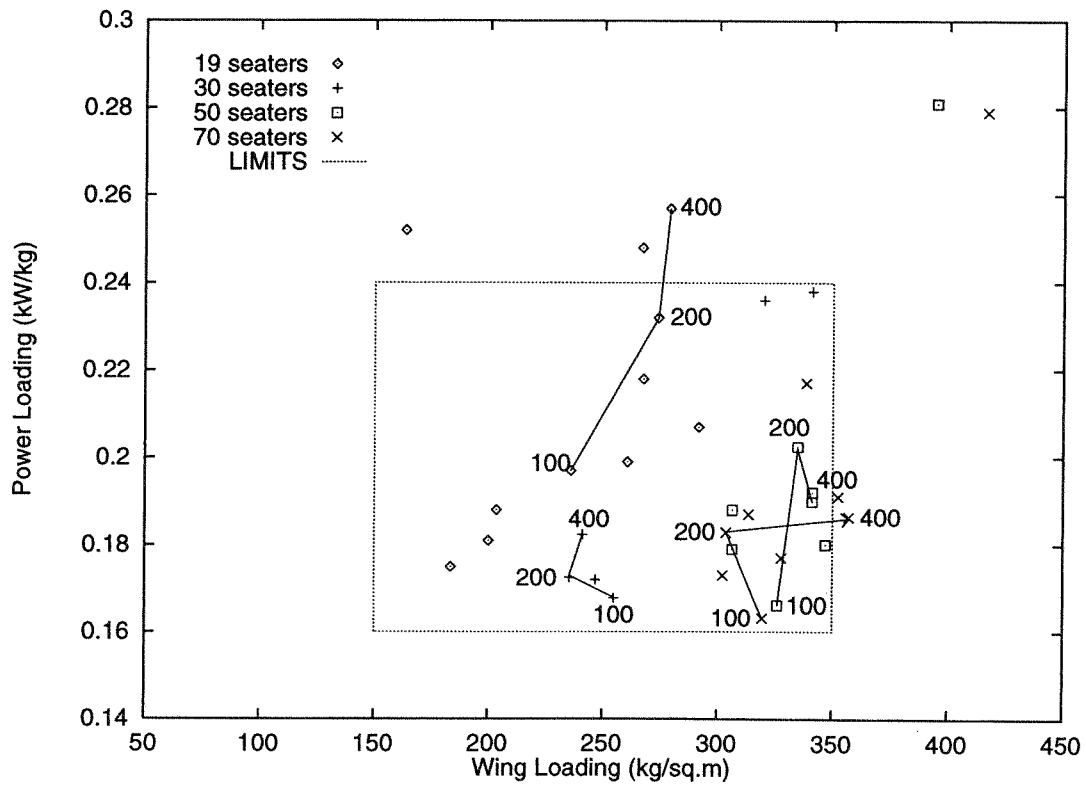


Figure 10.1: Wing loading & power loading of optimised & existing aircraft

the optimum 19 seater aircraft have moderate wing loadings and very high power loading, especially 19-OG-200 & 19-OG-400. This is because these aircraft have a low C_{apt} and C_{time} , hence the reduction in C_{gen} is mainly achieved by improving cruise performance, leading to a reduction in C_{flt} . The 19 seater aircraft are actually

a class of their own, because they are designed to different standards viz. FAR-23 or BCAR Part-K compared to the other aircraft, which are designed as per FAR-25 standards. Owing to their small size, they have larger structural mass fraction, hence the higher power loading also leads to improved payload capability. The 19 seater aircraft were found to have the lowest block time (T_{blk}) for all the three stage lengths compared to the other aircraft, and nearly the largest cruise stage fraction too.

The optimum 30 seater aircraft were found to have moderate wing loadings and low power loadings, very much in line with the SHORTS SD330-200 commuter aircraft. The other two 30 seater aircraft in Figure 10.1 are the JS-41 and DORNIER Do-328, which are stretched and high-performance aircraft, respectively. The optimum 50 & 70 seater aircraft had high wing loading and low power loading, in line with the general trend followed by the existing aircraft.

The variation of C_{gen} for all the aircraft and its components for various aircraft is shown in Figure I.3 in Appendix I. Figure 10.2 compares the change in C_{flt} , ($C_{flt} + C_{apt}$) and C_{gen} for the 30, 50 & 70 seater aircraft as a percentage of the corresponding values for the 19 seater aircraft for various stage lengths.

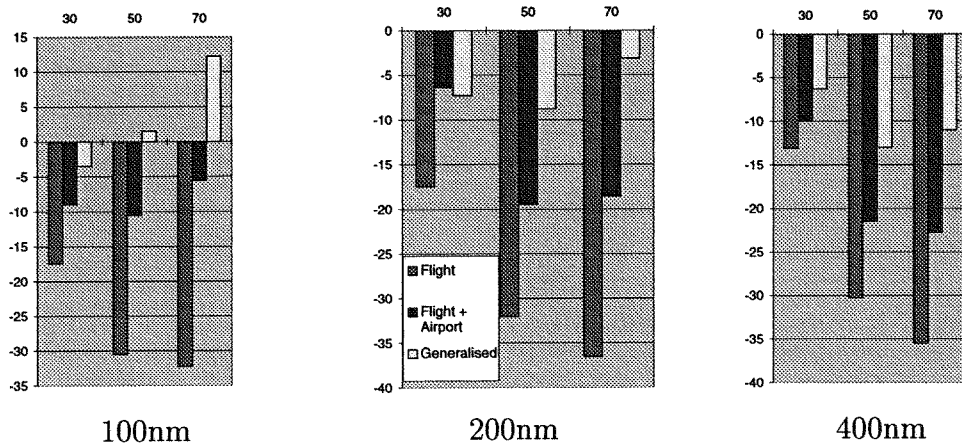


Figure 10.2: % change in C_{gen} terms with increase in capacity

It can be seen that for all the three stage lengths, as far as C_{flt} alone is concerned, the best aircraft is the 70 seater, since it has the largest % reduction compared to the 19 seater aircraft. Inclusion of C_{apt} leads to a marked reduction in this advantage, and the largest % reductions are seen for 50 seater, except at the stage length of 400 nm. With the inclusion of C_{time} (& Access cost), however, the 50 & 30 seater aircraft show much larger % reduction. In fact, at 100 nm stage the 50 & 70 seater aircraft have a higher C_{gen} compared to the 19 & 30 seater aircraft. The aircraft with lowest C_{gen} for the 100 nm sector is the 30 seater, followed by the 19 seater. For the 200 & 400 nm sectors, the the 50 seater aircraft has the lowest C_{gen} .

Figure 10.3 shows the variation of Generalised cost per nautical mile ($\hat{C}_{gen}$) and Flight cost per nautical mile ($\hat{C}_{flt}$) for the various stage lengths. As can be expected, $\hat{C}_{flt}$ reduces with increase in stage length for all aircraft, and high capacity aircraft always have a smaller $\hat{C}_{flt}$ at each stage length. However, a different trend is followed by $\hat{C}_{gen}$. For a specific aircraft, $\hat{C}_{gen}$ is also seen to decrease with increase in stage length. At stage lengths of 100 & 200 nm, the 30 seater aircraft is seen to have the best $\hat{C}_{gen}$, but at 400 nm, it moves to the third position behind the 50 & 70 seater aircraft. The 19 seater aircraft has the highest $\hat{C}_{gen}$ at a stage length 400 nm, while the 70 seater aircraft has the highest $\hat{C}_{gen}$ at a stage length 100 nm.

Compared to the conventional approach in which only the *DOC* (and hence C_{flt}) of the aircraft is considered as a merit function, the present approach proposes inclusion of C_{time} & C_{apt} also in the cost equation while comparing various aircraft for a particular market. The above analysis shows that inclusion of these two terms makes smaller aircraft more suitable, especially over short stage lengths. For this particular case study, it can be concluded that the 50 seater aircraft is the best solution for stage lengths of 200 & 400 nm, since it has the lowest C_{gen} as well as $\hat{C}_{gen}$. At a stage length of 100 nm, however, the 30 seater aircraft is better than the 50 seater for the same reasons. The 19 seater suffers from a very high C_{flt} , and hence has the highest C_{gen} at all the three stage lengths. For the 70 seater aircraft, C_{apt} and C_{time} are quite high, which counter the advantage of its low C_{flt} , especially at smaller stage lengths, hence it is not suitable under these conditions. However, as discussed in Chapter 8, if the annual passenger demand increases, the 70 seater aircraft may well have the lowest C_{gen} .

10.2.1 Minimum *DOC* & minimum C_{gen} configurations

The breakdown of C_{gen} for all the aircraft revealed that C_{flt} constitutes the largest component of C_{gen} for all the aircraft. Hence, the minimisation of C_{gen} was mainly achieved by altering those parameters that lead to a reduction in C_{flt} , which is analogous to *DOC*. Not much difference was therefore observed between the minimum *DOC* and minimum C_{gen} cases, except for those situations in which large reductions in C_{apt} were possible. One such example is discussed in Appendix I in which the optimum *DOC* aircraft 30-OD-400 is compared with 30-OG-400, in which the reduction in *BFL* lead to a lower ICAO Aerodrome Code Number, resulting in a 30% reduction in C_{apt} . The SIMANN optimiser was able to identify such cases, even though it involved a large step change in the airport module. It may be kept in mind that these results may not correspond to the global optimum, but only an indication of the trends, since a modified strategy of optimisation was adopted in the present work, due to a need for reduction of computational time for each run¹.

¹This strategy is discussed in Appendix I.

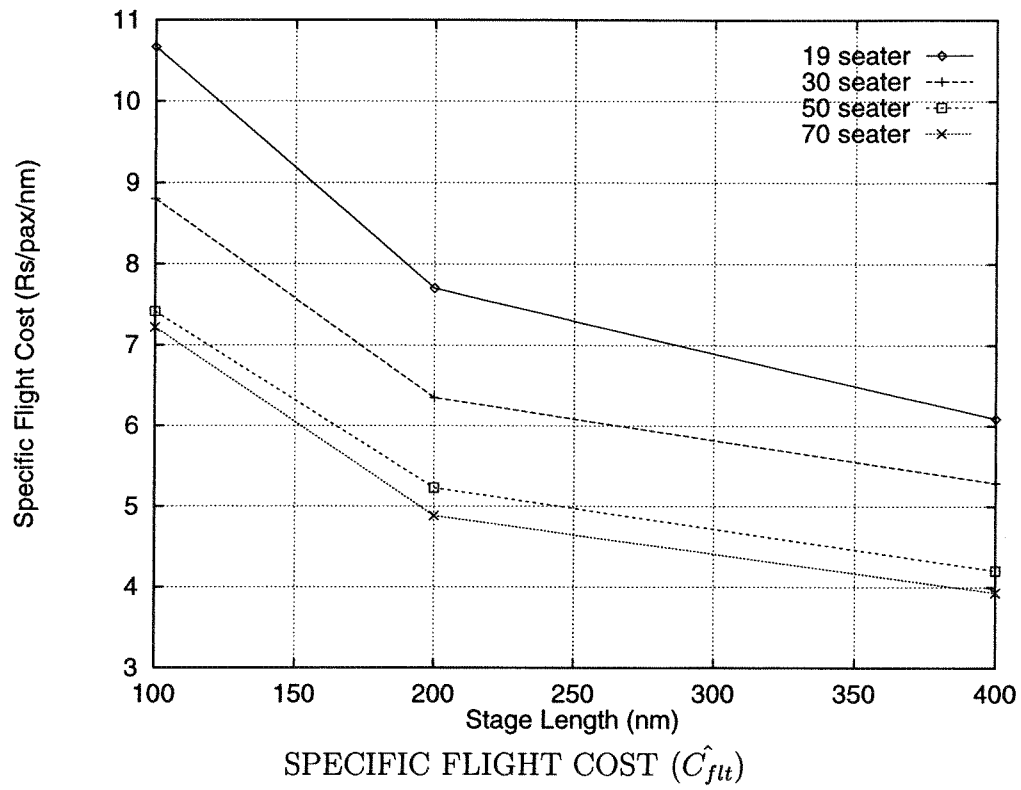
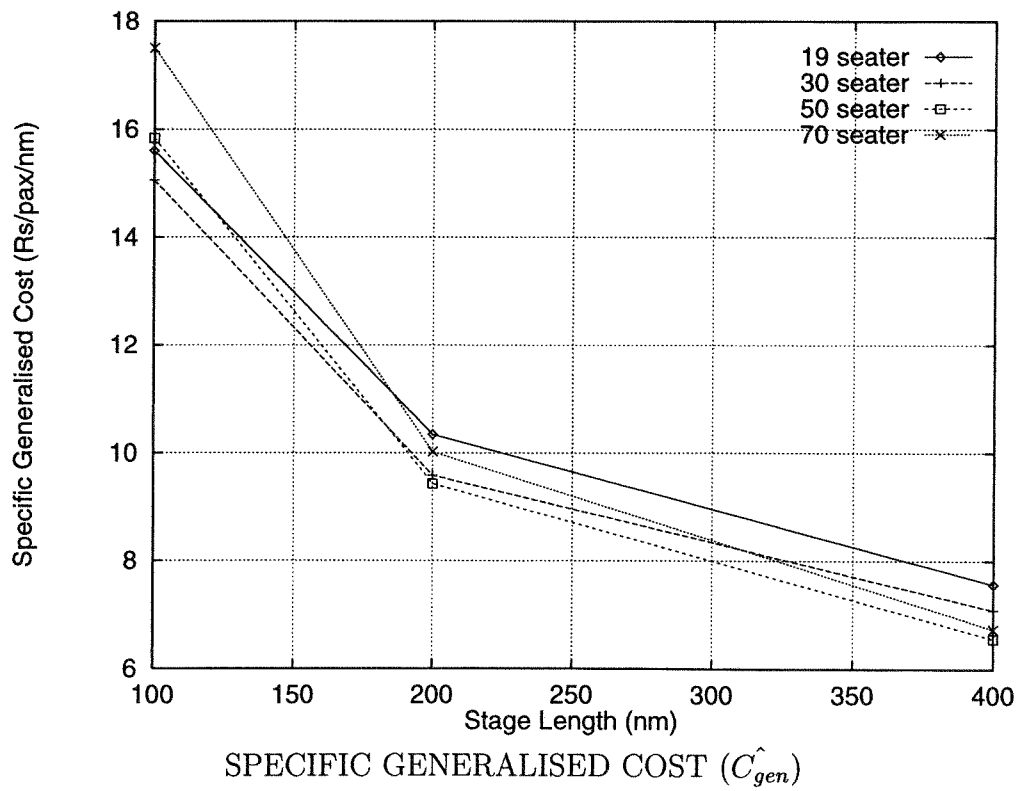


Figure 10.3: Comparison of specific Flight cost & specific Generalised cost

10.2.2 Sensitivity analysis of C_{gen} terms

The sensitivity of the two new terms in C_{gen} could be determined only if their values were artificially increased to make them of the same order as C_{fit} . The optimiser would then be strongly driven by the parameters related to these terms. These two types of runs are discussed in detail in Appendix I, a brief summary is provided below.

Non-linear nature of the airport module

For a given aircraft capacity, the airport level remains the same, hence the cost of equipment and annual operating costs are the same. A reduction in C_{apt} is achieved mainly by a reduction in size of the airport i.e. airport area. Due to the airport classification system followed by ICAO or FAA, large reductions in C_{apt} are sometimes possible by relatively small changes in aircraft parameters, if the category of the airport itself can be reduced. This brings in some non-linearity in the airport cost estimation module, which is further increased by the fact that certain components of the airport cost are almost independent of the airport size.

To demonstrate the effect of this non-linearity and to investigate how airport-related parameters affect the optimum solution, a sensitivity analysis was carried out in which C_{time} was ignored and excessively high land cost was assumed, along with a reduction in the airport depreciation period (Code ZVHA²). Two distinct mechanisms of reduction in C_{apt} emerged, which are described in detail for the 70-ZVHA-400 & 50-ZVHA-100 aircraft in Appendix I. In the case of 70-ZVHA-400 aircraft, reduction in airport area was achieved mainly by a large reduction in airport length; the aerodrome category, however, remained the same. The net reduction in C_{gen} in this case was approx. 5%. In the case of 50-ZVHA-400, however, the reduction in airport area was achieved mainly by reduction in airport width. Since the wingspan reduced below 24 m, the ICAO Aerodrome Code Letter was reduced from C to B. This lead to a large reduction in the taxiway width, taxiway-apron separation & apron-terminal building separation, and hence the airport width and area. The reduction in C_{gen} for this case was approx. 7%.

Effect of very high C_{time}

C_{time} consists of two components, a fixed component determined by the Defer Time (T_{defer}) and the variable component determined by the Block Time T_{blk} . T_{defer} is a function of the frequency of operation of the aircraft and has a fixed value

²Zero VOT High Airport cost.

for a specific aircraft capacity for a given annual travel demand. Thus, the effect of C_{time} on the optimum configuration and profile could be investigated only by assuming excessively high value of time and ignoring its fixed component i.e. T_{defer} . A sensitivity analysis was carried out in which a very high value of time ($\mathcal{V}$) was assumed and C_{apt} was ignored (Code HVZA³). The reduction in T_{blk} with this assumption was found to be only around 1%, which lead to a very slight ($< 1\%$) reduction in C_{gen} of 19-HVZA-400 and 30-HVZA-400 aircraft, compared to the 30-OG-400 & 30-OG-400 aircraft, respectively. Since the analysis was limited to conventional aircraft configurations, phenomenal reductions in T_{blk} were not possible, especially for operation over such short stage lengths. Details of the configuration and flight profile of these two aircraft are given in Appendix I.

10.2.3 Comparison of pressurised & un-pressurised aircraft

Many utility & commuter aircraft have un-pressurised cabins, since they are specifically designed for short-range operations. The advantage of un-pressurised cabins is the reduction in fuselage mass and complexity, and the possibility of using rectangular cross-section that enables maximum use of the cabin volume. However, an un-pressurised cabin leads to restrictions on the flight profiles that can be employed. Due to the absence of any artificial control on the rate-of-change of pressure altitude in the un-pressurised aircraft, a constraint on the max. rate of descent has to be specified, from the point of view of passenger comfort. The effect of this constraint was studied qualitatively by comparing the optimum configuration and flight profile of 19-OG-400 aircraft, and the corresponding un-pressurised aircraft 19-UP-400. A quantitative comparison of the configuration and C_{gen} of these two aircraft was not carried out because effect of several factors related to the un-pressurised aircraft, e.g. reduction in cost and complexity due to absence of the pressurisation system and higher perceived passenger discomfort, were not modelled in the present CRAGER.

It was seen that the un-pressurised aircraft cruised at the lowest permissible altitude, descended at a much lower speed, and covered a large fraction of its mission in the descent segment. This lead to an increased cruise Mach number, to keep T_{blk} low. Contrary to normal expectations, 19-UP-400 was found to have a higher mission fuel mass and higher Max. Takeoff Power (and hence MTOW) compared to 19-OG-400. Though no conclusive remarks can be made based on this qualitative study, the study did confirm the observations reported in [47] that un-pressurised aircraft suffer from severe operational limitations and associated penalties in fuel consumption and *DOC*. The configuration and flight profile of 19-OG-400 & 19-UP-400 are compared in Figure I.8 of Appendix I.

³High Value of time Zero Airport cost.

10.3 CRAGER as an aircraft evaluation tool

A study was carried out to demonstrate the usefulness of CASTOR as a tool to compare the suitability of existing aircraft for a particular market segment. DOC & C_{gen} of five existing regional turboprop aircraft of seat capacity around 50 seats were estimated, for operation over stage lengths of 100, 200 & 400 nm. These aircraft were then compared with the optimum C_{gen} 50 seater aircraft determined earlier using CRAGER in aircraft evaluation mode, rather than the optimiser mode. To ensure uniformity and consistency, the data related to the passenger capacity, mass, geometry, power-plant, field length, block time & block fuel of these aircraft were taken from a common source [139]. Their acquisition cost were, however, calculated using the methodology discussed in Appendix F.

Details of this comparative study and the breakdown of C_{gen} for all the aircraft are given in Appendix I. A relative comparison of DOC_{snm} and DOC of the various aircraft is shown in Figure 10.4, with the optimum aircraft obtained by CASTOR considered as the baseline for each stage length. The optimum aircraft determined by CRAGER were found to have the lowest DOC & DOC_{snm} for the stage length of 100 & 200 nm. For 400 nm stage length, however, the 40 seater ATR-42-320 was seen to have a very slightly lower Trip DOC and 52 seater SAAB-2000 was seen to have approx. 1% lower DOC_{snm} compared to 50-OG-400. Similarly, 50-OG-100 & 50-OG-200 had the lowest C_{gen} per seat-nm for stage lengths of 100 & 200 nm. For the 400 nm sector, however, SAAB-2000 had a 0.6% lower C_{gen} compared to 50-OPT-400. The possible reason for this could be the error and in-accuracies in the data that was used as input to the study.

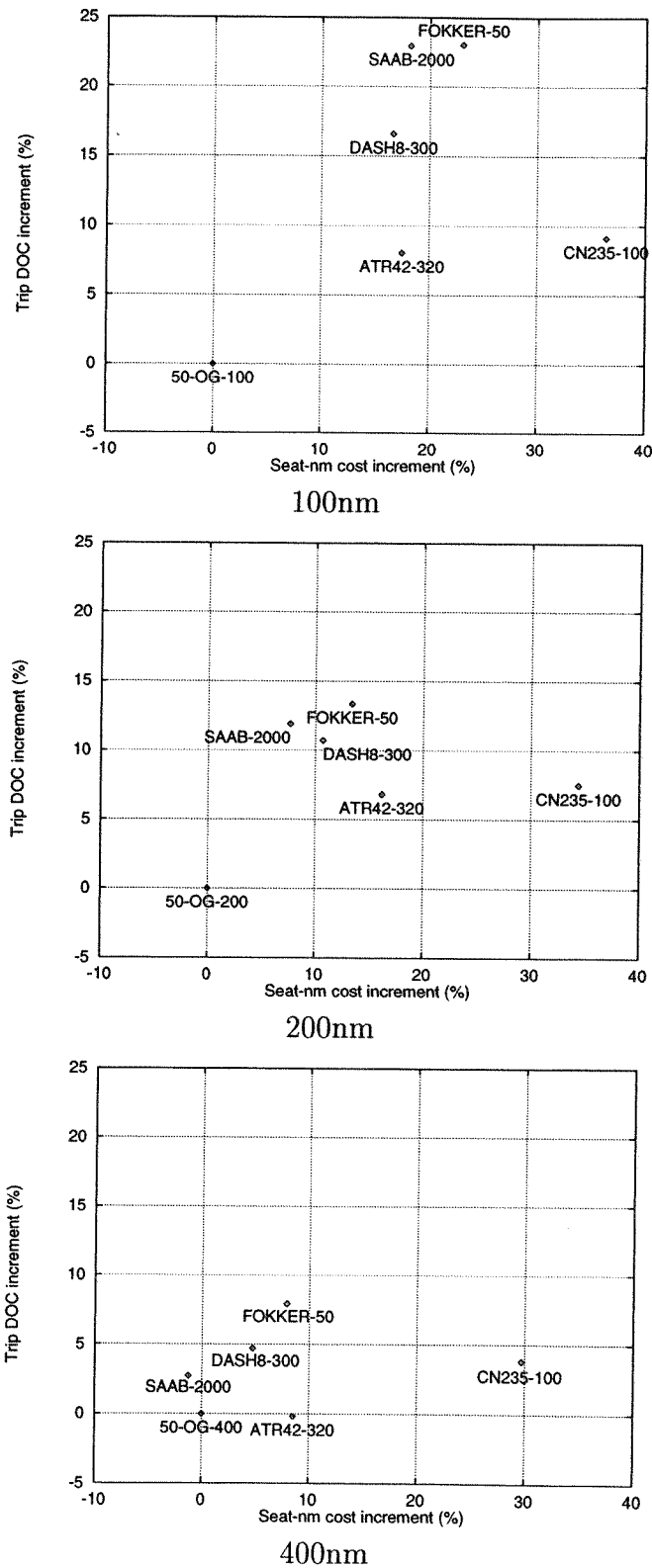


Figure 10.4: Comparison of DOC_{snm} and DOC per flight of various aircraft

Chapter 11

Discussion

This chapter provides a discussion of the main results obtained during the course of the present work. The limitations of CRAGER and the present work are also outlined.

The principle aim of this study was to develop a methodology for the incorporation of airport and time-related costs in the conceptual design and optimisation of commuter and regional transport aircraft, for operation over new or untested routes. The emphasis was on the ability to identify a baseline configuration that corresponded to the least Generalised cost (C_{gen}) for the passengers, for operation over a specific route. This baseline configuration could then be subjected to more detailed analysis and design.

Incorporation of cost and economic parameters in the aircraft conceptual design in a previous study resulted in a complex, highly non-linear multi-modal objective function, which was difficult to optimise using conventional gradient-based optimisation techniques. It was thus decided to investigate the suitability of stochastic optimisation techniques in handling such functions. Exploratory studies of two of the most commonly used stochastic optimisation techniques viz. Genetic Algorithms and Simulated Annealing, confirmed the efficacy of these techniques in optimising such functions. The study revealed that both the stochastic optimisation methods were able to arrive at better or comparable solutions compared to the gradient based methods. In particular, the general purpose Simulated Annealing code SIMANN was found to be fairly robust and easy to implement.

An existing computer code for design synthesis and trajectory optimisation of commuter aircraft (CASTOR) was obtained. As a means to provide a direct coupling between the aircraft and the associated airport, a new module for geometrical sizing and costing of regional airports was developed, based on the frequency of operation and geometrical and performance parameters of the aircraft. This airport module

was then applied to estimate costs related to setting-up and operating regional airports in India, based on a database of existing regional airports and relevant cost data. As a test case for short range business travel in India, the above airport module was coupled to the unmodified CASTOR code, and the SIMANN optimiser to obtain minimum *DOC* configurations of 15, 20, 30 & 60 seater aircraft. The C_{gen} of these aircraft for operation over stage a length of 100 nm for various annual passenger demand were compared. This case study revealed that as the aircraft capacity increases, the flight cost per passenger decreases. However, as the terms related to Time cost (C_{time}) and Airport cost (C_{apt}) are progressively included, the C_{gen} also increases with increase in aircraft capacity. The 30 seater aircraft was found to be the best overall compromise solution for the baseline case with an annual demand of 18000 one way passenger-trips. It was further revealed that for low annual passenger demand, the C_{gen} is dominated by C_{time} and C_{apt} , while at high annual passenger demand, the C_{gen} is dominated by Flight costs. The 20 seater aircraft was seen to have the lowest average C_{gen} for the various annual passenger loads investigated.

The code CASTOR was critically examined, and most of the sub-modules of this code were modified or corrected, based on the data related to contemporary twin-engined commuter and regional transport aircraft. The airport module and SIMANN code were coupled to the modified code, and it was renamed as CRAGER. Another case study was carried out using CRAGER, in which minimum C_{gen} configurations of 19, 30, 50 & 70 seater aircraft were obtained for business travel over stage lengths of 100, 200 & 400 nm in India. This study revealed that while the 30 seater aircraft had the lowest C_{gen} for operation over the stage length of 100 nm, the 50 seater aircraft had the lowest C_{gen} for operation over stage lengths of 200 & 400 nm. Here again, the advantage of low flight cost of the 70 seater aircraft were overcome by the higher Airport and C_{time} , while the C_{gen} of 19 seater aircraft were very high due to the high flight cost. A sensitivity analysis of the C_{apt} and C_{time} terms in the C_{gen} equation was carried out to investigate scenarios in which the optimum configuration might be driven by these cost terms. A direct comparison of the results obtained by CRAGER and CRAGER is not meaningful, since the various modules of the two codes differ a great deal from each other, and the values assigned to some of the Design Constants were different. The general trends that emerged from case studies using both the codes were quite similar.

The non-linear nature of the airport module was clearly demonstrated when very high land cost was considered in the estimation of C_{apt} . For a given aircraft size, the C_{apt} could be reduced only by achieving a reduction in the airport area. It was revealed that large reductions in C_{apt} were possible if the airport category itself could be reduced, either by lowering the ICAO Aerodrome Code Number (by reducing *BFL*) or by lowering the ICAO Aerodrome Code Letter (by reducing the wing span). In the former case, airport area is reduced mainly by reduction in airport length (i.e. along the runway), while in the latter case, the reduction is

achieved by reducing airport width.

To investigate the effect of very high C_{time} , a very high value of time was assigned and C_{apt} was ignored. However, since the study was limited to conventional configurations, substantial reductions in block time were not seen. Moreover, for a given aircraft capacity, a large fraction of C_{time} is fixed due to a constant Defer time (T_{defer}).

A qualitative comparison of the optimum configuration and mission profiles of un-pressurised and pressurised configurations of 19 seater aircraft was carried out, to demonstrate the operational constraints and penalties associated with un-pressurised configurations. For the un-pressurised aircraft, the descent speed and cruising altitude were seen to be quite low, with a much lower cruise stage fraction. This was seen to lead to higher mission fuel and hence severe repercussions in the aircraft sizing and performance.

Finally, the optimum 50 seater aircraft obtained by CRAGER for operation over the three stage lengths were compared with five contemporary 40-52 seat aircraft. It was found that the configurations obtained by CRAGER had substantially lower DOC per seat-nm and C_{gen} per passenger for operation over stage lengths of 100 & 200 nm. At a stage length of 400 nm, however, SAAB-2000 aircraft had a 0.6% lower DOC per seat-nm and C_{gen} . This study demonstrated the applicability of CRAGER as a tool for carrying out comparative analysis of existing aircraft, and revealed that though CRAGER is only a conceptual design tool, it does come up with better or comparable configurations compared to existing aircraft.

The CRAGER code developed during the course of this study has multiple applications. It can be used by government administrators and facility planners for assessing the overall system cost of setting up a new air-transport network. A cost-benefit analysis of airport development can also be carried out using CRAGER, by comparing the C_{gen} of various aircraft-airport combinations. It can be used by aircraft manufacturers for generating baseline specifications of a commuter or regional turboprop aircraft for a given market scenario, and to investigate the effect of change in travel demand on the optimum aircraft configuration. As demonstrated in one of the case studies, CRAGER can also be used by airlines for comparative analysis of various existing aircraft to enable selection of the most appropriate one for their own specific routes and market scenarios.

The present work has also demonstrated the efficacy of the Simulated Annealing optimisation technique in aircraft conceptual design and optimisation studies. The SIMANN code was found to be quite robust and easy to use, though a few trial runs were needed to tune the optimiser before it could be applied to a specific problem. However, the method was able to tackle a highly non-linear and multi-modal objective function, and came up with similar or better solutions compared to

conventional methods, as demonstrated in the exploratory case studies. The method was well suited for the present problem, since no prior information about the function behaviour was available. Since a very large number of function evaluations were required to converge to the global optimum, a new strategy was followed to arrive at reasonable or near-optimal solution quickly, which were then improved upon by more rigorous and longer runs. The aim of the present work was to generate only a baseline specification (rather than a final optimised solution), hence small deviations from the global optimum were acceptable. Apart from reducing the computational time, this strategy ensured that the function domain was well explored, thus reducing the chances of missing out other promising solutions. The SIMANN code was found to be relatively easy to implement and the run could be started from any random point. Once the optimisation run was started, no further interaction with the user was required till the run converged to a solution. The method needs far fewer internal calculations compared to classical optimisers, such as RQPMIN.

The present work provides insight and knowledge about the relative importance of the various cost terms in the C_{gen} equation for short range operations, and how they are affected by changes in stage length and travel demand. To the best of the knowledge of the author, CRAGER is the only aircraft conceptual design tool currently available, in which the airport and time related costs are directly included into the cost equation as an objective function. The airport module provides a direct means of coupling the aircraft with the minimum-configuration airport that is associated with it, rather than considering the runway length as a constraint, as in most other conceptual design methodologies. The improvement and modifications to the various modules of CASTOR and extending its applicability to regional aircraft is also a positive contribution.

It may be kept in mind that though the various case studies were carried out for Indian conditions, the C_{apt} and C_{gen} estimation modules of CRAGER are fairly generic in nature, and can be applied to various differing scenarios and market conditions, given suitable data. The airport geometry sub-module of the airport module is not limited to regional aircraft or ICAO regulations only, but it can also be used for the sizing of larger aircraft and airport design as per FAA regulations.

11.1 Shortcomings of CRAGER and the present work

Though CRAGER is a useful tool for conceptual design and optimisation of commuter and regional aircraft, it has several limitations as listed below. Further, several assumptions were made while the various case studies were carried out, which are also discussed below :

1. The geometry module of CRAGER is limited to conventional configurations of twin-engined turboprop aircraft, with wing mounted engines. While most of the commuter & regional aircraft currently available have this configuration, certain novel configurations such as those with canard or rear-mounted engines may lead to certain aerodynamic and structural improvements, that cannot be modelled in the present version of CRAGER.
2. The BFL , which is the principle parameter governing C_{apt} was estimated using an approximate formula, and that too at Sea-level ISA conditions. However, a more accurate estimation of BFL by using an iterative procedure or a step-wise integration approach would have lead to excessive computational time requirement.
3. The various case studies assumed no competition from other airlines, hence the entire travel demand is assumed to be fulfilled by one operator only. Though this assumption is usually valid on completely untested and untried markets, in many cases, only a limited market share can be captured by one operator. Provision of other facilities and offers such as frequent flier programs or cheaper off-peak rates can lead to a change in the market behaviour, which were not studied.
4. For determining the frequency of operation of the aircraft, it was assumed that the demand for travel is uniformly distributed throughout the day, whereas in real life, there are peak-time demand periods and seasonal variations in demand. Further, the passenger load factor was also assumed to be constant.
5. The travel demand is assumed to be constant with passage of time. In real life, the demand is expected to change with time, since the availability of a new mode of transportation changes the equilibrium of demand for travel between various modes of transportation, and usually leads to a change in travel demand.
6. The only means of income for the airport was assumed to be the aeronautical revenue from the landing charges. In real life, far more revenue may be earned by the airport from non-aeronautical sources, in the form of car-rental, advertisement, shops, restaurants, hangerage, sale of fuel and services etc. Further, the development of an airport may attract a substantial revenue from creation of flying clubs, other G.A. and air-taxi activity etc. In the present work, a very conservative costing approach was followed, in which the entire cost of setting-up and operating the airport was assumed to be recovered from the scheduled airline operations over a fixed period of time.
7. A constant Access cost (C_{acc}) was used for all the cases investigated. For short range travel, especially over stage lengths as low as 100 nm, the C_{acc} can be a large proportion of C_{gen} and hence the effect of parameters which

have a direct influence on the C_{acc} (such as location of the airport from the population centre of the city) should be included in the study.

8. While estimating C_{time} , the entire duration of T_{defer} was considered as a waste and was fully penalised. In real life, it might be possible use a part of T_{defer} productively, especially if it is quite large.

11.2 Further improvements to CRAGER

Apart from the shortcomings outlined above, many improvements and modifications could be carried out to CRAGER to improve its accuracy and usefulness. It could be extended to allow analysis of turbofan powered regional aircraft. As far as the aircraft analysis module is concerned, this has already been accomplished by Jenkinson [106] by inclusion of turbofan engine data, but use of a generic engine database on the same lines as GENENG [128] would make it more versatile. CRAGER could be modified for simultaneous analysis of multiple stage length solutions, or several different objective functions. This would provide the aircraft manufacturer with a good baseline specification that has the best average performance for various routes. Rather than assuming that the passengers always prefer the aircraft-airport combination that offers them the lowest C_{gen} , a logit model for estimating the market share of each aircraft could be developed, on the same lines as that developed by Alamdari [49] for analysing the competition between various airlines over a specific route. In a scenario where more than one airline has a market presence, this competition model could also be adopted to study the effect of competition on the market share and frequency of operation of aircraft by the various airlines, and its effect on C_{gen} .

Chapter 12

Conclusions and Recommendations

This chapter sums up the main conclusions of this work, and provides recommendations for future work.

12.1 Conclusions

Some of the conclusions reached during the course of this work were specific to the case studied investigated, while the remaining were general in nature.

12.1.1 General conclusions

- The robustness and efficacy of the SIMANN Simulated Annealing optimisation code in handling multi-modal objective functions was established.
- The airport module is quite non-linear due to the classification procedure followed by ICAO & FAA, and because all cost terms do not change linearly with the change in geometry and field performance of the aircraft. Large reductions in Airport cost C_{apt} are possible, if the aerodrome category itself can be lowered.
- When the demand for travel is low, the Generalised cost (C_{gen}) is dominated by Airport cost (C_{apt}) and Time cost (C_{apt}). At high travel demand, however, the Flight cost (C_{flt}) dominates C_{gen} .

- High capacity aircraft enjoy the advantage of low C_{flt} , but their C_{gen} is high due to high C_{time} and C_{apt} , compared to medium capacity aircraft. The low capacity aircraft, on the other hand, have a high C_{gen} due to high C_{flt} .
- Since C_{flt} is a major fraction of C_{gen} for most cases, the minimum DOC and minimum C_{gen} configurations are quite similar, unless large reductions in C_{apt} can be achieved.
- For conventional aircraft configurations, even an excessively high value of time ($\mathcal{V}$) does not lead to a great reduction in C_{time} for short-range operations.
- Compared to pressurised aircraft, the un-pressurised commuter aircraft suffer from severe penalties due to limitations imposed on their cruising altitude and descent profile.

12.1.2 Specific conclusions

- While minimising two aircraft conceptual design related objective functions, the stochastic methods viz. Simulated Annealing (SA) & Genetic Algorithms (GA) came up with better or similar solutions compared to the conventional gradient based methods.
- In the case study with CASTOR for business travel in Indian over a stage length of 100 nm, the 30 seater aircraft was seen to have the lowest C_{gen} for the baseline case of 18000 annual one-way passenger-trips.
- In the case study with CRAGER for business travel in India, the 30 seater aircraft was seen to have the lowest C_{gen} for 100 nm stage length. For the 200 & 400 nm stage length, however, the 50 seater aircraft had the lowest C_{gen} .
- The minimum C_{gen} 50 seater configurations optimised for 100 & 200 nm obtained that were obtained by CRAGER were found to have significantly lower DOC per seat-nm and C_{gen} compared to some contemporary regional aircraft of similar type. At a stage length of 400 nm, however, SAAB-2000 aircraft had almost identical DOC per seat-nm.

In conclusion, it can be said that the main aims of the present research have been achieved. A conceptual design tool for generating the baseline specifications of a twin-turboprop commuter or regional aircraft best suited for operation over specific network has been developed in the form of CRAGER. This FORTRAN code is robust, easy to implement and is structured in a modular form. A fairly generic airport cost estimation module has been developed as a sub-module of CRAGER, which provides a means for direct coupling of airport related parameters in the

conceptual design process. The final case study suggests that a 50 seater aircraft is most suited for short range business travel in India. It is very gratifying to note that the Indian government is planning to develop such an aircraft specifically for the domestic market [140].

12.2 Recommendations and suggestions for future work

The following recommendations are made for further improvements to CRAGER and future work in this area:

- The applicability of CRAGER could be extended to include turbo-fan aircraft.
- A hybrid optimisation method could be developed in which a stochastic optimiser such as Simulated Annealing is used to quickly identify promising areas of the design space, and then a gradient based optimiser is initiated from these promising points for the final fine-tuning to the optimal solution.
- A multi-criteria optimisation method could be coupled to CRAGER to obtain a quasi-optimal solution having the lowest objective function value for a series of stage lengths, or various differing objective functions.
- A comparative analysis of several different aircraft capacities could be carried out using Generalised cost as an input in a logit model for estimating the market share of each aircraft.
- A methodology for the estimation of C_{gen} by other modes of transportation e.g. rail and road should be developed to enable a comparative analysis of C_{gen} by these modes with that due to air-travel over short stage lengths.
- A more accurate estimation of the value of time of business travellers in India should be carried out based on a survey of passengers.
- Further studies are required to determine the proportion of T_{defer} that should be considered in the estimation of C_{time} .

APPENDICES

Appendix A

Database of existing Commuter & Regional aircraft

A.1 Introduction

A database of commercial twin-turboprop commuter & regional aircraft was prepared, which consists of a series of tables providing the relevant technical details and performance data for each aircraft on a common format. The database is listed in ascending order of seating capacity to provide easy means of comparison of similarly sized aircraft. The main source of information for this database was the 1995 directory of regional and utility aircraft published in [131]. This directory is based on a survey of piston & turbine-powered public transport aircraft carrying between 5 & 75 passengers and crew, which were in series production or under development in 1995. It also included several models no longer in production but in widespread use worldwide e.g. Embraer EMB-110 & Shorts SD360-300, though some such aircraft e.g. Fokker F-27, Avro HS-748 & DHC Dash-6 were excluded. Aircraft such as the 19 seater Arava 101B, 26 seater An-38 & 65 seater IL-114 were left out due to lack of data and information.

Data applicable to twin-engined turboprop driven aircraft was extracted from this directory, and was corrected and/or updated with information listed in various editions of *Jane's All the World's Aircraft* e.g. [110] and from the specification and performance booklets published by the manufacturers viz. [114], [115], [116], [117], [118], [132], [133] & [136].

Data related to the DHC Dash-8-400 aircraft was also included in this database. The data is presented in the form of series of tables for various groups of aircraft. The same format and nomenclature was followed for each table, which is explained

in Table A.1. There is no clear-cut and universally accepted definition of Commuter and Regional aircraft. Hence, in line with the nomenclature commonly followed in the air-transport industry, aircraft with a seat capacity of 30 seat or less are termed as Commuter aircraft, while the remaining are termed as regional aircraft.

A.2 Classification under eight categories

For ease in presenting the information, the aircraft were classified under the following eight categories:

1. Aircraft with seating capacity below 19 seats (Table A.2)
2. 19 seater aircraft (Table A.3)
3. Aircraft with seating capacity between 21 & 30 (Table A.4)
4. Aircraft with seating capacity between 31 & 40 (Table A.5)
5. Aircraft with seating capacity between 41 & 50 (Table A.6)
6. Aircraft with seating capacity between 51 & 60 (Table A.7)
7. Aircraft with seating capacity between 61 & 70 (Table A.8)
8. Aircraft with seating capacity above 70 seats (Table A.9)

A.3 Correlation between various parameters

Having obtained the data related to the various aircraft, it was decided to co-relate some of the parameters. The purpose of this exercise was :

- To obtain a better understanding of the interplay of parameters in the existing aircraft
- To develop “rules-of-thumb” for arriving at good initial values of these parameters
- To arrive at suitable upper & lower limits for parameter values in the design synthesis

ENTRY	UNITS	
MFG		Code name of aircraft manufacturer
MODEL		Model name and/or number of the aircraft
SEATS		Maximum possible seat capacity in commuter layout
ENGINE		Engine Manufacturer's designation
SERIES		Series number of Engine model
POWER	<i>kW</i>	Max. Power at Take-off rating
DPROP	<i>m</i>	Propeller Diameter
SPAN	<i>m</i>	Wing Span
AREA	<i>m²</i>	Wing Area
AR		Wing Aspect Ratio
LENGTH	<i>m</i>	Total length of the aircraft from nose
HT	<i>m</i>	Total height of the aircraft from ground
W-TRACK	<i>m</i>	Wheel Track
W-BASE	<i>m</i>	Wheel Base
TURN-RAD	<i>m</i>	Max. Turn Radius
HOLD-VOL	<i>m³</i>	Total volume of (front & rear) baggage hold
PITCH	<i>cm</i>	Seat Pitch
ABREAST		Number of passengers seated in each row
CAB-WD	<i>m</i>	Max. width of the passenger cabin
CAB-HT	<i>m</i>	Max. height of the passenger cabin
M-RAMP	<i>kg</i>	Max. Ramp mass
MTOW	<i>kg</i>	Max. permissible Take-off mass
MLW	<i>kg</i>	Max. permissible Landing weight
M0FUEL	<i>kg</i>	Max. Zero-fuel weight
M-OPSEMP	<i>kg</i>	Operating Empty weight
FUEL-CAP	<i>lit</i>	Standard internal fuel capacity
OPT-FUEL	<i>lit</i>	Optional extra fuel capacity
TO-STD	<i>m</i>	Factored Take-off distance at SL ISA conditions
TO-HT	<i>m</i>	Factored Take-off distance at SL ISA+20 deg C
TO-HI	<i>m</i>	Factored Take-off distance at 5000 ft at ISA conditions
TO-HT+HI	<i>m</i>	Factored Take-off distance at 5000 ft & ISA+20 deg C
LD-STD	<i>m</i>	Factored Landing distance at SL ISA conditions
LD-HT	<i>m</i>	Factored Landing distance at SL ISA+20 deg C
LD-HI	<i>m</i>	Factored Landing distance at 5000 ft at ISA conditions
LD-HT+HI	<i>m</i>	Factored Landing distance at 5000 ft & ISA+20 deg C
V2	<i>KTAS</i>	Take-off safety speed at MTOW
VAT	<i>KTAS</i>	Target threshold speed at MLW
VNO	<i>KCAS</i>	Max. & Normal operating speed
MNO		Max. operating Mach number
VNE	<i>KCAS</i>	"Never-Exceed" speed
V-MAX	<i>KTAS(CAS)</i>	Max. cruise speed
H-VMAX	<i>ft</i>	Altitude for operating at V-MAX
FF-VMAX	<i>kg/hr</i>	Fuel consumption when flying at V-MAX at H-VMAX
V-ECON	<i>KTAS</i>	Cost-economical cruise speed
H-VECON	<i>ft</i>	Altitude for operating at V-ECON
FF-VECON	<i>kg/hr</i>	Fuel consumption when flying at V-ECON at H-VECON
V-RGE	<i>KTAS</i>	Long-range cruise speed
H-VRGE	<i>ft</i>	Altitude for operating at V-RGE
FF-VRGE	<i>kg/hr</i>	Fuel consumption when flying at V-RGE at H-VRGE
MPL	<i>kg</i>	Max. Payload with still air en-route, ISA conditions, no reserves
R-MPL	<i>km</i>	Range with MPL under above conditions
PL-MFU	<i>kg</i>	Max. Payload possible with std. fuel tanks full
R-PL-MFU	<i>km</i>	Range with PL-MFU under above conditions

Table A.1: Nomenclature used in Tables A.2 – A.9

MFG		PARTENAVIA	BN	BEECH	BEECH	REIMS	HAMC
MODEL	UNITS	AP 68TP 600	BN-2T	SKA-350	SKA-B200	F406-CAR	Y-12-II
SEATS		10	10	12	13	14	17
ENGINE		A-250	A-250	PT 6A	PT 6A	PT 6A	PT 6A
SERIES		B 17 C	B17 C	60 A	42	112	27
POWER	<i>kW</i>	245	239	783	634	373	507
DPROP	<i>m</i>	2.03	2.03	2.67	2.50	2.36	2.49
SPAN	<i>m</i>	12.00	14.92	17.65	16.61	15.08	17.24
AREA	<i>m²</i>	18.60	30.19	28.80	28.15	23.48	34.27
AR		7.74	7.37	10.82	9.80	9.69	8.67
LENGTH	<i>m</i>	11.27	10.86	14.22	13.34	11.89	14.86
HT	<i>m</i>	3.64	4.18	4.37	4.57	4.01	5.58
W-TRACK	<i>m</i>	2.17	3.61	5.23	5.23	4.28	3.60
W-BASE	<i>m</i>	3.51	3.99	4.56	4.56	3.81	4.70
TURN-RAD	<i>m</i>	10.36	10.50	12.71	12.10	NA	14.80
HOLD-VOL	<i>m³</i>	NA	1.21	1.51	1.51	NA	1.20
PITCH	<i>cm</i>	NA	74	NA	72	NA	79
ABREAST		2	2	2	2	2	3
CAB-WD	<i>m</i>	1.13	1.09	1.37	1.37	1.42	1.46
CAB-HT	<i>m</i>	1.26	1.27	1.45	1.45	1.31	1.70
M-RAMP	<i>kg</i>	3025	3175	6849	5710	4502	5330
MTOW	<i>kg</i>	3000	3175	6804	5670	4468	5300
MLW	<i>kg</i>	2850	3084	6804	5670	4468	5300
MOFUEL	<i>kg</i>	2550	2994	5670	4990	3858	4700
M-OPSEMP	<i>kg</i>	1680	1832	4111	3799	2460	3000
FUEL-CAP	<i>lit</i>	840	855	2042	2061	1823	1313
OPT-FUEL	<i>lit</i>	NA	NA	NA	NA	NA	NA
TO-STD	<i>m</i>	600	381	1006	786	803	425
TO-HT	<i>m</i>	NA	410	1235	891	NA	480
TO-HI	<i>m</i>	NA	545	1303	997	NA	525
TO-HT+HI	<i>m</i>	NA	580	5376	1173	NA	560
LD-STD	<i>m</i>	700	339	802	867	674	620
LD-HT	<i>m</i>	NA	360	829	930	NA	640
LD-HI	<i>m</i>	NA	405	869	981	NA	700
LD-HT+HI	<i>m</i>	NA	425	911	1082	NA	730
V2	<i>KIAS</i>	NA	60	109	106	NA	80
VAT	<i>KIAS</i>	141	65	109	103	NA	77
VNO	<i>KCAS</i>	200	154	260	260	229	NA
MNO		NA	NA	NA	0.52	0.52	NA
VNE	<i>KCAS</i>	NA	195	315	292	NA	177
V-MAX	<i>KCAS</i>	214	170	311	289	246	157
H-VMAX	<i>ft</i>	10000	10000	24000	25000	NA	9800
FF-VMAX	<i>kg/hr</i>	180	180	350	298	NA	298
V-ECON	<i>KIAS</i>	170	150	301	282	200	135
H-VECON	<i>ft</i>	10000	10000	24000	25000	NA	9800
FF-VECON	<i>kg/hr</i>	167	140	158	198	NA	198
V-RGE	<i>KIAS</i>	170	150	240	246	200	144
H-VRGE	<i>ft</i>	8000	10000	35000	35000	NA	9800
FF-VRGE	<i>kg/hr</i>	123	105	175	173	NA	213
MPL	<i>kg</i>	870	1115	1456	1191	1563	1700
R-MPL	<i>km</i>	982	260	2537	NA	NA	757
PL-MFU	<i>kg</i>	670	610	2199	NA	NA	1100
R-PL-MFU	<i>km</i>	1594	1385	3826	4102	1153	1540

Table A.2: Comparison of 10 to 18 seater twin-turboprop commuter aircraft

MFG MODEL	UNITS	EMBRAER EMB-110	DASA DO228-212	ANTOLOV AN-28PT	FC METRO	BEECH B1900C	BEECH B1900D
SEATS		19	19	19	19	19	19
ENGINE		PT 6A	TPE 331	PT 6A	TPE-331	PT 6A	PT 6A
SERIES		34	5A-252D	65 B	12 UAR	65 B	67D
POWER	<i>kW</i>	555	579	820	746	820	954
DPROP	<i>m</i>	2.36	2.69	2.82	2.69	2.78	2.78
SPAN	<i>m</i>	15.32	16.97	22.06	17.37	16.60	17.67
AREA	<i>m²</i>	29.00	32.00	39.72	28.71	28.15	28.80
AR		8.09	9.00	12.26	10.51	9.79	10.84
LENGTH	<i>m</i>	15.08	16.56	13.10	18.09	17.63	17.63
HT	<i>m</i>	4.92	4.86	4.90	5.08	4.40	4.57
W-TRACK	<i>m</i>	4.94	3.30	3.41	4.57	5.23	5.23
W-BASE	<i>m</i>	5.01	6.29	4.35	5.83	7.26	7.25
TURN-RAD	<i>m</i>	12.70	14.80	3.00	11.70	12.02	12.55
HOLD-VOL	<i>m³</i>	3.20	3.50	1.20	5.40	5.15	4.96
PITCH	<i>cm</i>	79	75	72	75	76	76
ABREAST		3	2	3	2	2	2
CAB-WD	<i>m</i>	1.60	1.35	1.60	1.57	1.37	1.37
CAB-HT	<i>m</i>	1.60	1.55	1.74	1.45	1.45	1.80
M-RAMP	<i>kg</i>	5930	6430	6500	7530	7580	7738
MTOW	<i>kg</i>	5900	6400	6500	7484	7530	7688
MLW	<i>kg</i>	5700	6100	6500	7110	7302	7303
MOFUEL	<i>kg</i>	5450	5940	5884	6577	6350	6804
M-OPSEMP	<i>kg</i>	3855	3739	3900	4309	4536	4815
FUEL-CAP	<i>lit</i>	1666	2386	1960	2455	2525	2518
OPT-FUEL	<i>lit</i>	NA	NA	2530	NA	NA	NA
TO-STD	<i>m</i>	1235	793	280	1615	994	1139
TO-HT	<i>m</i>	1400	1035	325	1675	1128	1249
TO-HI	<i>m</i>	1495	1100	340	2045	1311	1401
TO-HT+HI	<i>m</i>	1800	1645	390	2225	1433	1560
LD-STD	<i>m</i>	1365	450	425	850	780	823
LD-HT	<i>m</i>	1365	480	NA	865	808	876
LD-HI	<i>m</i>	1525	520	NA	1005	860	918
LD-HT+HI	<i>m</i>	1525	550	NA	1070	893	956
V2	<i>KIAS</i>	85	80	75	120	114	111
VAT	<i>KIAS</i>	90	85	75	130	113	126
VNO	<i>KCAS</i>	230	223	185	NA	247	288
MNO		NA	NA	NA	NA	NA	NA
VNE	<i>KCAS</i>	NA	280	210	311	247	248
V-MAX	<i>KCAS</i>	225	202	189	293	267	288
H-VMAX	<i>ft</i>	10000	12000	9840	11000	16000	16000
FF-VMAX	<i>kg/hr</i>	310	306	520	395	NA	461
V-ECON	<i>KIAS</i>	180	124	160	NA	256	NA
H-VECON	<i>ft</i>	15000	12000	9840	NA	16000	NA
FF-VECON	<i>kg/hr</i>	193	180	265	NA	348	NA
V-RGE	<i>KIAS</i>	180	156	185	250	231	236
H-VRGE	<i>ft</i>	10000	12000	9840	25000	25000	25000
FF-VRGE	<i>kg/hr</i>	195	209	340	225	245	266
MPL	<i>kg</i>	1565	2201	1950	2325	1814	1989
R-MPL	<i>km</i>	575	445	700	1610	1470	1308
PL-MFU	<i>kg</i>	737	776	850	1265	NA	892
R-PL-MFU	<i>km</i>	1852	2371	1560	3713	NA	3189

Table A.3: Comparison of 19 seater twin-turboprop commuter aircraft

MFG MODEL	UNITS	LET L-410	BAe JS-S31	CASA C212-300	SHORTS SD330-200	DASA DO328	EMBRAER EMB-120
SEATS		21	21	26	30	30	30
ENGINE		MOTORLET	TPE-331	TPE 331	PT 6A	PW	PW
SERIES		M601 E	12UAR	10R 513C	45 R	119B	118A
POWER	<i>kW</i>	559	760	671	893	1625	1342
DPROP	<i>m</i>	2.30	2.69	2.79	2.82	3.50	3.20
SPAN	<i>m</i>	19.98	15.85	20.28	22.76	20.98	19.78
AREA	<i>m²</i>	34.86	25.20	41.00	42.09	40.00	39.43
AR		11.45	9.97	10.03	12.31	11.00	9.92
LENGTH	<i>m</i>	14.42	14.37	16.15	17.69	21.29	20.00
HT	<i>m</i>	5.83	5.38	6.60	4.95	7.24	6.35
W-TRACK	<i>m</i>	3.65	5.94	3.10	4.24	3.22	6.58
W-BASE	<i>m</i>	3.67	4.60	5.46	6.15	7.42	6.97
TURN-RAD	<i>m</i>	13.64	12.55	7.71	16.41	8.57	15.76
HOLD-VOL	<i>m³</i>	1.95	3.54	3.53	4.10	6.30	6.40
PITCH	<i>cm</i>	76	76	72	76	79	79
ABREAST		3	3	3	3	3	3
CAB-WD	<i>m</i>	1.95	1.85	2.10	1.98	2.18	2.10
CAB-HT	<i>m</i>	1.66	1.80	1.80	1.98	1.89	1.76
M-RAMP	<i>kg</i>	6420	7400	7750	10430	13720	11580
MTOW	<i>kg</i>	6400	7350	7700	10390	13640	11500
MLW	<i>kg</i>	6200	7080	7450	10250	13230	11250
M0FUEL	<i>kg</i>	5775	6500	7100	9336	12260	10500
M-OPSEMP	<i>kg</i>	3985	4578	4780	6682	8810	7500
FUEL-CAP	<i>lit</i>	1280	1850	2000	2180	4266	3308
OPT-FUEL	<i>lit</i>	1675	NA	NA	NA	NA	NA
TO-STD	<i>m</i>	915	1560	817	1158	1100	1420
TO-HT	<i>m</i>	1000	1880	1137	1430	1400	1620
TO-HI	<i>m</i>	1125	2400	1201	NA	1400	1760
TO-HT+HI	<i>m</i>	1270	2400	1440	NA	1400	1820
LD-STD	<i>m</i>	915	1220	866	1100	1010	1370
LD-HT	<i>m</i>	950	1220	953	1080	1140	1350
LD-HI	<i>m</i>	995	1350	958	NA	1140	1500
LD-HT+HI	<i>m</i>	1040	1350	985	NA	1140	1530
V2	<i>KIAS</i>	84	112	91	100	94	115
VAT	<i>KIAS</i>	84	114	94	111	102	115
VNO	<i>KCAS</i>	192	250	200	NA	NA	272
MNO		NA	0.51	NA	NA	NA	NA
VNE	<i>KCAS</i>	192	NA	NA	NA	270	NA
V-MAX	<i>KCAS</i>	205	260	191	200	335	310
H-VMAX	<i>ft</i>	13780	14000	10000	10000	20000	25000
FF-VMAX	<i>kg/hr</i>	330	361	350	420	715	430
V-ECON	<i>KIAS</i>	197	262	123	193	190	NA
H-VECON	<i>ft</i>	13780	20000	10000	10000	20000	NA
FF-VECON	<i>kg/hr</i>	300	299	220	418	363	NA
V-RGE	<i>KIAS</i>	160	230	162	158	315	260
H-VRGE	<i>ft</i>	13780	25000	10000	10000	31000	25000
FF-VRGE	<i>kg/hr</i>	230	238	270	320	495	340
MPL	<i>kg</i>	1615	1805	2320	2654	3450	2721
R-MPL	<i>km</i>	546	1289	660	875	834	926
PL-MFU	<i>kg</i>	885	1275	1330	1966	1400	1305
R-PL-MFU	<i>km</i>	1380	2277	1800	1695	3298	3185

Table A.4: Comparison of 21 to 30 seater twin-turboprop commuter aircraft

MFG MODEL	UNITS	BAe JS-41	EMB 120-ER	SAAB 340B	SHORTS SD360-300	DHC D8-100A	DHC D8-200A
SEATS		32	33	37	39	39	39
ENGINE		TPE-331	PW	GE	PT 6A	PW	PW
SERIES		14 GR/HR	118A	CT7-9B	67 R	120A	123C
POWER	<i>kW</i>	1230	1342	1394	1062	1491	1603
DPROP	<i>m</i>	2.90	3.20	3.35	2.74	3.96	3.96
SPAN	<i>m</i>	18.29	19.78	21.44	22.80	25.91	25.91
AREA	<i>m²</i>	32.59	39.43	41.81	42.18	54.35	54.35
AR		10.26	9.92	10.99	12.32	12.35	12.35
LENGTH	<i>m</i>	19.25	20.07	19.73	21.58	22.25	22.25
HT	<i>m</i>	5.74	6.35	6.97	7.27	7.49	7.49
W-TRACK	<i>m</i>	6.10	6.58	6.71	4.26	7.87	7.87
W-BASE	<i>m</i>	7.32	6.97	7.14	7.06	7.95	7.95
TURN-RAD	<i>m</i>	16.56	15.76	15.70	16.41	9.22	9.22
HOLD-VOL	<i>m³</i>	6.16	6.40	6.80	6.09	8.50	8.50
PITCH	<i>cm</i>	76	79	76	71	77	79
ABREAST		3	3	3	3	4	4
CAB-WD	<i>m</i>	1.85	2.10	2.16	1.93	2.49	2.49
CAB-HT	<i>m</i>	1.78	1.76	1.83	1.93	1.94	1.94
M-RAMP	<i>kg</i>	10483	12080	13210	12337	15740	16500
MTOW	<i>kg</i>	10433	11990	13155	12296	15650	16465
MLW	<i>kg</i>	10115	11700	12930	12020	15375	15375
MOFUEL	<i>kg</i>	9390	10900	12020	11037	14060	14515
M-OPSEMP	<i>kg</i>	6350	7560	8140	7872	10251	10338
FUEL-CAP	<i>lit</i>	3305	3308	3220	1305	3160	3160
OPT-FUEL	<i>lit</i>	NA	NA	NA	1465	5700	4174
TO-STD	<i>m</i>	1505	1550	1322	1435	942	960
TO-HT	<i>m</i>	1702	1780	1470	1510	1060	1040
TO-HI	<i>m</i>	2125	2040	1657	1220	1150	1160
TO-HT+HI	<i>m</i>	NA	2060	2180	1220	1580	1470
LD-STD	<i>m</i>	1317	1390	1065	1365	908	908
LD-HT	<i>m</i>	1317	1380	1065	1320	908	908
LD-HI	<i>m</i>	1480	1560	1160	105	908	908
LD-HT+HI	<i>m</i>	NA	1500	1160	106	1120	1117
V2	<i>KIAS</i>	113	115	114	195	NA	NA
VAT	<i>KIAS</i>	116	115	109	117	NA	94
VNO	<i>KCAS</i>	250	272	250	NA	NA	243
MNO		NA	NA	0.50	NA	NA	NA
VNE	<i>KCAS</i>	315	NA	250	215	NA	254
V-MAX	<i>KCAS</i>	295	313	285	475	265	300
H-VMAX	<i>ft</i>	12000	25000	25000	200	16000	16000
FF-VMAX	<i>kg/hr</i>	565	430	530	10000	570	709
V-ECON	<i>KIAS</i>	290	NA	280	475	255	282
H-VECON	<i>ft</i>	20000	NA	20000	180	25000	25000
FF-VECON	<i>kg/hr</i>	450	NA	470	10000	449	522
V-RGE	<i>KIAS</i>	250	270	249	367	235	248
H-VRGE	<i>ft</i>	25000	25000	25000	3185	25000	25000
FF-VRGE	<i>kg/hr</i>	345	NA	340	1020	393	425
MPL	<i>kg</i>	3040	2721	3766	2680	3815	4155
R-MPL	<i>km</i>	704	1501	778	1575	2829	3530
PL-MFU	<i>kg</i>	1406	1785	2314	NA	609	741
R-PL-MFU	<i>km</i>	3039	2908	2891	NA	1178	1111

Table A.5: Comparison of 31 to 40 seater twin-turboprop regional aircraft

MFG MODEL	UNITS	ANTONOV AN-26	LET L-610 G	CASA/IPTN CN-235-100	ATR 42-300	ATR 42-320	ATR 42-500
SEATS		40	43	45	50	50	50
ENGINE		ZMKB	GE	GE	PW	PW	PW
SERIES		Ai-24-VT	CT7-9D	CT7-9C	120	121	127E
POWER	<i>kW</i>	2074	1305	1305	1492	1566	1790
DPROP	<i>m</i>	3.90	3.50	3.35	3.96	3.96	3.96
SPAN	<i>m</i>	29.20	25.60	25.81	24.57	24.57	24.57
AREA	<i>m²</i>	74.98	56.00	59.10	54.50	54.50	54.50
AR		11.37	11.70	11.27	11.08	11.08	11.08
LENGTH	<i>m</i>	23.80	20.50	21.40	22.67	22.67	22.67
HT	<i>m</i>	8.58	8.19	8.18	7.59	7.59	7.59
W-TRACK	<i>m</i>	7.65	4.59	3.90	4.10	4.10	4.10
W-BASE	<i>m</i>	7.90	6.60	6.92	8.78	8.78	8.78
TURN-RAD	<i>m</i>	22.30	18.33	18.90	17.40	17.40	17.40
HOLD-VOL	<i>m³</i>	NA	7.55	6.01	8.40	8.40	8.40
PITCH	<i>cm</i>	NA	76	76	76	76	76
ABREAST		4	4	4	4	4	4
CAB-WD	<i>m</i>	2.78	2.54	2.70	2.57	2.57	2.57
CAB-HT	<i>m</i>	1.91	1.84	1.88	1.91	1.91	1.91
M-RAMP	<i>kg</i>	24000	14540	151200	16720	16720	18770
MTOW	<i>kg</i>	23000	14500	15100	16700	16700	18600
MLW	<i>kg</i>	23000	14200	14900	16400	16400	18300
MOFUEL	<i>kg</i>	20520	13200	14100	15200	15200	16700
M-OPSEMP	<i>kg</i>	15020	9000	9800	10285	10290	11250
FUEL-CAP	<i>lit</i>	6875	3500	5267	5730	5730	5730
OPT-FUEL	<i>lit</i>	NA	NA	NA	NA	NA	NA
TO-STD	<i>m</i>	1250	1095	1275	1090	1040	1130
TO-HT	<i>m</i>	1370	1245	1506	1260	1220	1240
TO-HI	<i>m</i>	1370	1390	1814	1340	1305	1370
TO-HT+HI	<i>m</i>	1400	1700	2256	1470	1470	1505
LD-STD	<i>m</i>	1740	1075	1116	1030	1034	1070
LD-HT	<i>m</i>	2200	1140	1116	1030	1034	1070
LD-HI	<i>m</i>	2450	1230	1228	1155	1140	1210
LD-HT+HI	<i>m</i>	2630	1310	1228	1140	1150	1165
V2	<i>KIAS</i>	NA	95	114	106	106	109
VAT	<i>KIAS</i>	NA	96	124	106	106	110
VNO	<i>KCAS</i>	NA	216	245	250	250	250
MNO		NA	NA	NA	0.55	0.55	0.55
VNE	<i>KCAS</i>	NA	216	248	NA	NA	NA
V-MAX	<i>KCAS</i>	235	251	248	265	269	304
H-VMAX	<i>ft</i>	19700	23620	15000	17000	17000	17000
FF-VMAX	<i>kg/hr</i>	NA	400	535	550	563	810
V-ECON	<i>KIAS</i>	NA	236	194	243	NA	NA
H-VECON	<i>ft</i>	NA	23620	18000	25000	NA	NA
FF-VECON	<i>kg/hr</i>	NA	365	349	NA	NA	NA
V-RGE	<i>KIAS</i>	215	152	200	242	242	256
H-VRGE	<i>ft</i>	19700	23620	18000	25000	25000	25000
FF-VRGE	<i>kg/hr</i>	NA	320	370	371	397	440
MPL	<i>kg</i>	5500	4200	4000	4915	4900	5450
R-MPL	<i>km</i>	1240	1370	389	1000	927	1850
PL-MFU	<i>kg</i>	3100	2800	1100	1915	1910	2850
R-PL-MFU	<i>km</i>	2660	3080	4143	4420	4150	2440

Table A.6: Comparison of 41 to 50 seater twin-turboprop regional aircraft

MFG MODEL	UNITS	SAAB 2000	XIAN Y7-100	XIAN Y7-200B	DHC D8-300	DASA F50	DASA F50HP	DASA F50U	DASA F50HPU
SEATS		54	55	56	56	58	58	59	59
ENGINE		A'SON	D'GAN	D'GAN	PW	PW	PW	PW	PW
SERIES		2100A	WJ5A-1	WJ5A-IG	123	125B	127	125B	127B
POWER	<i>kW</i>	3093	2080	2125	1755	1864	2051	1864	2050
DPROP	<i>m</i>	3.81	3.90	3.97	3.96	3.66	3.66	3.66	3.66
SPAN	<i>m</i>	24.76	29.67	29.20	27.43	29.00	29.00	29.00	29.00
AREA	<i>m²</i>	55.74	75.26	74.98	56.21	70.00	70.00	70.00	70.00
AR		11.00	11.69	11.37	13.39	12.01	12.01	12.01	12.01
LENGTH	<i>m</i>	27.03	24.22	24.45	25.68	25.25	25.25	25.25	25.25
HT	<i>m</i>	7.73	8.55	8.55	7.49	8.32	8.32	8.32	8.32
W-TRACK	<i>m</i>	8.23	7.90	7.90	7.87	7.20	7.20	7.20	7.20
W-BASE	<i>m</i>	10.97	8.36	8.60	10.01	9.70	9.70	9.70	9.70
TURN-RAD	<i>m</i>	19.70	11.83	12.00	19.84	18.07	18.07	18.07	18.07
HOLD-VOL	<i>m³</i>	10.20	11.10	11.10	7.93	10.40	10.40	10.40	10.40
PITCH	<i>cm</i>	81	75	75	74	76	76	76	76
ABREAST		3	4	4	4	4	4	4	4
CAB-WD	<i>m</i>	2.16	2.80	2.80	2.49	2.50	2.50	2.50	2.50
CAB-HT	<i>m</i>	1.83	1.90	1.90	1.94	1.96	1.96	1.96	1.96
M-RAMP	<i>kg</i>	22200	21950	21950	18642	19990	19990	21590	21590
MTOW	<i>kg</i>	22000	21800	21800	19500	19950	19950	21545	21545
MLW	<i>kg</i>	21500	21800	21200	19050	19500	19500	19730	19730
M0FUEL	<i>kg</i>	19400	19655	19700	17917	18600	18600	18600	18600
M-OPSEMP	<i>kg</i>	13500	14988	15000	11657	12520	12520	11760	11760
FUEL-CAP	<i>lit</i>	5185	5550	5484	3160	5136	5136	5136	5136
OPT-FUEL	<i>lit</i>	NA	6180	NA	5700	NA	NA	7475	NA
TO-STD	<i>m</i>	1360	546	1180	1180	1126	1050	1382	1270
TO-HT	<i>m</i>	1500	1398	1250	1320	1364	1194	1838	1450
TO-HI	<i>m</i>	1700	NA	1360	1520	1454	1315	1967	1596
TO-HT+HI	<i>m</i>	1960	NA	1630	1520	2174	1840	2174	2299
LD-STD	<i>m</i>	1250	645	1290	1040	1116	1116	1128	1128
LD-HT	<i>m</i>	1250	NA	NA	1040	1116	1116	1128	1128
LD-HI	<i>m</i>	1390	NA	NA	1150	1243	1243	1257	1257
LD-HT+HI	<i>m</i>	1390	NA	1450	1150	1317	1243	1317	1257
V2	<i>KIAS</i>	130	212	190	NA	98	98	98	98
VAT	<i>KIAS</i>	120	NA	NA	NA	NA	NA	NA	NA
VNO	<i>KCAS</i>	250	271	NA	287	227	227	227	227
MNO		0.62	NA	NA	NA	0.51	0.51	0.51	0.51
VNE	<i>KCAS</i>	NA	NA	NA	NA	NA	NA	NA	NA
V-MAX	<i>KCAS</i>	360	257	254	275	282	284	282	284
H-VMAX	<i>ft</i>	28000	19685	19685	18000	16000	18000	16000	18000
FF-VMAX	<i>kg/hr</i>	980	790	710	705	679	695	679	695
V-ECON	<i>KIAS</i>	300	228	227	136	NA	NA	NA	NA
H-VECON	<i>ft</i>	31000	19685	19685	16000	NA	NA	NA	NA
FF-VECON	<i>kg/hr</i>	NA	690	620	435	NA	NA	NA	NA
V-RGE	<i>KIAS</i>	282	228	228	247	242	239	242	239
H-VRGE	<i>ft</i>	28000	19685	19685	25000	25000	25000	25000	25000
FF-VRGE	<i>kg/hr</i>	615	690	620	515	424	430	424	430
MPL	<i>kg</i>	5745	4700	4700	6260	6080	6080	6840	6840
R-MPL	<i>km</i>	1684	910	750	704	556	2007	2709	2670
PL-MFU	<i>kg</i>	4200	2820	2850	5550	3350	4205	3853	3856
R-PL-MFU	<i>km</i>	2854	1982	1900	1705	3484	3934	5923	5989

Table A.7: Comparison of 51 to 60 seater twin-turboprop regional aircraft

MFG MODEL	UNITS	XIAN Y7-200A	IPTN N-250-100	DASA F60	DASA F60-U
SEATS		63	66	68	68
ENGINE		PW	ALLISON	PW	PW
SERIES		127	2100C	127B	127B
POWER	<i>kW</i>	2050	2386	2050	2050
DPROP	<i>m</i>	3.97	3.81	3.66	3.66
SPAN	<i>m</i>	29.66	28.00	29.00	29.00
AREA	<i>m</i> ²	75.26	65.00	70.00	70.00
AR		11.69	12.06	12.01	12.01
LENGTH	<i>m</i>	24.21	26.30	26.87	26.87
HT	<i>m</i>	8.55	8.37	8.34	8.34
W-TRACK	<i>m</i>	7.90	4.10	7.20	7.20
W-BASE	<i>m</i>	9.45	10.25	10.72	10.72
TURN-RAD	<i>m</i>	13.25	18.90	18.54	18.54
HOLD-VOL	<i>m</i> ³	11.10	10.30	13.54	13.54
PITCH	<i>cm</i>	75	76	76	76
ABREAST		4	4	4	4
CAB-WD	<i>m</i>	2.80	2.70	2.50	2.50
CAB-HT	<i>m</i>	1.90	1.93	1.96	1.96
M-RAMP	<i>kg</i>	21300	22100	21995	22955
MTOW	<i>kg</i>	21200	22000	21950	22950
MLW	<i>kg</i>	20800	21800	21750	21750
M0FUEL	<i>kg</i>	19020	19665	20700	20700
M-OPSEMP	<i>kg</i>	13800	13665	13328	12648
FUEL-CAP	<i>lit</i>	5732	5267	5136	5136
OPT-FUEL	<i>lit</i>	NA	NA	NA	7475
TO-STD	<i>m</i>	1100	1220	1347	1524
TO-HT	<i>m</i>	1170	NA	1559	1939
TO-HI	<i>m</i>	1300	NA	1806	2309
TO-HT+HI	<i>m</i>	1630	NA	2251	2251
LD-STD	<i>m</i>	1120	1220	1175	1243
LD-HT	<i>m</i>	NA	NA	1175	1243
LD-HI	<i>m</i>	NA	NA	1310	1360
LD-HT+HI	<i>m</i>	1250	NA	1305	1385
V2	<i>KIAS</i>	190	NA	102	102
VAT	<i>KIAS</i>	NA	NA	NA	NA
VNO	<i>KCAS</i>	NA	NA	250	250
MNO		NA	NA	0.51	0.51
VNE	<i>KCAS</i>	NA	NA	NA	NA
V-MAX	<i>KCAS</i>	248	330	276	276
H-VMAX	<i>ft</i>	19685	20000	16000	16000
FF-VMAX	<i>kg/hr</i>	610	NA	726	726
V-ECON	<i>KIAS</i>	227	300	NA	NA
H-VECON	<i>ft</i>	19685	20000	NA	NA
FF-VECON	<i>kg/hr</i>	535	NA	NA	NA
V-RGE	<i>KIAS</i>	228	NA	245	245
H-VRGE	<i>ft</i>	19685	NA	25000	25000
FF-VRGE	<i>kg/hr</i>	535	NA	479	479
MPL	<i>kg</i>	4700	6000	7372	8052
R-MPL	<i>km</i>	1220	1482	1807	1462
PL-MFU	<i>kg</i>	3110	NA	5531	4189
R-PL-MFU	<i>km</i>	2500	2038	3498	4979

Table A.8: Comparison of 61 to 70 seater twin-turboprop regional aircraft

MFG MODEL	UNITS	ATR 72-200	ATR 72-210	BAe JS-61	BAe JS-ATP	DHC D8-400
SEATS		74	74	74	74	78
ENGINE		PW	PW	PW	PW	PW
SERIES		124B	127	127D	127D	150
POWER	<i>kW</i>	1790	2051	2051	2051	3602
DPROP	<i>m</i>	3.96	3.96	4.19	4.19	4.11
SPAN	<i>m</i>	27.05	27.05	30.63	30.63	28.12
AREA	<i>m²</i>	61.00	61.00	78.30	78.32	62.05
AR		12.00	12.00	11.98	11.98	12.74
LENGTH	<i>m</i>	27.17	27.17	26.01	26.00	31.60
HT	<i>m</i>	7.65	7.65	7.54	7.59	8.10
W-TRACK	<i>m</i>	4.10	4.10	8.46	8.46	8.50
W-BASE	<i>m</i>	10.77	10.77	9.70	9.70	10.01
TURN-RAD	<i>m</i>	19.76	19.76	9.75	9.75	NA
HOLD-VOL	<i>m³</i>	6.40	6.40	9.23	8.72	13.80
PITCH	<i>cm</i>	76	76	79	79	79
ABREAST		4	4	4	4	4
CAB-WD	<i>m</i>	2.57	2.57	2.50	2.50	2.49
CAB-HT	<i>m</i>	1.91	1.91	1.93	1.93	1.94
M-RAMP	<i>kg</i>	21530	21530	23746	23746	NA
MTOW	<i>kg</i>	21500	21500	23678	23678	25855
MLW	<i>kg</i>	21350	21350	23133	23133	25628
M0FUEL	<i>kg</i>	19700	19700	21772	21410	15558
M-OPSEMP	<i>kg</i>	12500	12400	14424	14242	15580
FUEL-CAP	<i>lit</i>	6365	6365	6365	6364	NA
OPT-FUEL	<i>lit</i>	NA	NA	NA	NA	NA
TO-STD	<i>m</i>	1410	1205	1300	1345	1128
TO-HT	<i>m</i>	1560	1365	1570	1675	NA
TO-HI	<i>m</i>	1620	1530	NA	NA	NA
TO-HT+HI	<i>m</i>	1600	1670	NA	NA	NA
LD-STD	<i>m</i>	1208	1052	1030	1125	1247
LD-HT	<i>m</i>	1208	1052	1030	1125	NA
LD-HI	<i>m</i>	1335	1160	NA	NA	NA
LD-HT+HI	<i>m</i>	1235	1140	NA	NA	NA
V2	<i>KIAS</i>	113	112	110	112	NA
VAT	<i>KIAS</i>	113	113	105	103	NA
VNO	<i>KCAS</i>	250	250	230	230	NA
MNO		0.55	0.55	NA	NA	NA
VNE	<i>KCAS</i>	NA	NA	NA	NA	NA
V-MAX	<i>KCAS</i>	278	280	270	265	350
H-VMAX	<i>ft</i>	17000	17000	14000	14000	20000
FF-VMAX	<i>kg/hr</i>	695	740	764	666	NA
V-ECON	<i>KIAS</i>	248	NA	NA	NA	NA
H-VECON	<i>ft</i>	23000	NA	NA	NA	NA
FF-VECON	<i>kg/hr</i>	NA	NA	NA	NA	NA
V-RGE	<i>KIAS</i>	247	247	235	235	305
H-VRGE	<i>ft</i>	25000	25000	22000	22000	NA
FF-VRGE	<i>kg/hr</i>	467	465	545	545	NA
MPL	<i>kg</i>	7200	7250	7452	7167	6370
R-MPL	<i>km</i>	860	765	1308	1147	1713
PL-MFU	<i>kg</i>	4100	4050	4188	NA	6370
R-PL-MFU	<i>km</i>	3780	3474	3936	NA	1963

Table A.9: Comparison of twin-turboprop regional aircraft with ≥ 71 seats

Many of the above aircraft can be considered to belong to a particular family, since they are stretched versions of a baseline aircraft type. 8 such families were identified, and classified as under¹ :

1. FOKKER, with F-50, F-50U, F-50HP, F-50HPU, F-60 & F-60U aircraft
2. XIAN, with Y7-100, Y7-200A & Y7-200B aircraft
3. ATR, with ATR42-300, -320, -500 & ATR72-210 aircraft
4. BEECH, with B1900C & B1900D aircraft
5. DHC, with Dash8-100A, -200A, -300 & -400 aircraft
6. BAE, with Jetstream Super 31 & JS-41 aircraft
7. SHORTS, with SD330-200 & SD360-300 aircraft
8. SAAB, with S-340B & S-2000 aircraft

All the other aircraft were classified under the “GENERAL” category. The correlations were developed using data related to the aircraft from “GENERAL” category, and the baseline aircraft of each family. In most cases, linear correlation formulae between the parameters were obtained and listed in the figures, along with the *Coefficient of determination*² or R^2 value as it is commonly referred. Parameters of the aircraft belonging to the various families were also superimposed on these correlations.

A.3.1 Size related parameters

Figure A.1 shows the variation of wing aspect ratio (AR_w) with increase in M_{TO} for all the aircraft. While a large variation in AR_w (between 8 to 12) is seen for commuter aircraft, for the regional aircraft AR_w tends to be between 11 & 13. All the aircraft in the FOKKER F-50 family and ATR42 series use the same wing, hence AR_w also remains the same. The same is true for the stretch of SD360-300 from SD330-200, and from Dash8-100 to 200. An increase in AR_w leads to a heavier wing, hence most aircraft with high AR_w tend to be heavier.

¹ATP is a stretched version of HS-748 aircraft, but since this aircraft was not listed in the database, ATP was placed in the GENERAL category.

²Coefficient of determination is a commonly used measure of the *goodness* of fit of a linear model. It represents the square of the correlation coefficient R between the independent variable X and the actual value Y and the predicted value Y' of the dependent variable [141].

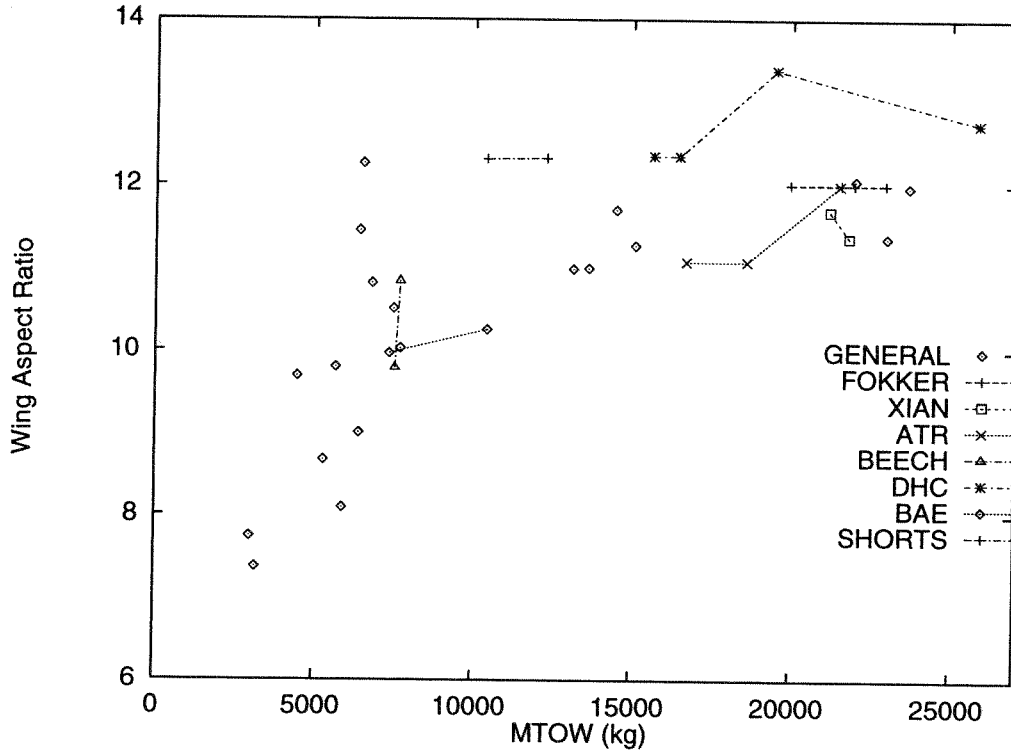


Figure A.1: Variation of AR_w with M_{TO}

Figure A.2 shows that the trend of increase in wing area with increase in M_{TO} . Aircraft manufacturers tend to use the same wing for all the aircraft of a family as far as possible. However, it is worth noting that the increase in wing area with M_{TO} for these aircraft is mostly along the same lines as the trend followed by the "GENERAL" aircraft.

Square Cube Law

It is a well known fact that for two geometrically similar airplanes designed to the same stress levels and using similar materials,

$$S \propto l^2 \text{ \& } W \propto l^3, \quad \text{thus, } l \propto W^{\frac{1}{3}} \quad (\text{A.1})$$

where l is some characteristic length, S is wing area & W is MTOW. This is commonly referred to as *Square-Cube Law*. Hence, it can be expected that

$$\frac{W}{S} \propto W^{\frac{1}{3}} \quad (\text{A.2})$$

Figure A.3 demonstrates the Square-Cube law for the various aircraft. It can be seen that all stretched aircraft follow similar trends of increase in dimensions with increase

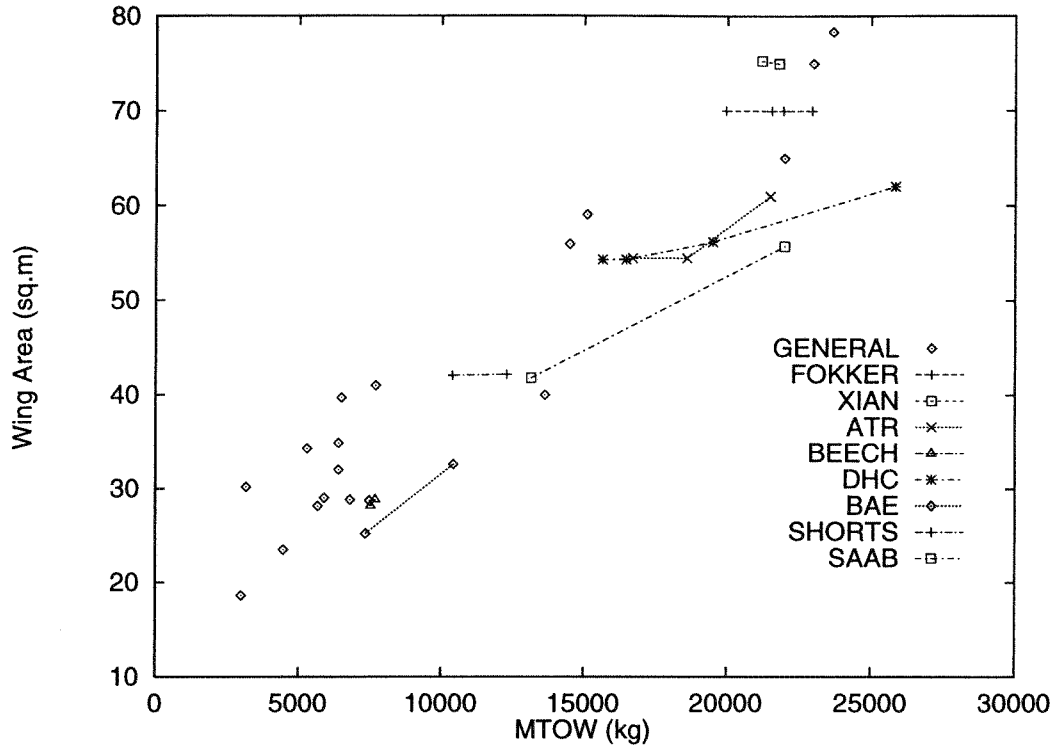


Figure A.2: Variation of wing area with M_{TO}

in size. Except JS-Super 31 aircraft, it can be seen that all the aircraft lie within the upper and lower limits of wing loading suggested in [126]. The stretch of JS-S31, viz. JS-41, however, lies on the upper boundary of the limit wing loading. Figure A.4 shows that most aircraft in the database lie within a box enclosed by power loading between 0.08 to 0.24 kW/kg and wing loading between 150 & 350kg/sq.m. The only exception to this are the AN28-PT and BN-2T aircraft from the general category, and a few stretched aircraft such as B1900D, SAAB-2000 & Dash8-400. Generally speaking, higher power loading corresponds to better payload capability & cruise performance at the cost of inferior field performance. This is exemplified by the stretch of B1900D aircraft from B1900C, in which the wing loading remains almost the same, but the power loading increases by 13.8 %. This results in a 16.6 % increase in max. cruise speed and 9.7% increase in max. payload capacity even with 6.2 % increase in OEW , but a 14.4 % increase in FAR Take-off distance and 5.5 % increase in FAR Landing distance. However, in the case of the stretch of ATR42-320 from -300, a 5.2% increase in power loading with the same wing loading results in 4.6 % improvement in the FAR Take-off distance, and improved “hot and high” performance, coupled with a 3-4 kt higher cruise speed [134].

Higher wing loading corresponds to high cruising speed capability and lower gust-load factor hence better ride quality for the passengers, which are important considerations in civil transport aircraft. Lower wing loading, however, corresponds

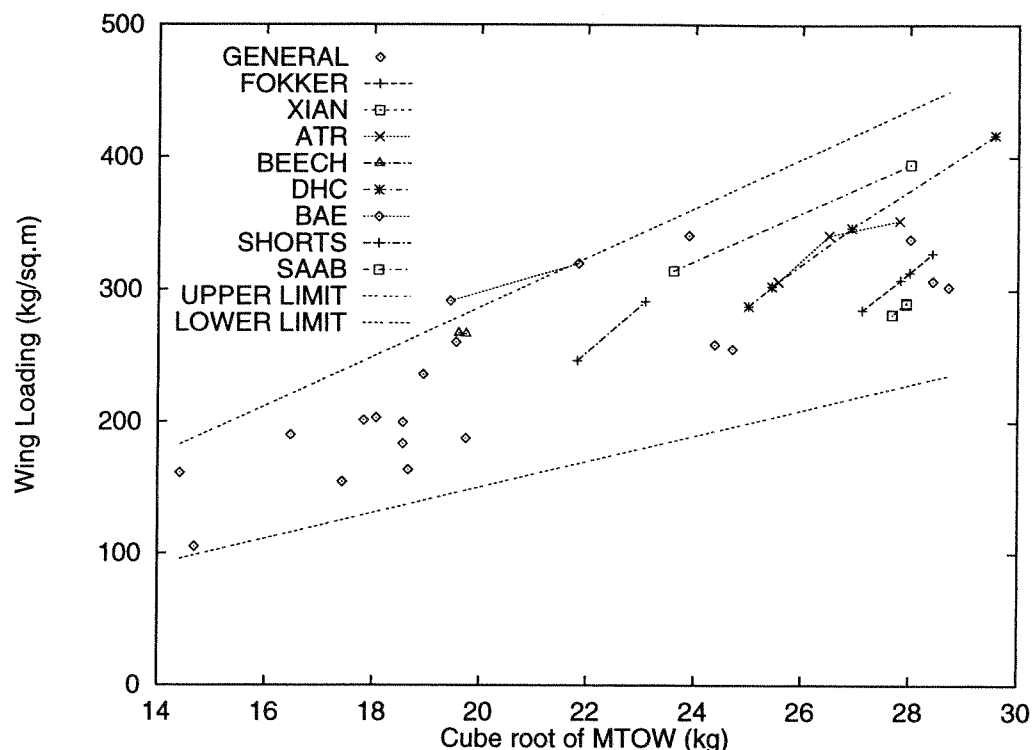


Figure A.3: Illustration of the *Square-Cube law*

to better field performance. Thus the aircraft located near the lower left corner of the box in Figure A.4 correspond to low speed aircraft with low payload capability, but good field performance. On the other hand, the aircraft that lie on the top right corner are high speed aircraft with higher payload capability, but poor field performance. Thus, the AN28-PT and BN-2T aircraft seem to be designed for performance considerations that are totally opposite to the Dash8-400 & SAAB-2000 aircraft. Most regional aircraft tend to occupy the right half of the box, while most commuter aircraft are located in the left half.

A.3.2 Passenger cabin layout

Figure A.5 shows the variation of number of passengers seated abreast in a row with increase in aircraft capacity. It can be seen that most aircraft have two-abreast seat layout up to 19 seat capacity, with the exception of AN28PT & EMB-110, which have a three abreast layout. Between 20 & 40 seats, all aircraft have a three-abreast layout, while above 40 seats the most preferred layout is four-abreast. The SAAB-2000 aircraft is an exception to this rule, since it was developed from the 3 abreast S340B aircraft retaining the same fuselage diameter.

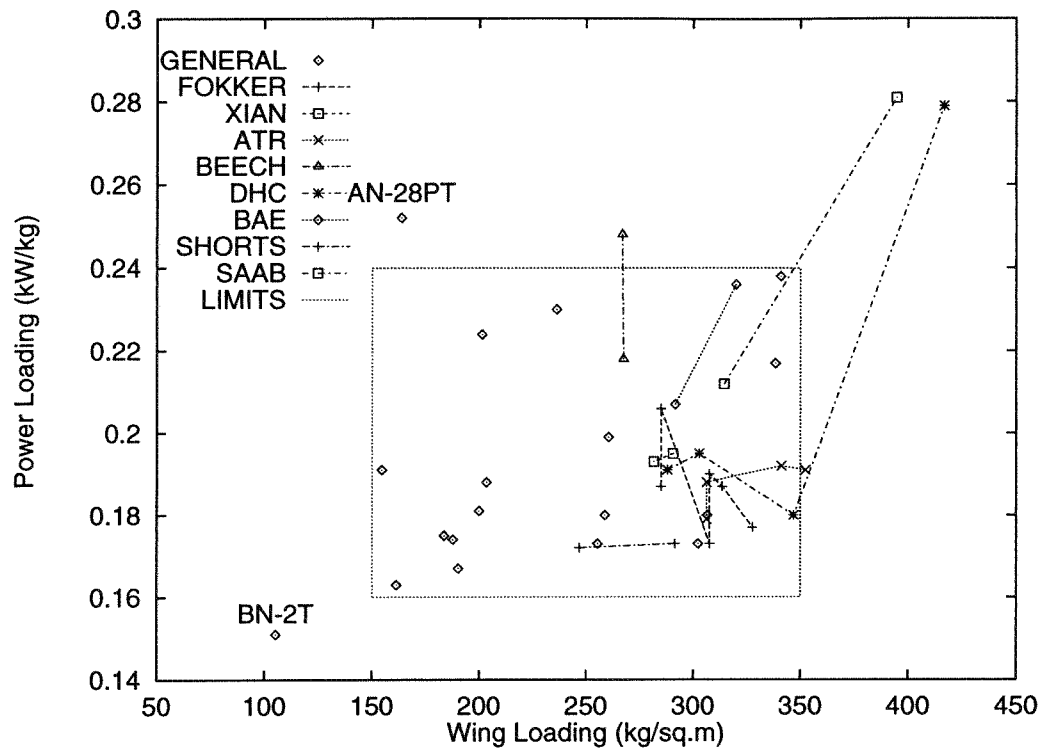


Figure A.4: Correlation between wing loading & power loading

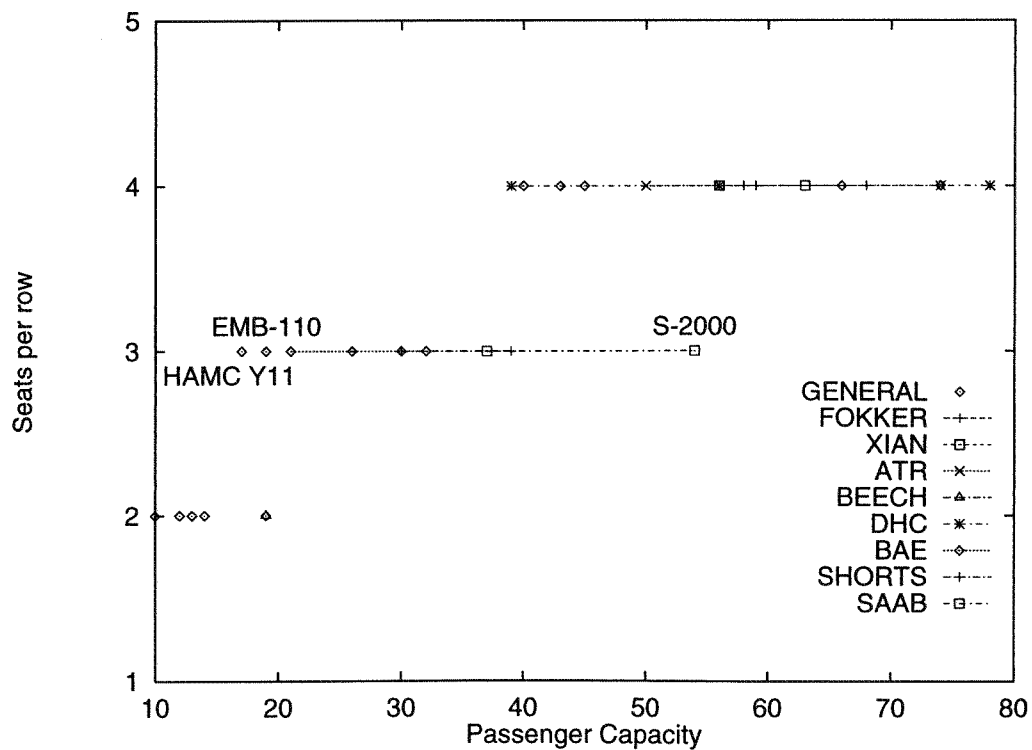


Figure A.5: Correlation between No. of passengers seated abreast & seat capacity

A.3.3 Airport related parameters

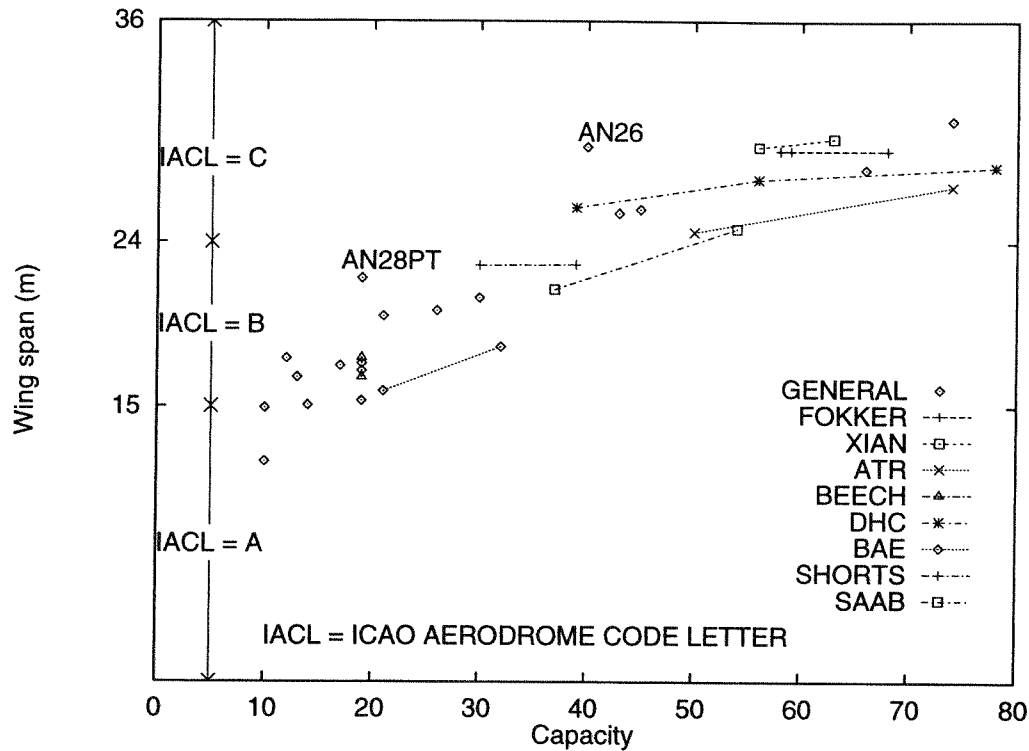


Figure A.6: Correlation between wingspan & max. seating capacity

Figure A.6 & A.7 show the variation of the wingspan with M_{TO} and seating capacity, respectively. The zones corresponding to the IACL (ICAO Airport Classification Letter³) A, B, & C are also shown. It can be seen that most aircraft correspond to IACL B & C, and that most aircraft with IACL = A have the wingspan between 15 & 18 m, while those with IACL = B have the wingspan between 25 & 31 m. Most of the stretched aircraft are also seen to have same or similar wingspan. From Figure A.6, it can be seen that AN28PT & AN26 have a much larger wingspan compared to average 19 & 40 seater aircraft. However, in Figure A.7, the wingspan of AN26 falls within the general trend, due to its high M_{TO} . Figure A.8 demonstrates the link between FAR take-off distance of various aircraft under ISA conditions and M_{TO} . The ICAO Aerodrome Code Number (IACN) based on the FAR Take-off distance is also shown for each aircraft⁴. IACN directly affects the land area required and construction cost of the airport, since the minimum recommended width of the

³ICAO airport classification specifies Code Letters based on the wingspan (and wheel-track) and Code Numbers based on Reference Field Length. (Refer Chapter 7).

⁴The ICAO classification of IACN is based on the Reference Field Length, which is the actual runway take-off length (including the stopway & clearway, when provided) converted to an equal length at mean sea-level, 15 deg. C & 0 % gradient. FAR Take-off field length is used here as an approximation to the Reference Field Length.

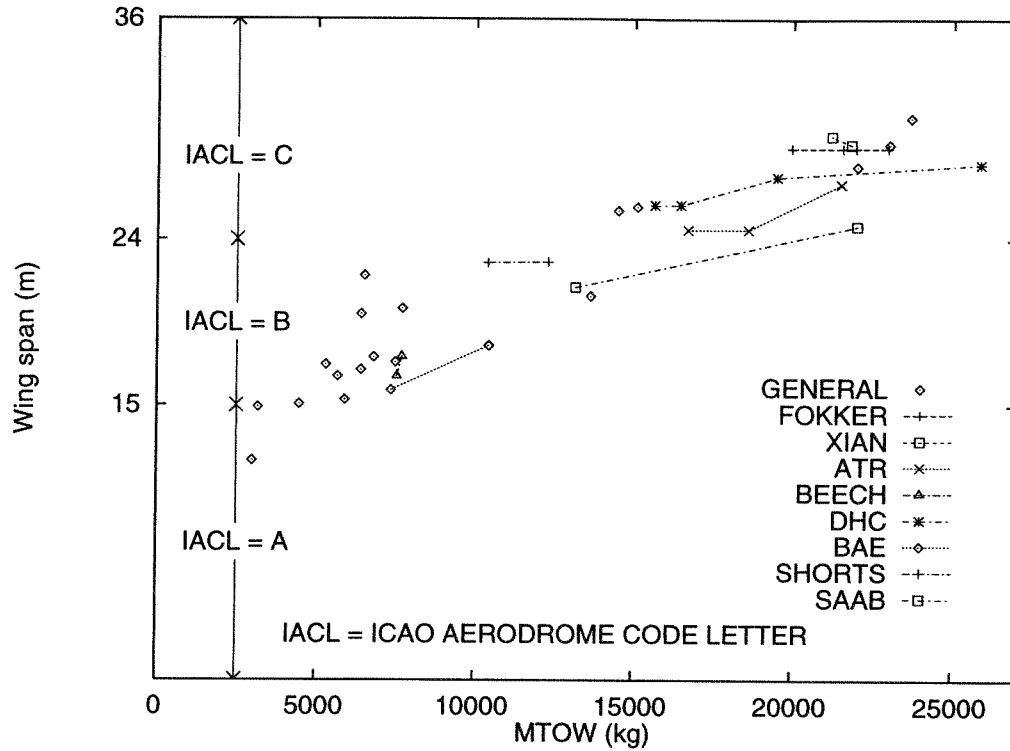


Figure A.7: Correlation between wingspan & M_{TO}

runway pavement and the runway strip increase as IACN increases. It can be seen that while regional aircraft have an IACN of 2 or 3, most of the commuter aircraft have IACN of 1 or 2. It can also be seen that all aircraft in the BEECH, DHC, ATR & XIAN family correspond to IACN of 2. Further, the stretch of F-50 to -50HP reduces the IACN from 3 to 2. The worst field performance for commuter aircraft is demonstrated by Metro-23, Shorts SD360-300 and the two Jstream aircraft of the BAE family, all of which correspond to IACN of 3.

A.3.4 Power-plant related parameters

The strong correlation between P_{TO} and M_{TO} is shown in Figure A.9, including most stretched aircraft which involve increase in P_{TO} . The ball-park value of P_{TO} in kW for all aircraft is roughly 9-10 % of M_{TO} in kg. SAAB-2000 & Dash8-400 are exceptions to this rule, as they exhibit very high aircraft power to weight ratio.

Figure A.10 shows that propeller diameter (D_{prop}) varies linearly with TO_{SHP} . Many aircraft are seen to have D_{prop} between 2.25 to 3.0 m, while most of the stretched aircraft tend to use the same propeller. In the case of SD330-200 & SD360-300, a trend opposite to the usual is seen since D_{prop} decreases with the

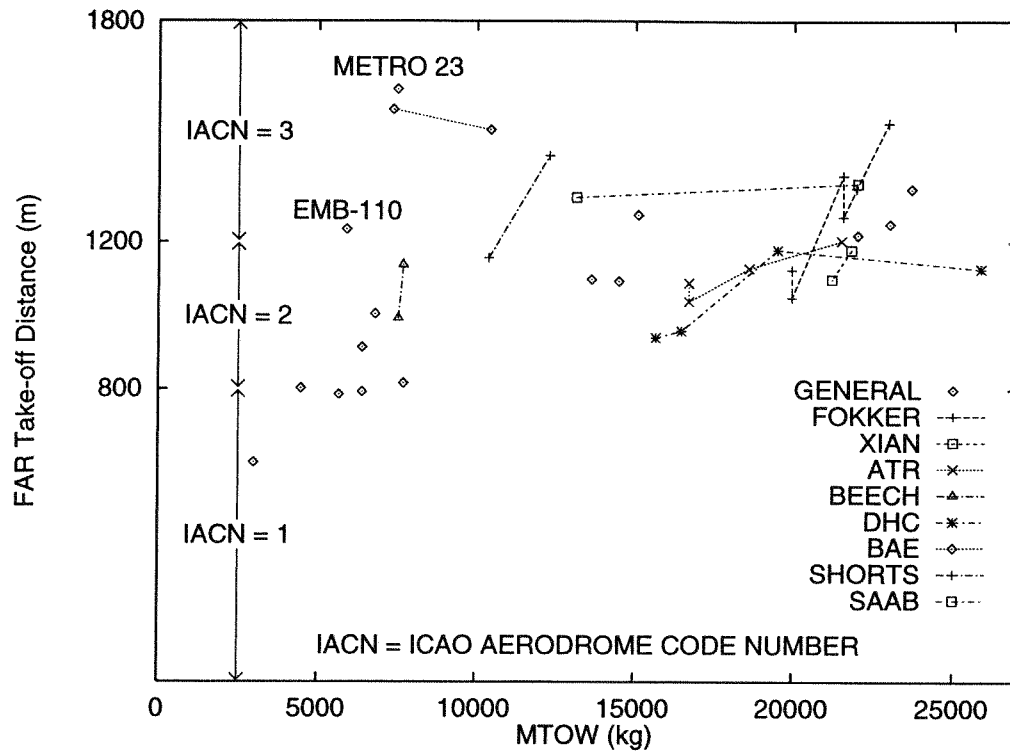


Figure A.8: Variation of FAR Take-off distance with M_{TO}

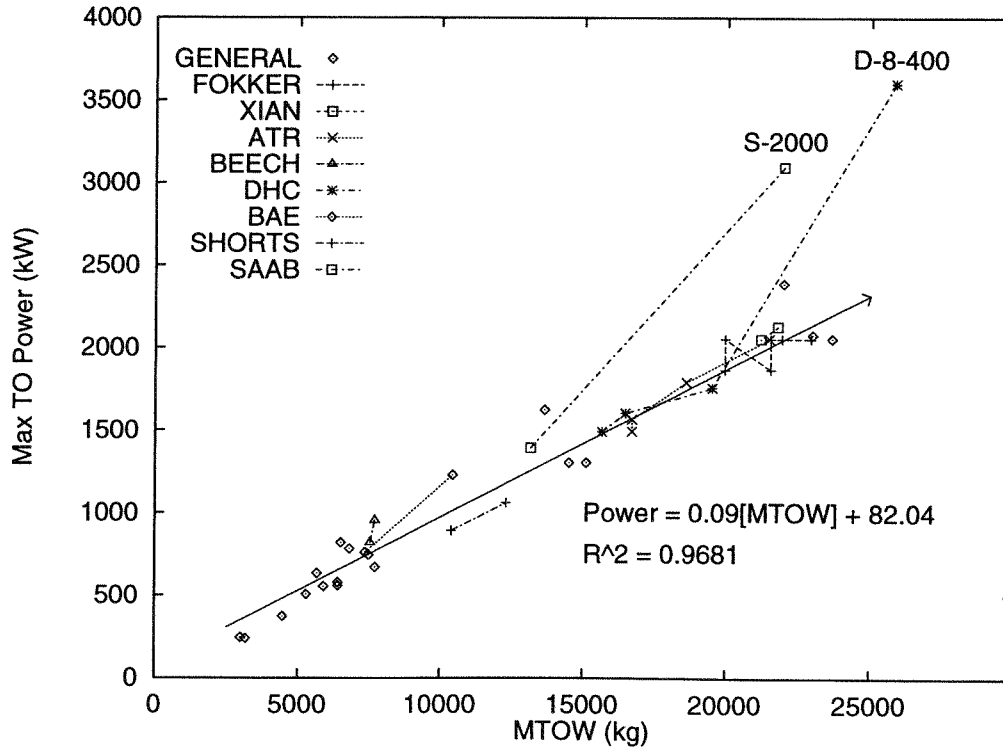


Figure A.9: Correlation between P_{TO} and M_{TO}

increase in power. Many aircraft manufacturers choose existing or slightly modified propellers for their aircraft, for e.g. IPTN N-250-100 & SAAB-2000 use the similar propeller from DOWTY. Both these aircraft have much smaller D_{prop} compared to their TO_{SHP} . Further, ATP is seen to have an unusually large D_{prop} . It may be noted that selection of D_{prop} is affected by many other considerations such as number of blades, tip speed, noise levels and ground or fuselage clearances, apart from TO_{SHP} . A more appropriate methodology for selection of D_{prop} was used in the present work, which is discussed in Chapter 9.

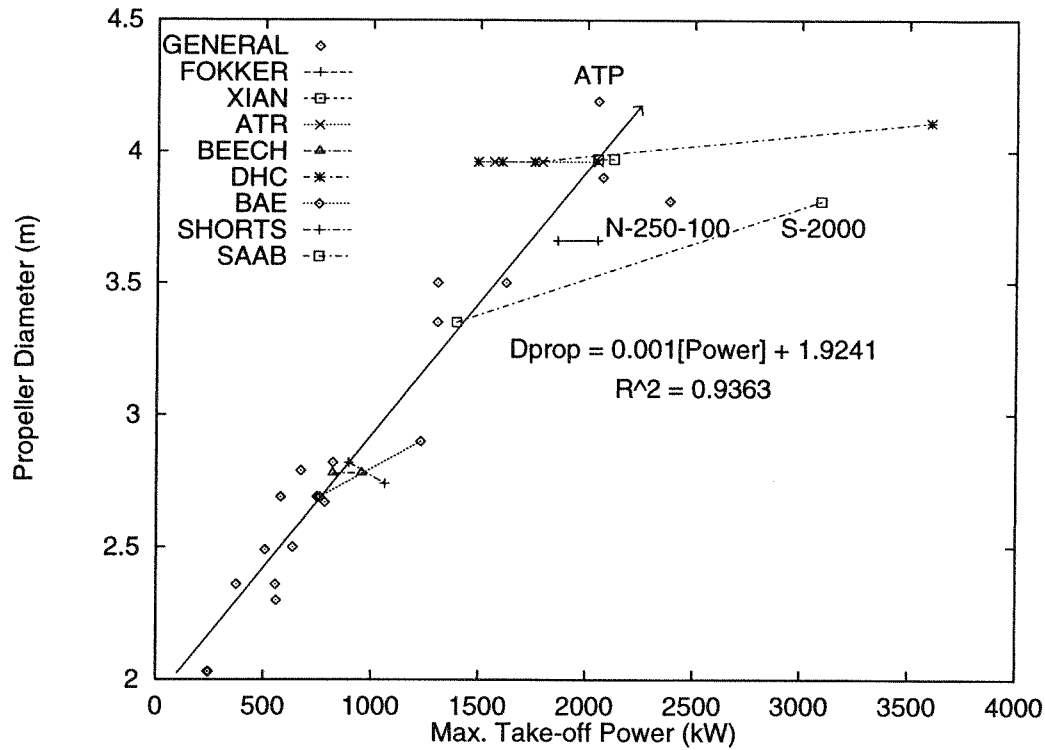


Figure A.10: Correlation between D_{prop} & TO_{SHP}

A.3.5 Mass related parameters

Figure A.11 shows the linear dependence of M_{TO} on the aircraft capacity. Compared to the general trend, most stretched aircraft achieve increase in capacity with a lower corresponding increase in M_{TO} . The stretch of S-2000 from S-340B is, however, against this trend, probably due to the highly powered engine that it uses to achieve its high performance goals. The stretch of X7-100 to -200A is very peculiar, since an increase in capacity is accompanied by a decrease in M_{TO} (as well as lower OEW , refer Figure A.14). It may however be noted that while X7-100 & -200B are seen to be heavier compared to the other 55 seater aircraft, the mass of X7-200A is in line

with the general trend. The Do-328 is also found to be much heavier than other 30 seater aircraft.

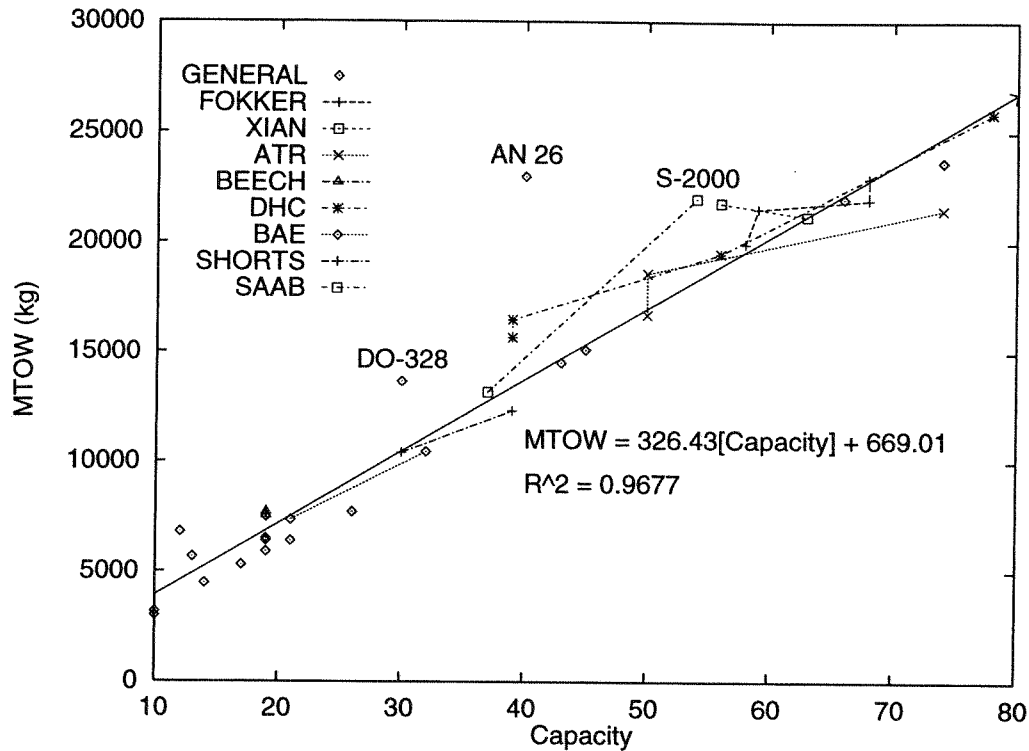


Figure A.11: Correlation between M_{TO} and aircraft capacity

Figure A.12 & A.13 show the linear correlation between the max. payload carried by the aircraft and its M_{TO} and seating capacity, respectively. Most aircraft can carry 28% of their M_{TO} as payload, or approx. 100 kg per passenger. This figure also demonstrates that most stretched aircraft achieve increase in payload far in exceedence with the general trend. Another interesting feature is that for most of the stretched aircraft, the individual trend lines for payload increase are mutually parallel. ATP is seen to have a higher than average payload carrying capacity, while the payload carried by AN26 and the XIAN X-7 series is far lower than the general trend. The stretch of SD330-200 to SD360-300, X7-100 to -200B & Dash8-300 to -400 is to achieve a higher seat capacity with same or similar payload. On the other hand, the stretch of Dash8-100 to -200, ATR42-300 to -500, F-50 to -50U & F-60 to -60U is aimed at increasing the payload and not capacity.

Figure A.14 shows the very strong correlation between the operating empty mass (OEM) of the aircraft and its M_{TO} . For all aircraft, OEW is found to be roughly 61.5 % of M_{TO} , including most stretched aircraft.

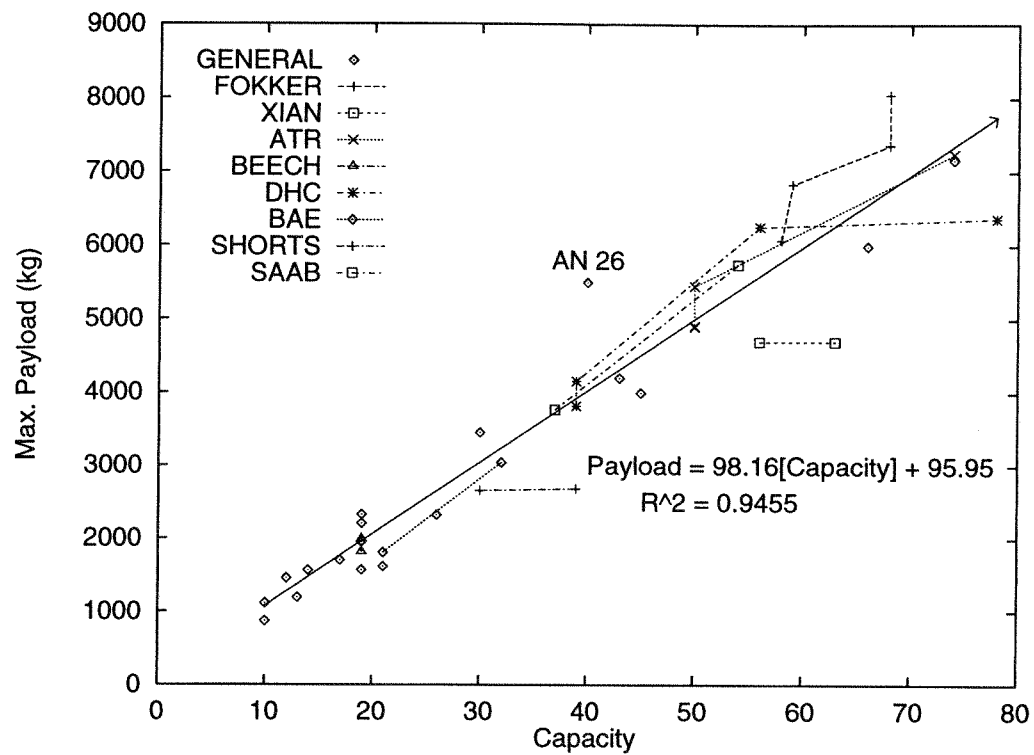


Figure A.12: Correlation between max. Payload and aircraft capacity

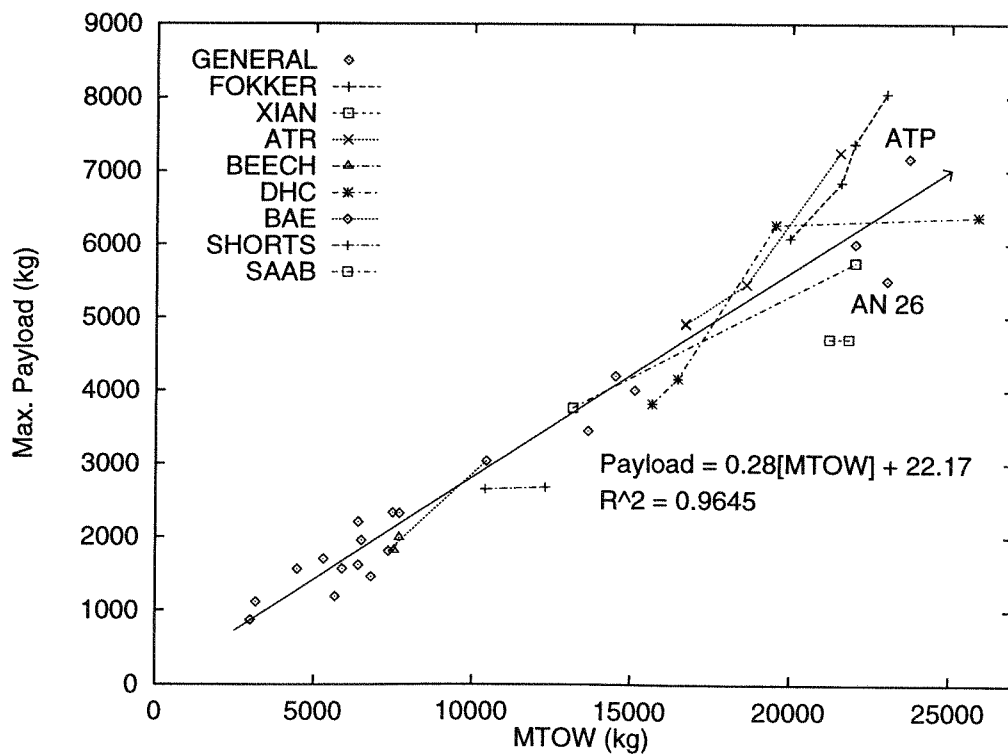


Figure A.13: Correlation of max. Payload with M_{TO}

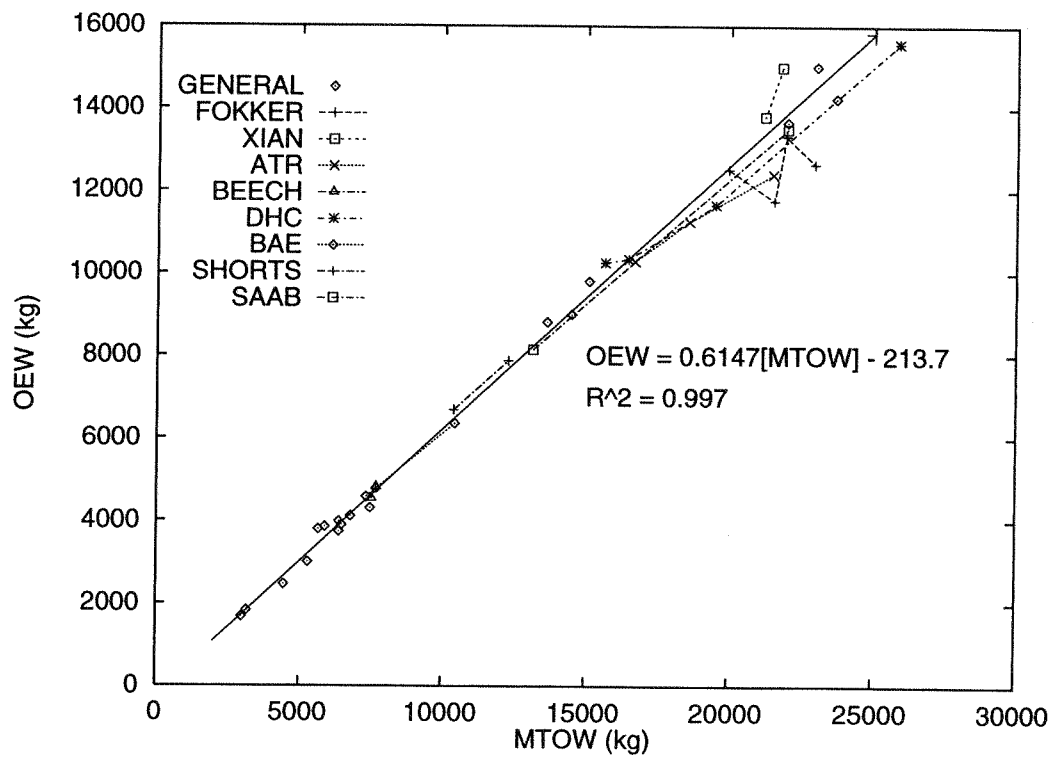


Figure A.14: Correlation between OEM and M_{TO}

Appendix B

Database of regional airports in India

This database was prepared in order to arrive at an idea of the kind of equipment and facilities currently available at regional airports in India. While there is no clear-cut definition of what is meant by a regional airport, it is generally assumed that such airports are suitable for operation of short-haul civil transport aircraft, with passenger capacity up to about 75 seats. The upper limit on the runway requirement of such aircraft operating under hot-and-high conditions (ISA + 20 deg. C and 5000 ft) appears to be 6000 ft¹.

Details of 30 airports in India with runway length ≤ 6000 ft were obtained from [107] & [108], as shown in Table B.1. Military airports with civil enclaves were not included in this database, because they usually have facilities far in excess of the minimum required for operation of civil aircraft. These airports could be classified under three categories based on the runway length (almost in line with ICAO system). The only thing common to all these airports is that they have only one runway (except Agartala), a Control Tower (TWR) & Non-Directional Beacon (NDB) installation, and they are open only for the duration during which flights are scheduled or other operational requirements exist. Further, certain similarities can be seen in the airports of a specific type, which are outlined below :-

- Runway length below 4000 ft (1220 m)

There are eight airports in this category, all of which have the runway constructed of Tarmac or Asphalt (except Kota) with LCN between 10 to 14. Most of these airports seem to have been designed for the operation of small commuter aircraft such as Dornier Do-228-212, except Shimla, which is sized for

¹This can be surmised by a study of the runway requirements of the largest of such aircraft currently available in the market (ATR-72-210 & JS-61).

the operation of Avro HS-748. None of these (except Cooch Behar) have any provision for selling fuel. They don't seem to be suitable for bad weather/night use, since they don't have any lighting or Aerodrome Beacon. No information is available regarding the category of fire protection service available at these airports, except at Kailashahar which is listed to have an ICAO Cat-3 service.

- Runway length between 4000 ft & 5000 ft (1220 m & 1524 m)

There are six airports in this category, most of which have the runway constructed of Tarmac (except Tirupati), with LCNs ranging from 14 to 16. Most of these airports have a runway of 4500 ft and seem to be designed to enable operation of commuters such as Fokker F-27 and Avro HS-748 or for short-haul turboprops such as Boeing 737 series aircraft. None of them are reported to have any facility to provide fuel, nor any runway lighting. Only Porbandar & Tirupati have an aerodrome beacon. Two of these airports are listed as having fire protection service of ICAO Cat-4 and two others with ICAO Cat-5.

- Runway length between 5000 ft & 6000 ft (1524 m & 1830 m)

There are 16 airports in this category; with various types of runway, and LCN varying between 10 to 40. These airports are designed with the operation of short-haul turboprop aircraft in mind (e.g. Boeing 737-200 and Airbus A320), and represent the top-end of the regional airports. Most of these have Emergency Lights, Aerodrome Beacons, Runway Lights and some form of Approach Lighting (usually AVASIS). Nearly half of these airports have a facility for supplying Aviation Turbine fuel (AVTUR), while at one, Aviation Gasoline (AVGAS) is also available. Most of these airports have an aerodrome beacon, while nearly half have an Air to Ground station, some sort of Approach guidance & VOR/DME installations, while ILS/DME is available at two of them. As regards lighting at the aerodrome, most of them seem to have emergency lighting & runway/strip lights. Nearly half of them also seem to have either AVASIS or PAPI systems. The fire protection service varies between ICAO Cat-4, -5 & -6.

[illegible]

Appendix C

Details of Terminal Building sizing & costing

C.1 Introduction

There are some military airports in India from which civil aircraft operations are also conducted. Special civil enclaves are constructed at such airports, as and when the increase in passenger demands merits their need. The budgetary cost breakdown for constructing one such civil enclave designed for 400 passengers (200 arriving & 200 departing) was obtained from the National Airports Authority of India [107]. A methodology was developed to scale down the costs related to this passenger terminal for smaller airports. The specifications & guidelines for sizing and costing a commercial building vary from country to country and depend on various local factors. However, certain basic scaling and apportioning laws remain the same, and can be used almost globally. Guidelines and advice from certified quantity surveyors were obtained on scaling down the facilities and costs.

C.2 Scaling down of costs

The terminal building of this civil enclave had a floor area of approx. 14 m^2 per passenger, which is quite similar to the recommendations for domestic airports in [5] & [56]. Some factors were applied to take into consideration items which cannot directly be scaled down (such as toilets). The costs of various area-related items such as civil works, electrification, fire-fighting, furnishing, and airport signage were scaled down per area. For some items, such as chairs in the lobby, hand dryers,

window AC units, baggage trolleys, and metal detectors, the number of additional passengers that would justify provision of an additional item was determined. Costs related to PA/CCTV¹ and Baggage conveyers (which are quite costly), were allotted per passenger, while the costs of Intercom Equipment and X-ray baggage scanner were considered constant. The deposit payable to the Electric Company was seen to be 9.4% of cost of total electrification costs, hence the same factor was used for all airports.

To scale down the costs related to construction of residential accommodation the airport, it was assumed that each room in the transit hostel consists of one unit, and a Type-II house consists of 2 rooms (units), with a progressive increase of one unit as the Type rating increased from Type-II to Type-IV. Number of houses of each type required (thus units) would decrease progressively as the airport size reduced (in terms of the passenger terminal capacity). The costs related to civil works and electrification of residential quarters were calculated per unit, based on data available, and then apportioned accordingly.

The PA/CCTV and Baggage conveyers were not provided in Level-1 airport, though adequate space was provisioned in the terminal building for their installation at a later date. The length to width ratio of the terminal building was assumed to be 4:1. Furthermore, the terminal building was assumed to grow along its length (by addition of blocks of 50 Pax terminal). The control tower was assumed to be a part of the passenger terminal building, for which 50 sq. meter additional area is provided. The cost of constructing an approach road was assumed to be the same for all airports.

The above methodology was used to estimate costs of terminal building for 50, 100, 150, 200 & 250 passengers. The details of this exercise are shown in Table C.1. It was found that terminal building costs T_{cost} (in million Indian Rupees) vary approx. linearly with number of passengers N_{pax} as per the formula $T_{cost} = 5.23423 + 0.33544 \cdot N_{pax}$

¹Public Address & Centrally Controlled Television.

Terminal Building Cost Breakdown

All cost terms in 10⁵ Indian Rupees

Passengers in Terminal	400	-	-	50	-	100	-	150	-	200	-	250	-
Total Floor Area (sq m)	5675	-	-	709	-	1419	-	2128	-	2838	-	3549	-
ITEMS APPORTIONED PER UNIT AREA													
Head	Qty	Cost	per sqm	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Terminal Building:-													
Civil Works	-	51.93	1178.27	-	6.49	-	12.98	-	19.48	-	25.97	-	32.46
Internal electrification	-	6.69	1178.27	-	0.84	-	1.67	-	2.51	-	3.34	-	4.18
Fire Fighting	-	1.70	299.15	-	0.21	-	0.42	-	0.64	-	0.85	-	1.06
External Development	-	19.29	3399.19	-	2.41	-	4.82	-	7.23	-	9.65	-	12.06
Air Conditioning	-	2.70	474.89	-	0.34	-	0.67	-	1.01	-	1.35	-	1.68
Fire Detection / Alarm System	-	1.10	193.83	-	0.14	-	0.28	-	0.41	-	0.55	-	0.69
Sub-station equipment	-	7.81	1376.21	-	0.98	-	1.95	-	2.93	-	3.91	-	4.88
LT distribution	-	1.89	333.68	-	0.24	-	0.47	-	0.71	-	0.95	-	1.18
Ventilation of Non-AC areas	-	1.43	251.98	-	0.18	-	0.36	-	0.54	-	0.72	-	0.89
Furnishing & Interior decoration	-	2.99	526.84	-	0.37	-	0.75	-	1.12	-	1.49	-	1.87
Airport Signage	-	0.83	145.37	-	0.10	-	0.21	-	0.31	-	0.41	-	0.52
Elect. Sub-Station & Pump Room													
Civil works	-	2.97	523.07	-	0.37	-	0.74	-	1.11	-	1.48	-	1.86
Electrification	-	0.30	52.52	-	0.04	-	0.07	-	0.11	-	0.15	-	0.19
Motor Transport section													
Civil Works	-	0.63	110.70	-	0.08	-	0.16	-	0.24	-	0.31	-	0.39
Electrification	-	0.10	16.80	-	0.01	-	0.02	-	0.04	-	0.05	-	0.06
Canteen for snacks													
Civil works	-	0.35	61.97	-	0.04	-	0.09	-	0.13	-	0.18	-	0.22
Electrification	-	0.04	6.45	-	0.00	-	0.01	-	0.01	-	0.02	-	0.02
Type IV Quarters (3 BR + K)	2	0.00	-	1	-	1	-	1	-	1	-	2	-
Type III Quarters (2 BR + K)	6	0.00	-	1	-	2	-	3	-	3	-	4	-
Type II Quarters (1 BR + K)	6	0.00	-	1	-	2	-	3	-	3	-	4	-
Transit Rooms	10	0.00	-	2	-	3	-	3	-	5	-	7	-
Civil works	48	8.31	0.17	11	1.91	17	2.94	22	3.81	24	4.16	35	6.06
Internal Electrification	48	0.55	0.01	11	0.13	17	0.20	22	0.25	24	0.28	35	0.40

continued on next page

All cost terms in 10^5 Indian Rupees

Passengers in Terminal	400	-	-	50	-	100	-	150	-	200	-	250	-
Total Floor Area (sq m)	5675	-	-	709	-	1419	-	2128	-	2838	-	3549	-
ITEMS APPORTIONED PER GROUP OF PASSENGERS													
Head	Qty	Cost	per sqm	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Window A/C Units, VIP room	6	0.23	67	1	0.04	2	0.06	3	0.09	3	0.12	4	0.14
Water Coolers	4	0.13	100	1	0.03	1	0.03	2	0.07	2	0.07	3	0.10
Hand Driers (in toilets)	10	0.08	40	2	0.02	3	0.02	4	0.03	5	0.04	7	0.06
Lounge Chairs	400	0.88	1	50	0.11	100	0.22	150	0.33	200	0.44	250	0.55
Baggage Trolleys	150	0.17	3	19	0.02	38	0.04	57	0.06	75	0.08	94	0.10
Metal Detectors	6	0.06	67	1	0.01	2	0.02	3	0.03	3	0.03	4	0.04
ITEMS APPORTIONED PER UNIT													
Head	Qty	Cost	per unit	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
PA/CCTV system	8	2.75	0.34	1	0.34	2	0.69	3	4.13	4	2.75	5	1.72
Baggage Conveyors	8	2.49	0.31	1	0.31	2	0.62	3	3.73	4	2.49	5	1.55
FIXED ITEMS													
Head	Qty	Cost	-	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Intercom Equipment	-	0.28	-	-	0.28	-	0.28	-	0.28	-	0.28	-	0.28
X-Ray Baggage Scanner	-	3.00	-	-	3.00	-	3.00	-	3.00	-	3.00	-	3.00
MISCELLANEOUS													
Deposit to Electricity Company		1.64	-	-	0.21	-	0.42	-	0.62	-	0.82	-	1.03
Sub-Total	-	123.29	-	-	19.24	-	34.22	-	54.94	-	65.90	-	79.24
Contingencies (3% of sub-total)		3.70	-	-	0.58	-	1.03	-	1.65	-	1.98	-	2.38
Total		126.99	-	-	19.82	-	35.25	-	56.59	-	67.88	-	81.62
Project management @ 7%	-	8.47	-	-	1.13	-	2.19	-	3.66	-	4.43	-	5.36
GRAND TOTAL	-	135.46	-	-	20.95	-	37.43	-	60.25	-	72.31	-	86.98

Table C.1: Terminal Building Cost breakdown [107]

Appendix D

Regional airlines operations in India

D.1 Introduction

This Appendix provides a brief overview of the regional and commuter airline operations in India. The government policies currently in force and their effect on the short-haul operations are examined. The details of a model that was developed for predicting domestic air-travel demand between a hub & a spoke city in India are also presented.

At present, there are 5 international airports, 82 domestic airports and 28 civil enclaves at defence airports in India. Nearly half the airports have no commercial operations at the moment. The domestic air-travel demand in India in 1994-95 (excluding the domestic travel from 5 international airports) was approx. 7.8 million passengers from 54 airports [9]. Even though only about 1% of the total population of India currently travels by air, the demand for domestic air travel has been steadily growing in the last two decades by 10%. This demand is predicted to grow annually by almost 11%, due to the steadily increasing GDP which is predicted to outstrip that of any other country in the Asia/Pacific region over the next 10 years [8], [142].

D.2 Partial de-regulation of the domestic market

In keeping with the general policy of economic liberalisation, the domestic air-travel segment was partially de-regulated by the Indian government in March 1994. This has resulted in the creation of 8 privately operated scheduled airlines, and 25 air-

taxi operators, with many more such projects in the pipeline [9]. These airlines mainly operate on the well established and profitable trunk routes connecting the four major metropolitan cities (Mumbai¹, New Delhi, Calcutta & Chennai²) with each other and three other major cities viz. Hyderabad, Bangalore & Ahmedabad.

D.2.1 Categorisation of the domestic routes

To ensure that the newly setup privately owned airlines do not restrict their operation to the commercially attractive (but already saturated) trunk routes, certain restrictions were imposed on their route structure in 1994. The domestic routes were split under three categories. All the trunk routes mentioned above were classified as Cat-I routes. Cat-II covers the “social” routes, including destinations in the north-east, Jammu & Kashmir, Andaman & Nicobar islands, and Lakshadweep. All the remaining routes were classified under Cat-III. Each scheduled operator flying on Cat-I routes has to deploy an additional minimum of 10% of that capacity (measured in ASK³) on Cat-II routes. Moreover, 10% of the capacity deployed on Cat-II routes has to be operated within those regions with some of the least economic fares. Further, at least 50% of the ASKs flown on Cat I routes have to be additionally deployed on Cat-II routes [143]. The rationale for these restrictions seems to ensure that the airlines fulfill the social obligations of providing the benefits of air-travel to certain remotely located and politically sensitive areas, apart from operating on the established routes. Many of these airlines have acquired turboprop commuter and regional transport aircraft to operate profitably on the Cat-II & III routes. As a result of this categorisation, competitive services are now being provided on 36 routes as compared to about 20 routes in 1993/94, without significant increase in the total aircraft capacity with the private operators [144].

D.2.2 The importance of Cat-III operations

Under the present regulations, the growth potential of the airlines are strongly linked to profitable operations under the Cat-III routes, some of which might be virgin territories, thus offering large market shares to airlines operating in them. These routes are not as densely operated as the trunk (Cat-I) routes, and airlines are establishing their own niche markets. Though they are not as profitable as the Cat-I routes, they are better than the Cat-II routes. Further, Cat-I routes are already suffering with over-capacity, and the entry of other operators in the market is only going to worsen the situation. In a recent study it was shown that all Cat-II routes

¹formerly known as *Bombay*.

²formerly known as *Madras*.

³Available Seat-Kilometers.

flown by a particular airline were loss-making with break-even load factors averaging above 90%. However, all the Cat-I and Cat-III routes were profitable, with average break-even load-factors of 39.4% and 56%, respectively [142].

To avoid excess over-capacity on the trunk routes, and to ensure a regulated growth, the de-regulation policy was further modified in August 1994. According to the new policy, no new entrants were permitted to enter the field and limited import of larger aircraft were permitted on a case-to-case basis by the existing airlines [145]. This policy change also indicates that the government is keen to encourage short-haul operations, since no restrictions have been imposed on the acquisition of feeder (commuter) aircraft of 30 seater category. An indication of the potential of these feeder routes is that 12 out of the 17 air-taxi operators in the country applied and were granted permission exclusively for smaller aircraft suitable for feeder roles [146]. Additional capacity is also being created on Cat-III routes, since the national domestic carrier Indian Airlines is progressively withdrawing operation of Boeing 737 aircraft on short-haul routes, due to their economic non-viability. Some of the new airlines operative exclusively or mainly on Cat-III routes, with turboprop commuter & regional aircraft e.g. NEPC Airlines with Fokker F-27, Archana Airways with LET L-410 & Dash 8-200, Jagson Airlines with Do-228-201 & Do-328-110 & Raj Air with Do-328-110 [8]. Sahara India Airlines is also considering 30-70 seater aircraft such as Jetstream 41 & ATR72-210, although no firm decision on these types have been made so far.

D.3 Model for predicting air-travel demand

Most major cities in India already have an airport in their vicinity. With improvements in India's economy, industrial growth is spilling over to non-metro towns, creating a demand for quick and efficient travel. Given the conditions of road and rail travel, foreign businessmen and tourists opt for air-travel. Even for the Indian businessmen based in industrial and commercial centres, the savings in time and comfort make the higher fare worthwhile [146].

The potential for air-traffic at these new industrial and commercial centres (such as Solapur & Rourkela) may be high enough to justify setting up new regional airports, or to construct civil enclaves at existing military airports (such as Nashik). Most of the traffic on these routes is expected to be from these new locations (spokes) to the nearest metropolitan cities (hubs), though some inter-spoke traffic cannot be ruled out. The stage lengths are expected to be below 750 KM on all these routes. To keep the infrastructure related costs (related to setting up new airports, or to operate from existing airports) as well as the airline operating costs to the barest minimum levels, the operation of small capacity (15 to 70 seat) turboprop aircraft

would be most economical on these routes.

D.3.1 Description of the model

A demand-prediction model was developed to predict the likely demand for air-travel between a hub and any other spoke in its vicinity. The demand for air travel was assumed to be directly influenced by two main variables viz. population of the city to be linked, and its distance from the nearest metropolitan city. 5 slack variables were also considered which represent increase in travel demand due to :

1. Poor connectivity by rail and / or road, or remote location of the city
2. Business & Commercial activities
3. Tourism & Pilgrimage
4. Political, Government, or Administration related
5. High income levels of the local population

This technique is similar to the demand forecasting technique used by IATA which seeks to explain traffic growth using demand generators such as population demographics, disposable income aggregates, tourist movements and business trends appropriate to a given region. An analysis of the data related to annual number of passengers handled at major domestic airports in India between 1991 to 1995 [142] revealed no particular trends. This is because many of these airports suffered partial or total closure during this period as the airline operations were suspended. Many of these airports were served by the national regional airline *Vayudoot* which was merged with Indian Airlines in 1993. Further, the introduction of privately managed air-taxi operators and scheduled airlines has lead to resumption of operations from a few of these airports in recent years. Hence, it was decided to base this model on the published traffic data for 1994-95 between 50 cities and the 4 metropolitan cities [107]. The data related to Bangalore, Hyderabad & Ahmedabad was not included in this model, since a large proportion of the traffic from these cities is likely to be on inter-spoke routes. For the remaining 47 cities, the distance by rail / road from nearest metropolis was obtained from travel guides & maps. Further, appropriate values were empirically assigned to the 5 slack variables for each city, based on the personal knowledge and information provided in travel guides [147]. The population of literate people above 6 years of age in these cities was obtained from the 1991 population census data [148]; it was felt that this sub-set of the population was likely to lead to a better co-relation for air-travel demand, rather than using

the total population. For each city, the population figures were scaled up to the probable population in 1995 assuming annual increase of 2.3%.

The following regression equation was obtained using the statistical package **SPSS** for this set of data.

$$D = 0.0015P \cdot \frac{L^{0.3}}{350} \cdot (1 + C)^{3.0} \cdot (1 + B)^{1.21} \cdot (1 + T)^{1.19} \cdot (1 + I)^{1.15} \cdot (1 + G)^{1.05} \quad (D.1)$$

Where

- D = Annual demand for travel
- P = Population of literate people above 6 years old in the city
- L = Distance from nearest metropolis by rail / road (KM)
- C = slack variable for poor connectivity
(0 = well connected, 3 = poorly connected)
- B = slack variable for Business Potential
(0 = none, 2 = some, 3 = high)
- T = slack variable for Tourism / Pilgrimage
(0 = none, 2 = some, 3 = high, 4-6 very high)
- I = slack variable for Income of local population
(0 = low, 2 = medium 3 = high)
- G = slack variable for Govt./Admin./Political travel
(0 = none, 2 = some, 3 = high)

Table D.1 lists the data that was used for the regression analysis, and the % error between actual and estimated traffic. The predicted demand compared fairly well (within 15 %) with the actual demand for most cities, as can be seen in Table D.1. However, for 6 cities (viz. Kanpur, Allahabad, Udaipur, Belgaum, Pantnagar & Gaya), there was a large mismatch. Figure D.1 provides a graphical comparison of the actual and calculated demand for the 47 cities listed in Table D.1. Figure D.2 shows a map of India, indicating the various cities listed in Table D.1, and how they form a network with the four metropolitan hubs.

No	City	Nearest Metropolis	actual traffic	6+ Lit. Pop. 1995	Dist km	C	T	B	P	I	Calc. traffic	% diff
1	Guwahati	Calcutta	408337	452035	1151	2	1	1	2	0	437702	6.71
2	Goa	Mumbai	323042	87618	582	2	6	0	2	1	302812	-6.68
3	Cochin	Chennai	316718	1037119	669	1	1	1	0	2	294892	-7.40
4	Calicut	Chennai	280720	708652	709	1	0	2	1	2	303921	7.63
5	Mangalore	Chennai	234494	351847	717	1	1	2	1	1	213216	-9.98
6	Agartala	Calcutta	232870	136101	1808	3	0	1	3	0	212071	-9.81
7	Coimbatore	Chennai	199796	851664	511	0	2	3	1	2	216665	7.79
8	Jaipur	N. Delhi	199744	963658	261	0	3	1	2	2	186739	-6.96
9	Vadodra	Mumbai	182871	870839	425	0	2	3	1	2	209627	12.76
10	Pune	Mumbai	166777	1880651	200	0	1	2	1	2	157357	-5.99
11	Nagpur	Mumbai	156217	1270362	750	0	1	2	2	1	149301	-4.63
12	Jammu	N. Delhi	154986	142379	727	1	3	1	4	0	138830	-11.64
13	Udaipur	N. Delhi	144889	223865	635	0	6	2	1	2	112575	-28.70
14	Lucknow	N. Delhi	133107	1101880	569	0	1	2	3	1	161239	17.45
15	Patna	Calcutta	117149	771987	595	1	0	1	3	0	107730	-8.74
16	Imphal	Calcutta	115994	158704	1730	3	1	0	1	0	116241	0.21
17	B'neshwar	Calcutta	104622	315285	480	1	1	1	1	1	103709	-0.88
18	Indore	N. Delhi	103183	781927	870	0	2	2	1	1	101693	-1.47
19	Silchar	Calcutta	99434	91800	1530	2	1	1	2	0	96814	-2.71
20	Aurangabad	Mumbai	87044	401659	388	1	5	0	1	0	86806	-0.27
21	Vizag	Chennai	82132	718069	800	0	1	2	2	1	86042	4.54
22	Rajkot	Mumbai	65954	482210	742	1	0	2	0	1	62497	-5.53
23	Agra	N. Delhi	63182	517280	204	0	7	2	1	0	61314	-3.05
24	Bhavnagar	Mumbai	62475	279516	671	1	2	1	1	0	72192	13.46
25	Dibrugarh	Calcutta	59602	87970	1596	2	2	0	2	0	65801	9.42
26	Bhopal	N. Delhi	58311	698448	741	0	1	1	2	1	50075	-16.45
27	Madurai	Chennai	56923	858247	450	0	1	2	1	1	56532	-0.69
28	Trichy	Chennai	53057	570737	330	0	2	2	1	1	55496	4.39
29	Porbandar	Mumbai	31340	113223	929	2	1	1	0	0	32437	3.38
30	Jamnagar	Mumbai	31291	259395	830	2	0	0	1	0	28184	-11.02
31	Bhuj	Mumbai	28182	86066	1082	1	2	0	1	1	25301	-11.39
32	Shimla	N. Delhi	13967	92852	368	1	2	0	2	0	13251	-5.40
33	Tirupati	Chennai	13869	140210	143	0	3	1	1	2	14819	6.41
34	Ludhiana	N. Delhi	12092	688492	350	0	0	1	1	1	11286	-7.14
35	Belgaum	Mumbai	11803	304719	350	1	0	1	1	0	17515	32.61
36	Gwalior	N. Delhi	11174	467275	319	0	2	1	1	0	12069	7.42
37	Nanded	Mumbai	10764	200351	650	1	0	0	0	2	10700	-0.59
38	Jamshedpur	Calcutta	9583	597614	560	0	0	2	1	0	8075	-18.67
39	Keshod	Mumbai	9415	124943	885	1	1	0	0	1	10309	8.67
40	Kandla	Mumbai	8943	54761	900	1	1	1	1	0	9534	6.20
41	Aggati	Chennai	8121	16428	2500	2	2	0	1	0	9185	11.58
42	Rajmundary	Chennai	4712	255023	850	0	0	1	1	1	5455	13.63
43	Kanpur	N. Delhi	3170	1374918	440	0	0	0	0	0	2209	-43.51
44	Pantnagar	N. Delhi	1344	43809	250	1	2	0	0	0	1757	23.49
45	Jabalpur	N. Delhi	1032	568475	750	0	0	0	0	0	1072	3.71
46	Allahabad	N. Delhi	604	582594	492	0	0	0	0	0	968	37.60
47	Gaya	Calcutta	446	195072	421	0	0	0	0	0	309	-44.21

Table D.1: Domestic travel statistics for 47 Indian cities in 1994-5 [107]

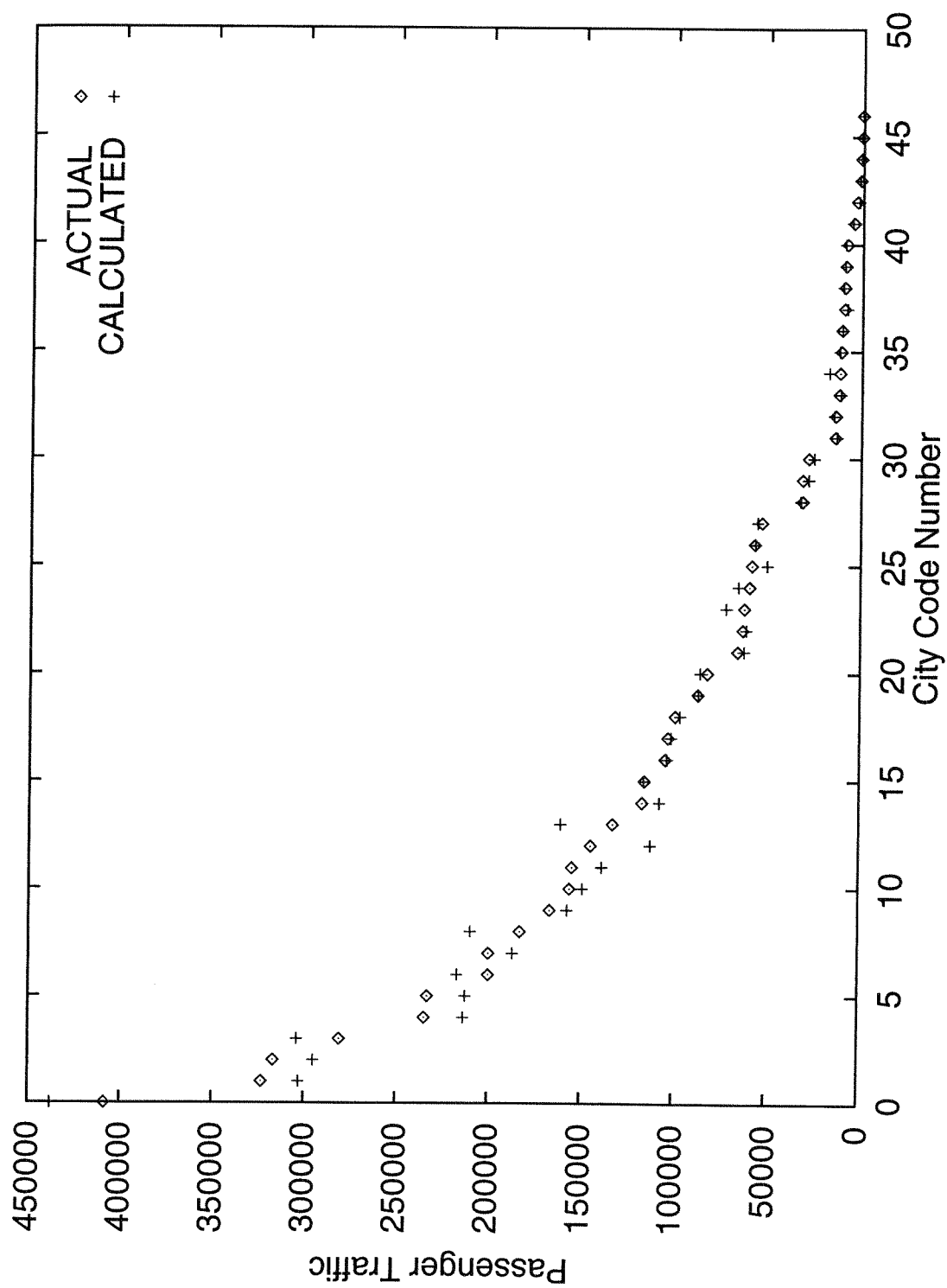


Figure D.1: Actual & calculated domestic air-travel demand for 47 cities in India

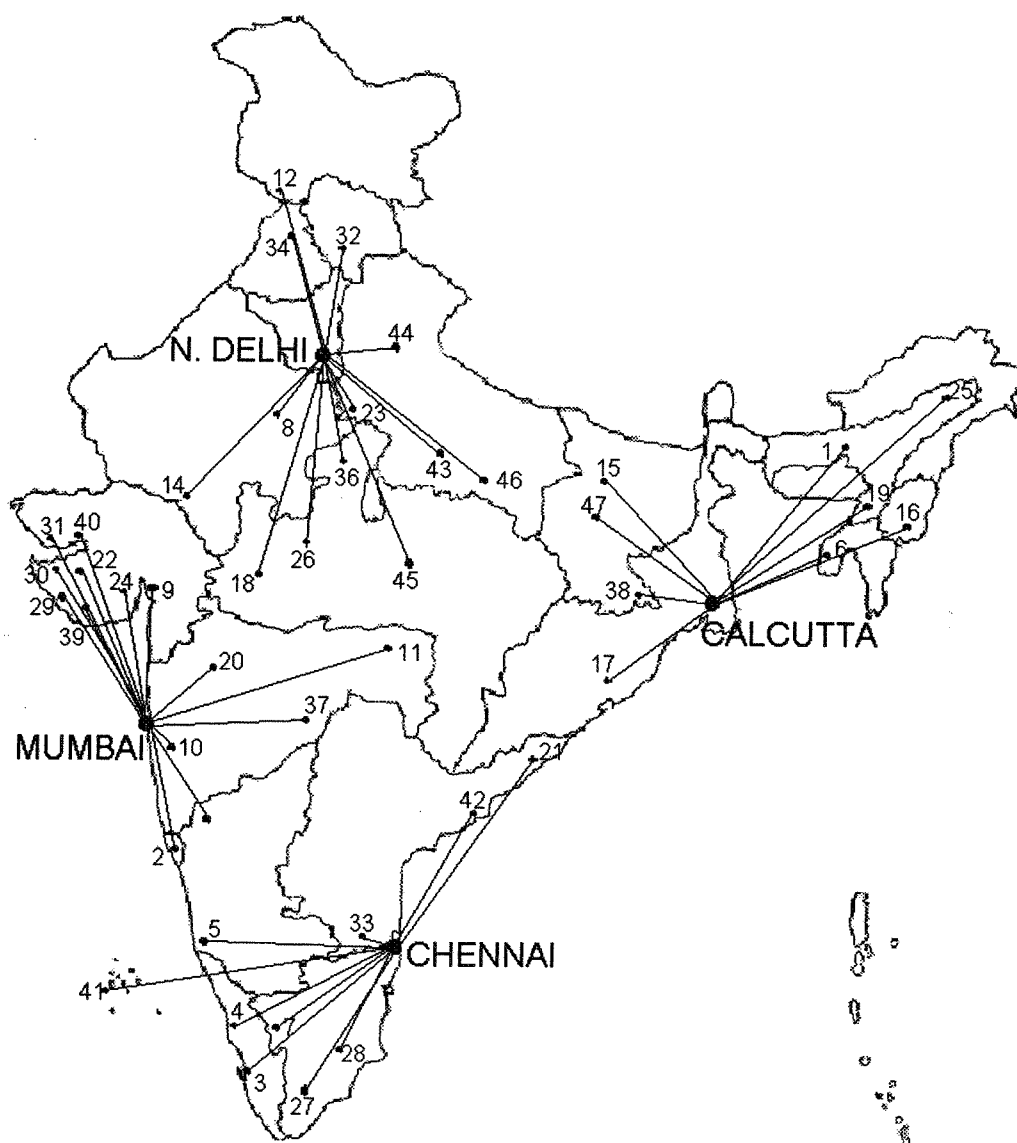


Figure D.2: The 47 cities and 4 metropolitan hubs of Table D.1

Appendix E

Component mass estimation module

E.1 Introduction

Much effort has been put in the past by various researchers to arrive at estimates of aircraft component mass breakdown. In the earlier days, most of these formulae were purely statistical in nature (and sometimes lead to surprisingly good correlations), and errors of the order of 20% are not uncommon, as reported in [149]. But their chief criticism is that they do not provide indications of parameter sensitivities to predicted masses. Many attempts have also been made to co-relate component masses with the most significant design parameters of the aircraft. These empirical formulae are reported widely in aircraft design literature such as [12], [13], [14], [96], & [150]. Many attempts have also been made to estimate component masses as a function of strength & stiffness considerations, augmented by experimental results & statistical data [151]. With the steady growth in computational methods such as FEM, more and more automation was built into the prediction of component masses, but they require a very detailed amount of information as input, rendering them unsuitable for conceptual design work. Sophisticated formulae based on previous experience and in-house data are commonly used by the aircraft manufacturers, but they are not available in open literature.

Over the past four decades, mass prediction methods have continually evolved in the College of Aeronautics, most of which is in the form of unpublished lecture notes & supplements [152]. A few of them have been formally published in the late fifties [97], and also quite recently [123]. These methods provide quite comprehensive information and formulae for various types of aircraft and were considered a good starting point for the present work. An attempt was made to validate them

with whatever data and information related to present day commuter & regional aircraft could be obtained. Some of these formulae were suitably modified based on correlation with aircraft component mass data obtained from manufacturers & other sources, as discussed in Appendix A.

E.2 Estimation of manufacturer's empty aircraft mass

For the purpose of estimation of the manufacturer's empty mass (M_{empty}), the aircraft can be broken down into the following major components:

- Wing
- Fuselage
- Power-plant
- Empennage
- Nacelle
- Landing Gear
- Systems & Equipment
- Furnishings

The empirical, semi-empirical & statistical formulae for mass estimation of the above components listed in [12], [47] & [152] were critically reviewed, and the component masses estimated by them were compared with available data. New correlation formulae were obtained, for some components, when large discrepancies were seen to exist, as described below.

E.2.1 Wing mass

Of all the aircraft components, the wing has received the largest attention by various researchers for generating formulae for mass estimation. Not only is the wing one of the heaviest component (roughly 12% of the total empty mass), but also it is the one that is most amenable to optimisation. It has a well defined structural role and it's mass is affected by many parameters. Two approaches are usually adopted

while developing these formulae. The first is to develop empirical relations that aim to predict mass as a function of the main geometric & operational parameters and co-related to actual values. The other is to develop detailed formulae for estimation of various sub-components of the wing (wing box, high lift devices, ribs and hard points) have been developed based on strength & volume considerations. While both such methods are quoted in literature e.g.[123] & [149], the former are more useful for conceptual design.

The following formula from [123] was used in the present work.

$$M_{wing} = c_1 \left[AR_w^{0.5} S_w^{1.5} \sec \phi_e \left(\frac{1 + 2\lambda}{3 + 3\lambda} \right) \frac{M_{TO}}{S_w} \bar{N}_{ult}^{0.3} \left(\frac{V_D}{\tau} \right)^{0.5} \right]^{0.9} \quad (E.1)$$

where

- c_1 = Coefficient for Aircraft type
= $0.0012 - 0.013 M_{TO} \cot 10^{-6}$ for twin-engined turboprop transport a/c
- M_{TO} = Design Take-off mass (kg)
- S_w = Wing area (m^2)
- AR_w = Wing aspect ratio
- ϕ_e = Effective Sweep of wing
- λ = Wing taper ratio
- $\bar{N}_{ult}$ = Equivalent ultimate design factor, as described below.
- V_D = Design diving speed (m/s)
- τ = Equivalent centerline thickness/chord ratio

In Equation E.1, ϕ_e is equal to the wing quarter chord sweep ϕ_0 , unless it differs a great deal from the wing structural sweep angle ϕ_s , in which case $\sec \phi_e = (\sec \phi_0 \cdot \sec \phi_s)^{0.5}$. $\bar{N}_{ult}$ is the greatest of that resulting from a design manoeuvre from an initially trimmed condition ($\bar{N}_m$) and that when the trimmed aircraft encounters a discrete gust ($\bar{N}_g$). An ultimate factor of 1.5 is usually applied to this value. Expressions for $\bar{N}_m$ & $\bar{N}_g$ have been derived in [123] as:-

$$\begin{aligned} \bar{N}_g &= 1.65 + \frac{6.45 V_D S_w}{M_{TO} (2/AR_w + \sec \phi_e)} \\ \bar{N}_m &= 1.5 (n_1 + 0.1), \text{ where} \end{aligned}$$

$$n_1 = \begin{cases} 3.8 & \text{if } M_{TO} \leq 1882 \text{ kg} \\ 2.1 + \frac{10900}{4530 + M_{TO}} & \text{if } 1882 \leq M_{TO} \leq 22720 \\ 2.5 & \text{if } M_{TO} \geq 22720 \text{ kg} \end{cases}$$

E.2.2 Fuselage mass

Fuselage mass prediction is fraught with difficulties since its structure & layout is influenced by many and varied layout & design considerations, all of which cannot easily be incorporated in a generic formula. The only option is then to use relatively simple empirical formulae or semi-empirical relationships which are applicable to a broad class of aeroplanes. For un-pressurised aircraft, the fuselage mass has been found to be closely related to its external surface area (also called *wetted* area) and the design diving speed. For pressurised aircraft, the fuselage mass is also affected by the limit cabin differential pressure. The following formulae from [153] were used for fuselage mass estimation:

Un-pressurised Fuselage

$$M_{fus} = c_2 k_s [L(B + H) V_D^{0.5}]^{1.5} \quad (E.2)$$

Pressurised Fuselage

$$M_{fus} = \frac{(\delta p)_{lim}}{f_s} S_{F_{wet}} [9.75 + 5.84B] \quad (E.3)$$

where

- c_2 = coefficient for Aircraft type
= 0.034 for twin-engined turboprop transport aircraft
- k_s = Cross sectional shape factor
 $k_s = 1.0$ for circular or elliptical cross-section
 $k_f = 1.4$ for fully rectangular cross-section
- L = Fuselage Length (m)
- B = Maximum breadth of fuselage (m)
- H = Maximum height of fuselage (m)
- V_D = Design diving speed (m/s)
- $(\delta p)_{lim}$ = limit cabin differential pressure (bar)
- f_s = ratio of allowable working stress to 100 MN/m²
= 0.9(Typical value)
- $S_{F_{wet}}$ = Fuselage wetted area (m²)

For reasonably regular streamlined fuselages, $S_{F_{wet}}$ can be estimated as :-

$$S_{F_{wet}} = k_f (B+H)^2 \left[\frac{2L}{(B+H)} - (f_n + f_t) + 0.325 (4f_n^2 + 1)^{0.5} + 0.322 (4f_t^2 + 1)^{0.5} \right] \quad (E.4)$$

where

$$\begin{aligned}
k_f &= \text{Cross section shape factor} \\
&\quad k_f = 0.785 \text{ for circular/elliptical cross sections} \\
&\quad k_f = 1.000 \text{ for fully rectangular cross sections} \\
f_n &= \text{Front Fuselage (nose) fineness ratio} \\
f_t &= \text{Rear Fuselage (tail) fineness ratio}
\end{aligned}$$

f_n & f_t can be obtained by dividing their length up to parallel section (or point of maximum depth) with average fuselage diameter i.e. $(B+H)/2$.

E.2.3 Power-plant mass

The power-plant mass consists the mass of dry engines, propellers, and assemblies related to engine installation. Formulae that co-relate the engine dry mass with Take-off SHP abound in literature, for e.g. [13], [12], [154], but none of these have been validated for the power-plants used on present day twin-turboprop aircraft. Data related to the dry-mass of modern engines was obtained from [155]. A correlation between the quoted dry-mass and the max. Take-off SHP was obtained as :

$$M_{eng} = 0.2812 \cdot [SHP_{TO}]^{0.9529} \quad (\text{E.5})$$

This correlation is shown in Table E.1. The power-series regression line represented by Equation E.5 co-relates well with the quoted data, as can be seen in Figure E.1. The propeller mass was estimated using the following correlation formula with Max. Take-off power from [154]:

$$M_{prop} = 0.0634 \cdot [n_{eng} SHP_{TO}] \quad (\text{E.6})$$

To take into consideration the mass of power-plant installation structure (including the engine mountings), a factor of 1.7 was applied to the total engine dry mass, which includes the mass of the propeller as suggested in [154]. Thus, the propulsion system group mass was estimated as

$$M_{prgr} = 1.7 \cdot n_{eng} [M_{eng} - M_{prop}] \quad (\text{E.7})$$

E.2.4 Empennage mass

Though empennage mass is typically only about 2% of M_{TO} , it strongly affects the c.g. location due to its extreme location. Accurate estimation of empennage mass

Maker	Model	Variant	Max.TO Power	Quoted Dry-mass	Co-related Dry-mass
Units			SHP	Kg	Kg
Allison	GMA2100	A	3740	702	714
Garrett	TPE 331	5-252D	776	164	160
		5-252D	760	164	156
		10R-511C	900	173	184
		10U-531C	925	173	188
		11	1100	182	222
		12UAR	1020	176	207
		14GR/HR	1500	257	299
	TPF 351	20	1300	341	261
GEAE	CT7	5A2	1735	350	343
		9B	1750	361	346
Isotov	TV7	117	2368	520	462
Mototlet		M601E	750	194	154
P&W	PT6A	27	620	143	129
		34	750	145	154
		65B	1100	219	222
		50	1120	276	226
		45R	1198	198	241
		67D	1280	230	257
		65AR	1424	221	284
		67R	1424	234	284
		PW118	1800	391	356
		PW119	1815	419	358
		PW120	1800	419	356
		PW121	1950	425	384
		PW124	2160	482	423
		PW123	2380	451	464
		PW125B	2500	482	486
		PW126A	2653	482	515
		PW127	2750	482	533
RR	DART	MK 542	3060	569	590

Table E.1: Correlation between Engine dry-mass & Max. Take-off SHP

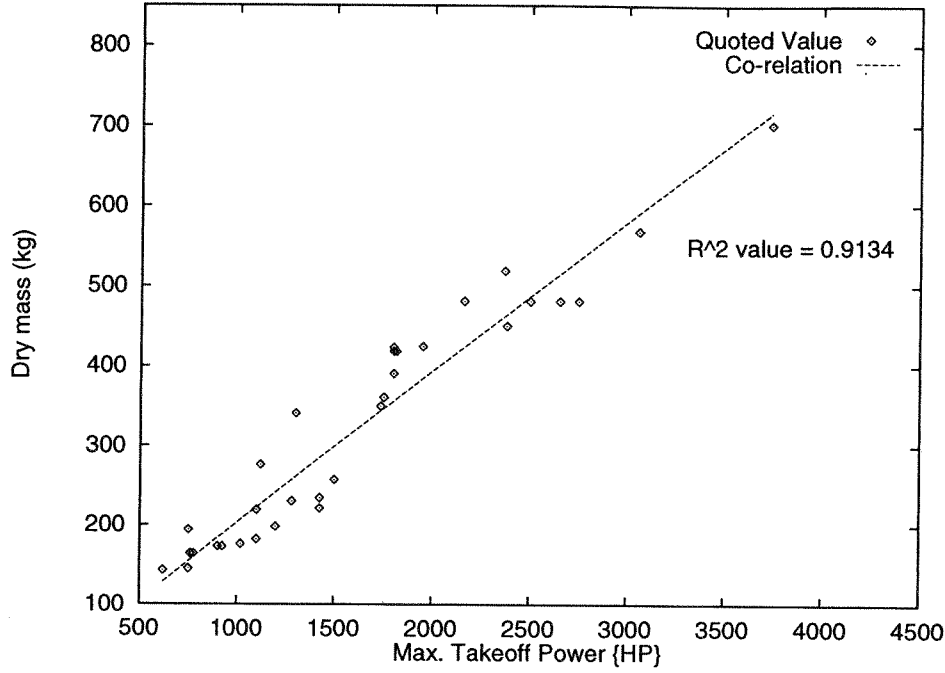


Figure E.1: Correlation between Engine drymass & Max. Take-off SHP

is possible only after the design loads and structural layout are decided. Empirical relationships between empennage mass, V_D , and the total area of the vertical & horizontal tail surfaces have been listed in [14] & [153]. The following formula based on the empirical relationships from [153] was used.

$$M_{emp} = c_3 V_D S_{emp}^{1.2} \quad (E.8)$$

where

$$\begin{aligned} c_3 &= \text{Coefficient for Empennage type} \\ &= 0.039 \text{ for conventional Tail} \\ &= 0.0727 \text{ for T-Tail} \\ S_{emp} &= \text{Total area of vertical \& horizontal tail surfaces} \end{aligned}$$

E.2.5 Nacelle mass

Assuming a wing mounted nacelle as a fixed fairing, its mass can be considered proportional to its surface or *wetted* area S_{wet} . The following empirical formula for

calculation of $S_{n_{wet}}$ was used [14] assuming it to be a streamline shaped body.

$$S_{n_{wet}} = \pi d_{nac} l_{nac} \left(0.5 + \frac{\bar{l}_{nac}}{l_{nac}} \right)^{0.667} \cdot \left(1.015 + \frac{0.3}{\left(\frac{l_{nac}}{d_{nac}} \right)^{1.5}} \right) \quad (E.9)$$

where

$$\begin{aligned} d_{nac} &= \text{Max. nacelle diameter (m)} \\ l_{nac} &= \text{Nacelle length (m)} \\ \bar{l}_{nac} &= \text{Location of nacelle max. diameter from nose (m)} \end{aligned}$$

The following formula for nacelle mass was used, as suggested in [153]:

$$M_{nac} = 10.0 \cdot S_{n_{wet}} \quad (E.10)$$

E.2.6 Landing Gear mass

The mass of a typical Landing gear is reported to be between 3–6% of M_{TO} , and is a function of layout, location, length of struts and the rough field capability & flotation characteristics desired [111]. In general, wing mounted landing gears are found to be heavier than fuselage mounted ones, mainly due to larger strut lengths. High flotation capability also adds substantially to the landing gear mass. Two empirical formulae for landing gear mass estimation are given in [111]. These formulae are suitable for conceptual design of a specific aircraft, since they use use factors for strut length, rough field capability, flotation characteristics and the year of manufacture. But they do not provide substantially more accurate prediction than simple empirical formulae for a general class of aircraft. Hence, the following formula from [153] was considered quite adequate:

$$M_{lg} = c_4 \cdot M_{TO} \quad (E.11)$$

where

$$\begin{aligned} c_4 &= \text{Wing location factor} \\ &= 0.035 \text{ for fuselage mounted undercarriages} \\ &= 0.045 \text{ for wing mounted undercarriages} \end{aligned}$$

E.2.7 Systems & Equipment mass

Correlation of information on the various systems of an aircraft e.g. flight control system, hydraulic system, pneumatic system, electric system etc. is very difficult,

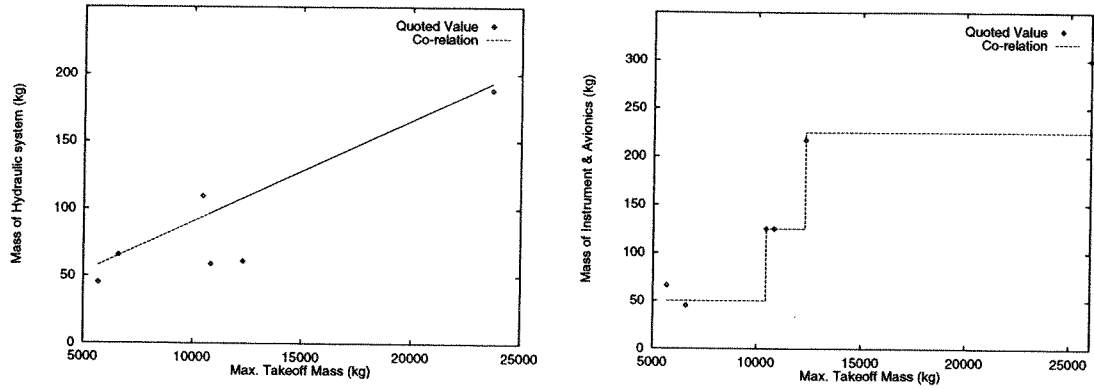


Figure E.2: Actual and calculated mass of Hydraulic system and Avionics. & formulae

unless detailed information is available. The term *Equipment* includes mechanical instruments, avionics, communication & navigation equipment, safety & fire protection & external paint. Mass of these equipment & system-wise mass breakdown of a few turboprop commuter & regional aircraft were obtained from manufacturers & other sources, and were checked against the empirical formulae listed in [154]. New correlation formulae for some systems for this class of aircraft were developed, since the empirical formulae showed a huge mismatch. These formulae are listed in Table E.2. Figure E.2 shows the correlation between the actual mass and the

System	Formula	Type
Surface Controls	$0.13 \cdot M_{TO}^{0.75}$	empirical
Hydraulic System	$0.0075 \cdot M_{TO} + 15.639$	co-related
Fuel System	$0.05 \cdot M_{TO}^{0.80}$	empirical
Electrical System	$0.75 \cdot M_{TO}^{0.67}$	empirical
A/C & Press. System	$5.0 \cdot N_{pax}$	empirical
De-icing System	$0.0092 \cdot M_{TO} - 45.0$	co-related
Electrical System	$0.75 \cdot M_{TO}^{0.67}$	empirical
Fire Protection System	$0.002 \cdot M_{TO}$	empirical
External Paint	$1.0 \cdot S_w$	co-related
Instruments & Avionics	$= 125$ if $N_{pax} \leq 19$ 200 if $19 < N_{pax} \leq 30$ 300 if $30 < N_{pax} \leq 45$ 350 if $45 < N_{pax} \leq 65$ 400 if $N_{pax} > 65$	co-related

Table E.2: Formulae for system mass estimation

derived formulae for hydraulic systems and avionic equipment of a few aircraft.

E.2.8 Mass of Furnishings

Furnishings include the mass of passenger & crew seats, cabin decor, sound-proofing, partitions, galleys, wardrobes, & toilets, if installed. Depending on what is considered as a basic fit by the manufacturer, and what is left as an option for the airline to install, there is a considerable spread in the mass of furnishings installed on commuter & regional aircraft. Empirical formulae that relate furnishing mass to M_{TO} or passenger capacity have been suggested in [12], [152] and other similar sources, but they were not found to be accurate for this class of aircraft. Detailed mass breakdown of furnishings was obtained from manufacturers ([114], [116], [121]) and other sources ([122] & [156]). Good correlation of total furnishing mass with M_{TO} (with Coefficient of determination $R^2 = 0.91$) and N_{pax} (with Coefficient of determination $R^2 = 0.92$) was observed, and the following formula was developed using the correlation with N_{pax} :

$$M_{furn} = 34.55N_{pax} - 359.28 \quad (E.12)$$

The manufacturer's empty mass M_{empty} can thus be estimated as

$$M_{empty} = M_{wing} + M_{fus} + M_{prgr} + M_{emp} + M_{nac} + M_{lg} + M_{sys} + M_{furn} \quad (E.13)$$

E.3 Operating Empty mass

The aircraft operating empty mass (M_{opsemp}) is the mass of the aircraft with all operational items installed, but without the fuel, cargo, passengers and the associated baggage. It can be considered as the summation of the manufacturer's empty mass, mass of crew (and associated baggage), and the mass of catering items, toilet fluids & trapped oil & fuel.

$$M_{opsemp} = M_{empty} + M_{crew} + M_{fluids} \quad (E.14)$$

Twin-turboprop commuter & regional aircraft usually have two crew members in the cockpit, and one cabin attendant for every 35 passengers. Mass of each crew member (including baggage) of 100 kg & mass of each cabin attendant of 80 kg (including baggage) was assumed, based on the data provided in [114], [116], [121], & [156]. M_{fluids} was assumed to be 50 kg for all aircraft, in the absence of any uniform guideline.

E.4 Max. Take-off mass

M_{TO} is the summation of M_{opsemp} , mass of payload (M_{pay}) & mass of fuel (M_{fuel}). Based on [114] & [122], a payload of 93.0 kg per passenger (77 kg + 16 kg baggage)

was assumed. To allow for the installation of optional equipment in the cabin & to take into consideration any cargo that may be carried apart from the passengers, a mass of 18 kg per passenger was added to the payload, hence:

$$M_{pay} = 111 \cdot N_{pax} \quad (\text{E.15})$$

It may be noted that all the correlation formulae for component masses were obtained using the data related to turboprop commuter & regional aircraft between 15 to 70 seat capacity, and hence are strictly applicable to only these types of aircraft.

Appendix F

Acquisition and operating cost estimation module

The aim of this module is to estimate the *TOC* i.e. the Total Operating Cost per trip of the aircraft in terms of the important design variables and the dependent variables used in the study. *TOC* is the sum of Direct Operating Cost *DOC* associated with the operation of the aircraft and the Indirect Operating Cost *IOC* associated with the running of the airline and providing the service. The module consists of the following two sub-modules, which are described below in detail:

- Aircraft acquisition cost (C_{acq}) estimation sub-module
- *DOC* estimation sub-module

F.1 Acquisition cost estimation sub-module

F.1.1 Introduction

In conceptual design of civil (& military) aircraft, estimation of C_{acq} is largely based on statistical methods. In most of these methods, cost data for a number of aircraft are curve-fitted to develop *Cost Estimating Relationships* (CERs) for the principal cost elements. Several aircraft manufacturers have developed their own CERs based on costs incurred during previous in-house design & manufacture and the experience gained during projects. But these methods are not usually available in open literature, and even if they are, they are difficult to generalise.

Various methodologies for estimation of C_{acq} in conceptual aircraft design are available in textbooks e.g. [2], [13] & [96], in institutional reports and theses e.g. [33], [44], or in conference papers e.g. [157]. Many of these are based on the CERs developed by The Rand Corporation in early seventies [158] which are constantly being updated (e.g. [159]). Based on a critical evaluation of these methods from the point of view of application in the present study, it was decided to adopt the method presented in [2], with some modifications and simplifications, which are explained below.

One of the strong features of this cost estimation method is that it uses many co-relations for mass & cost terms based on data related to actual (and fairly recent) aircraft, so it is possible to update & correct these estimates as and when relevant data becomes available. Further, the method is fairly easy to implement, and can be used to evaluate the effect of some important design variables (such as M_{TO} , V_{max} , SHP_{TO}) on C_{acq} . An attempt was made to make the method fairly generic, so that the appropriate cost escalation factors and man-hour rates for various activities related to manufacture of the aircraft could be applied.

The two major components of C_{acq} are the RDT&E costs (C_{rdte}) and the Production cost (C_{prodn}). C_{rdte} is the cost related to the Research, Design, Test & Evaluation of the airplane. All the costs incurred during the initial feasibility study, conceptual design, preliminary design, system integration and detailed design & development phases of a project fall under this category. In this sub-module, the man-hours required for RDT&E and production by the Engineering, Tooling, Manufacturing & Quality-Control group are estimated in terms of certain aircraft and production related parameters. These are then multiplied by appropriate hourly rates to yield costs. CERs for Development Support, Flight-test, and Manufacturing Material costs are also provided.

F.1.2 Estimation of RDT&E costs

C_{rdte} can be further broken down into 7 components, and formulae for their estimation are provided in [2]. These formulae are based on the CERs suggested in [158] & [159], and are explained below.

1. Airframe Engineering & Design cost (C_{aed_r})

C_{aed_r} is the product of the total engineering man-hours required to complete the three phases of aircraft design that RDT&E covers (MHR_{aed_r}), and the associated man-hour rate (R_{e_r}). Most of the engineering hours in a project are primarily expended in the RDT&E phase, but there is also some engineering effort required throughout the production run. As a ball-park figure cited in [2], the total engineering effort required for a 500 aircraft production run is

about three times that required for a one-aircraft production run. MHR_{aed_r} can be estimated as:

$$MHR_{aed_r} = 0.0396 \cdot (M_{ampr})^{0.791} \cdot (V_{max})^{1.526} \cdot (N_{rdte})^{0.183} \cdot F_{diff} \cdot F_{cad} \quad (F.1)$$

where,

- M_{ampr} = AMPR Mass (lb)
- V_{max} = Maximum level flight speed (knots, EAS)
- N_{rdte} = Number of aircraft produced for the RDT&E phase
- F_{diff} = Judgement factor for *difficulty* or complexity
- F_{cad} = Judgement factor for the effect of CAD on Engineering costs

M_{ampr} ¹ consists of the mass of the un-equipped empty shell of the aircraft produced at the manufacturer's site, and then later equipped with wheels, brakes, engines, starters, cooling fluid, fuel cells, batteries, electrical equipment, power supply, instruments, avionics, APU², trapped fluids & ECS³. R_{e_r} varies from country to country, and depends on the local standard of living, availability of suitable manpower, union contracts etc. In [2], the R_{e_r} prevalent in USA for airframe engineering activity is listed for every two years between 1960 & 1972, and also for 1988 & 1989. In the present study, it was decided to use these data-points for estimation of R_{e_r} ; values for years between 1970 & 1989 were obtained using linear interpolation, and the curves were extrapolated linearly after 1989 (up to 1999), as shown in Figure F.1.

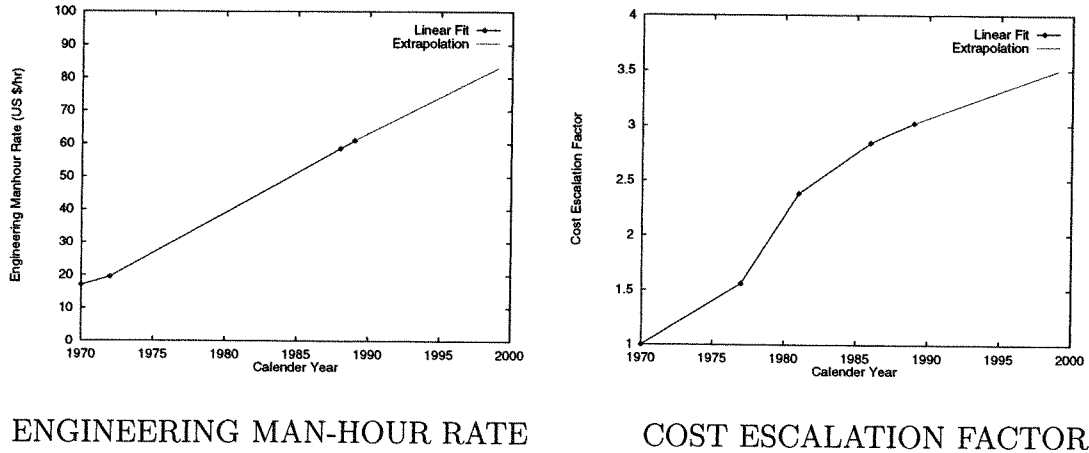


Figure F.1: Determination of R_{e_r} & CEF

¹ Aeronautical Manufacturer's Planning Report.

² Auxiliary Power Unit.

³ Environment Control System.

2. Development support & Testing cost (C_{dst_r})

C_{dst_r} consists of costs associated with all testing and validation activities carried out during the RDT&E phases e.g. wind-tunnel testing, structural tests, system design and simulation, and propulsion related tests. It can be estimated from:

$$C_{dst_r} = 0.008325 \cdot (M_{ampr})^{0.873} \cdot (V_{max})^{1.89} \cdot (N_{rdte})^{0.346} \cdot F_{diff} \cdot CEF_{year} \quad (F.2)$$

In equation F.2, CEF_{year} is the cost escalation factor, which accounts for the escalation of costs with the calendar year, and can be estimated based on suitable economic indices. One of the most widely used index for this purpose is the Consumer Price Index (CPI). Graphical variation of the CPI for USA from 1965 to 1989 is provided in [2], with 1970 year as a baseline ($CPI = 1$). In the present study, this graph was approximated by a series of five lines between 1970 & 1989, and linearly extrapolated up to 1999, as shown in Figure F.1. The CEF_{year} for any year could then be obtained by linear interpolation. Costs can thus be scaled from the year X to the year Y using the following formula:

$$Cost_Y = Cost_X \frac{CEF_Y}{CEF_X} \quad (F.3)$$

3. Flight Test Aircraft cost (C_{ftar})

This is the cost of manufacturing the prototype aircraft that are subjected to various proof & certification tests. It consists of the following 6 major components :

3(i) Manufacturing labour cost (C_{mfg_r})

For estimating the costs related with manufacturing, tooling & quality control, the man-hours required for these activities are estimated and multiplied by the corresponding man-hour rates. The man-hour rates prevalent for manufacturing & tooling for US conditions for every two years between 1960 & 72 and for 1988 & 1989 are given in [2]. Using this data, curves for the man-hour rates applicable for the manufacturing labour (R_{mfg_r}) & Tooling activities (R_{tlgr}) were obtained on the same lines as Figure F.1 for R_{er} .

The man-hours required for manufacturing activities during the RDT&E phase can be estimated from:

$$MHR_{lab_r} = 28.984 \cdot (M_{ampr})^{0.74} \cdot (V_{max})^{0.543} \cdot (N_{rdte})^{0.524} \cdot F_{diff} \quad (F.4)$$

hence:

$$C_{mfg_r} = R_{mfg_r} \cdot MHR_{lab_r} \quad (F.5)$$

3(ii) Tooling cost (C_{tlgr})

On the same lines as MHR_{lab_r} , MHR_{tlgr} can be estimated from:

$$MHR_{tlgr} = 4.0127 \cdot (M_{ampr})^{0.764} \cdot (V_{max})^{0.899} \cdot (N_{rdte})^{0.178} \cdot (R_{rdte})^{0.066} \cdot F_{diff} \quad (F.6)$$

where R_{rdte} = Annual rate of production of prototype aircraft hence:

$$C_{tlgr} = R_{tlgr} \cdot MHR_{tlgr} \quad (F.7)$$

- 3(iii) Quality Control Cost (C_{qc_r})
 C_{qc_r} is assumed to be 13% of C_{mfg_r} , i.e.:

$$C_{qc_r} = 0.13 \cdot C_{mfg_r} \quad (F.8)$$

- 3(iv) Manufacturing Material & Equipment cost (C_{mme_r})
 C_{mme_r} can be estimated as:

$$C_{mme_r} = 37.632 \cdot (M_{ampr})^{0.689} \cdot (V_{max})^{0.624} \cdot (N_{rdte})^{0.792} \cdot (R_{rdte})^{0.066} \cdot F_{mat} \quad (F.9)$$

where F_{mat} = Judgement factor for cost of airframe materials

- 3(v) Power-plant cost (C_{pplant})

Price data for various types of engines is provided in Appendix B of [2], for the base year of 1989. The turboprop engine and propeller price is estimated as a function of the Takeoff Shaft Horsepower per engine at sea-level standard conditions (SHP_{TO}). For $400 \leq SHP_{TO} \leq 5000$, the engine cost is estimated from:

$$\log_{10} C_{eng} = 2.5262 + 0.9465 \cdot \log_{10} SHP_{TO} \quad (F.10)$$

Equation F.10 includes the cost of engine gear-box. For the propeller cost (C_{prop}), separate formulae are provided in [2] for metallic & composite propellers, which are:

$$\log_{10} C_{prop} = P_{coeff} + 1.1432 \cdot \log_{10} SHP_{TO}, \quad (F.11)$$

where,

$$\begin{aligned} P_{coeff} &= \text{Coefficient for propeller type} \\ &= 0.6119 \text{ for metallic propellers} \\ &= 0.7746 \text{ for composite propellers} \end{aligned}$$

C_{eng} & C_{prop} can be scaled to any reference year using Equation F.3. The power-plant cost can thus be estimated using:

$$C_{pplant} = n_{eng} [C_{eng} + C_{prop}] \quad (F.12)$$

- 3(vi) Avionics cost (C_{avion})

A reliable estimate of avionics cost (C_{avion}) can be made if the detailed list of avionic equipment installed on the aircraft is made, and their prices

are obtained from vendors. As a rough guideline listed in [2], C_{avion} can be assumed to be of the order of 10% of the aircraft cost. The avionic fit of the present day commuter & regional aircraft is fast approaching the levels of the avionic fit of the larger jet transport aircraft of the late-eighties. The following equation for estimating commercial jet-transport aircraft price is listed in Appendix A of [2]:

$$\log_{10} C_{airc} = 2.5262 + 0.9465 \cdot \log_{10} M_{TOlb} \quad (F.13)$$

where,

$$\begin{aligned} C_{airc} &= \text{estimated aircraft price (US \$)} \\ M_{TOlb} &= \text{max. Takeoff mass (lb)} \end{aligned}$$

It may be noted that equation F.13 is based on the quoted prices of such aircraft in 1987, corrected to 1989 prices using equation F.3. In the present study, C_{avion} was estimated as 10% of the estimated aircraft price using equation F.13.

4. Test & Simulation facilities cost (C_{tsfr})

Many aircraft programs require construction of special & dedicated test platforms to test various sub-systems or novel concepts used. In the present study, this cost has not been considered, since the aircraft types under consideration have conventional configurations and are assumed to be built using well established technologies.

5. Cost of Flight Test Operations during RDT&E (C_{ftor})

C_{ftor} accounts for the costs incurred during the prototype flight testing phase. It can be estimated as:

$$C_{ftor} = 0.001244 \cdot (M_{ampr})^{1.16} \cdot (V_{max})^{1.371} \cdot (N_{rdte} - N_{stat})^{1.281} \cdot F_{diff} \cdot CEF_{year} \quad (F.14)$$

where N_{stat} = number of prototypes developed for static testing only

6. RDT&E Profit cost (C_{prof_r})

It is desirable to include a profit margin on RDT&E phases, since these activities are likely to spread over many years, and involve substantial amounts of money. This is especially true in the case of RDT&E work carried out by a privately owned enterprise. A factor of 10% has been suggested in [2], which seems quite reasonable. Hence:

$$C_{prof_r} = 0.10 \cdot C_{rdte} \quad (F.15)$$

7. Cost to finance RDT&E phases (C_{fin_r})

To finance the vast amount of money required to finance the RDT&E phases,

interest has to be paid on the invested capital, whether it is generated from in-house funds, or borrowed from the market. Actual interest rates vary from country to country, but 10% can be considered a good ball-park value, as suggested in [2]. Hence:

$$C_{fin_r} = 0.10 \cdot C_{rdte} \quad (F.16)$$

Summing up, C_{rdte} can be estimated from the following formula

$$C_{rdte} = C_{aed_r} + C_{dst_r} + C_{fta_r} + C_{fto_r} + (N_{rdte} - N_{stat}) \cdot (C_{pplant} + C_{avion}) + C_{prof_r} + C_{fin_r} \quad (F.17)$$

F.1.3 Estimation of Production cost

The total production cost related to the manufacture of N_{prod_n} aircraft (C_{prod_n}) consist of the following six components:

1. Airframe Engineering & Design cost (C_{aed_m})

At the end of the RDT&E phase, the aircraft configuration & systems are finalised and frozen, but a considerable amount of engineering effort is still required during the production phase. This could be due to various reasons, for instance to overcome the problems that come to light during the RDT&E phase, to meet special requests from customers, liaison with the vendors, incorporating design changes & overcoming errors made during manufacturing process. C_{aed_m} can be estimated from:

$$C_{aed_m} = [MHR_{aed_{tot}} \cdot R_{e_m}] - C_{aed_r} \quad (F.18)$$

where,

R_{e_m} = Engineering man-hour rate for manufacturing program,
= R_{e_r} from Figure F.1

$MHR_{aed_{tot}}$ = Manufacturing man-hours required for RDT&E & Production
from equation F.1, replacing N_{rdte} with N_{total}

$N_{total} = N_{rdte} + N_{prod_n}$

N_{prod_n} = number of aircraft produced for sale

C_{aed_r} = Airframe Engineering & Design cost for RDT&E phase

2. Airplane production cost (C_{apc_m})

On the same lines as C_{fta_r} , C_{apc_m} consists of components related to the cost of Manufacturing labour, Materials, Tooling, Quality control, Power-plant &

Avionics. These cost terms can be estimated from the same formulae as for C_{fta_r} , but replacing N_{rde} with N_{prodn} . Thus,

$$C_{apc_m} = C_{mfg_m} + C_{tlg_m} + C_{qcm} + C_{mme_m} + N_{prodn} \cdot [C_{pplant} + C_{avion}] \quad (F.19)$$

3. Flight Test Aircraft cost (C_{ftom})

C_{ftom} accounts for the costs incurred in flight testing the production aircraft before delivering to the customer, by the test pilots of the manufacturer as well as the customer pilots. C_{ftom} can be quite high, and hence may not be negligible. In the present study, C_{ftom} was assumed to be US\$ 100,000 per each production aircraft, assuming 10 hours of flight testing at an operating cost of US\$ 2500 per hour with an overhead factor of 4.

4. Cost of aircraft interior & furnishings (C_{furn})

For the production aircraft, an additional cost component towards the cost of interiors and furnishings (C_{furn}) is also to be considered. In the present study, the following formula from [2] was used:

$$C_{furn} = F_{intr} \cdot N_{pax} \cdot \frac{CEF_{year}}{CEF_{1990}} \quad (F.20)$$

where,

$$\begin{aligned} F_{intr} &= \text{Interior cost factor expressed in US\$ per passenger} \\ &= \text{US\$ 1000 per passenger for regional transport aircraft} \end{aligned}$$

5. Cost of financing the manufacturing program (C_{fin_m})

On the same lines as C_{fin_r} , C_{fin_m} was assumed to be 10% of the total production cost C_{prod_n} . item **Profit on manufacturing activities** (C_{prof_m})
Here again, C_{prof_m} was assumed to be 10% of the total production cost C_{prod_n} , just as in the case of C_{prof_r} .

Having estimated the above six components of C_{prod_n} , the airplane program production cost C_{prog} can be estimated using:

$$C_{prog} = C_{apc_m} + N_{prod_n} \cdot C_{furn} \quad (F.21)$$

Hence, C_{prod_n} can be estimated using:

$$C_{prod_n} = 1.2 \cdot (C_{prog} + C_{aed_m} + N_{prod_n} \cdot C_{ftom}) \quad (F.22)$$

F.1.4 Estimation of aircraft acquisition cost

The aircraft acquisition cost (C_{acq}) is the price at which the customers acquire the aircraft from the manufacturers, i.e., the selling price of the aircraft. The actual selling price is usually driven by market forces, such as the marketing strategy being employed by the aircraft manufacturer, the quantity being ordered by a specific customer and the *Standard of Preparation*⁴. After estimating C_{rdte} & C_{prodn} as described above, C_{acq} from purely technical considerations can be estimated from:

$$C_{acq} = \frac{C_{rdte} + C_{prodn}}{N_{prodn}} \quad (F.23)$$

F.1.5 Modifications to cost terms and formulae

While the above formulae come up with reasonable estimates for the various cost terms, in some cases, their values were a bit unrealistic. For instance, in many cases C_{pplant} estimated by equation F.12 seemed to be unrealistically low, of the order of 8% to 15% of the C_{acq} . Going by the industry estimates, a good ball-park value for C_{pplant} is 20% of C_{acq} . Hence it was decided to increase C_{pplant} to 20% of C_{acq} , if the values estimated by F.12 was lower than that.

F.2 Validation of acquisition cost estimation sub-module

As an illustrative example of the application of the cost estimation procedure, C_{rdte} , C_{prodn} & C_{acq} of a hypothetical aircraft *OURANIA* are estimated in [2]. *OURANIA* is a twin-turbofan 150 seater aircraft, and the various cost terms are estimated for a reference year of 1992.

As a test case, the present cost estimation module was applied to *OURANIA* aircraft. The input data for the module is shown in Table F.1, which was taken from [2]. Table F.2 lists the comparison between the calculated values and quoted values of various components of C_{rdte} , C_{prodn} & C_{acq} . A slight difference was observed between the quoted and calculated man-hour rates R_{er} , R_{mr} , & R_{tr} , since these were extrapolated from the available data. However, the difference between the estimated & quoted C_{rdte} , C_{prodn} & C_{acq} values due to this was found to be less than 3%.

⁴The detailed list of various standard and optional items installed on the aircraft by the manufacturer for a specific customer.

Type	Input Parameters				
Aircraft related	$MTOW$	N_{cap}	V_{max}	T_{SLS}	N_{eng}
	56117.5	150	151.76	23813	2
Production related	N_{prodn}	R_{prodn}	Q_{proto}	r_{proto}	Q_{stat}
	500	5	5	0.33	2
Fudge factors	F_{diff}	F_{cad}	F_{mat}	F_{obs}	F_{tsf}
	1.8	0.9	2.3	1.0	0.2
Costing factors	F_{intr}	F_{int}	F_{prof}	I_{year}	I_{ref}
	2000	0.1	0.1	1992	1970

Table F.1: Input data for *OURANIA* aircraft C_{rdte} and C_{prodn} estimation

F.2.1 Acquisition cost of some contemporary twin-turboprop aircraft

The sub-module was then applied to estimate C_{acq} of nine contemporary twin-turboprop regional aircraft, and the values of the various input parameters for these aircraft and the estimated cost terms for the reference year of 1996 are shown in Table F.3. It can be seen that for 5 out of the 9 aircraft listed in Table F.3, the calculated C_{acq} is within $\pm 10\%$ of the values quoted by AVMARK [160] for February 1996. For Dornier Do228-212 & Do328, Dash8-300 & ATR72-210 aircraft, however, the mismatch is much larger. It may be noted that the values quoted by AVMARK are the average selling prices of the respective aircraft, which are market driven, and not the actual manufacturing costs. The market price of the 30 seater DO-328 aircraft is driven by the fact that two other well established and cheaper aircraft of the same class (viz. SAAB 340-B & Embraer EMB-120) are competing with it in the market place. Further, Dash8-300 & ATR72-210 are derivatives of well-established existing aircraft, and hence their C_{acq} estimated by this sub-module are bound to show large differences with the prevailing market prices.

The estimated C_{acq} is also strongly affected by the values of the various input parameters listed in Table F.3; these were assigned based on published information about the aircraft or by judgement. Wherever no clearcut information was available, same values were assumed for all the aircraft, for e.g. for all aircraft except Do228-212, V_{max} at sealevel was assumed to be 250 KEAS (129 m/s). Q_{proto} was assumed to be 2 for all derivative aircraft, and 3 for others.

The above results also show that C_{acq} for small commuter aircraft such as Do-228-212 is grossly over-estimated by this module. If these high values were used in the *DOC* formulae described in the next section, then the entire cost estimation would come up with unrealistic numbers. It was decided to impose an upper limit of US \$ 200,000 per passenger on C_{acq} for all aircraft, going by industry estimates

ESTIMATION OF C_{rdte}			
AMPR Mass	M_{ampr}	39436.8	39437.0
Engineering man-hours required	MHR_{aed_r}	2.185	
Engineering man-hour rate	R_{e_r}	67.6	63.64
Airframe Engineering & Design cost	C_{aed_r}	147.708	139.046
Development, Support & Testing cost	C_{dst_r}	40.201	38.819
Manufacturing man-hours required	MHR_{mfg_r}	6.696	
Manufacturing labour man-hour rate	R_{mfg_r}	34.9	35.35
Manufacturing labour cost	C_{mfg_r}	233.673	236.68
Tooling man-hours required	MHR_{tlg_r}	4.820	
Tooling man-hour rate	R_{tlg_r}	46.7	44.2
Tooling cost	C_{tlg_r}	225.072	213.015
Quality control cost	C_{qc_r}	30.377	30.765
Manufacturing Material & Eqpt. cost	C_{mme_r}	50.718	48.975
Avionics cost per prototype	C_{avion}	2.763	
Power-plant cost per prototype	C_{pplant}	1.614	
Flight test operations cost	C_{fto_r}	15.319	14.791
TOTAL RDT&E COST	C_{rdte}	1268.402	1232.43

ESTIMATION OF C_{prodn} & C_{acq}			
Engineering man-hours required	$MHR_{aed_{prod}}$	2.899	
Airframe Engineering & Design cost	$C_{aed_{prod}}$	196.004	184.51
Flight test operations cost	$C_{fta_{prod}}$	50.000	50.000
Tooling man-hours required	$MHR_{tlg_{prod}}$	8.293	
Tooling cost	$C_{tlg_{prod}}$	387.279	366.533
Manufacturing man-hours required	$MHR_{mfg_{prod}}$	68.475	
Manufacturing labour cost	$C_{mfg_{prod}}$	2389.77	
Quality control cost	$C_{qc_{prod}}$	310.67	314.669
Manufacturing Material & Eqpt. cost	$C_{mme_{prod}}$	1910.751	1845.11
Cost of a/c Interior & Furnishings	C_{intr}	0.312	
TOTAL PRODUCTION COST	C_{prodn}	10261.63	10056
AIRCRAFT ACQUISITION COST	C_{acq}	23.06	22.576

Table F.2: *OURANIA* aircraft C_{rdte} and C_{prodn} estimation

INPUT DATA	UNITS	Do228-212	SAAB340-B	Do328	CN235-100	Dash8-300	ATR42-320	F50-100	ATR72-210	SAAB-2000
N_{cap}		19	33	30	44		50	50	66	54
M_{TO}	Kg	6400	13155	13640	15100	18897	16700	19990	21500	22000
SH_{PTO}	HP	776	1750	2180	1396	1777	1567	1866	3089	3740
Q_{proto}		2	3	2	3	3	2	2	3	2
F_{diff}		0.8	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.2
F_{cad}		0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
F_{instr}	US\$/pax	500	1000	1000	1000	1000	1000	1000	1000	1000
N_{prodn}		300	400	400	300	400	400	400	400	400
Q_{stat}		0	1	1	1	1	1	0	0	0
V_{max}	m/s	115	129	129	129	129	129	129	129	129
ESTIMATION OF C_{rdte}										
M_{amp}	lb	6036.0	11252.8	11610.6	12677.5	15460.7	13830.7	16156.9	17206.8	17552.2
MHR_{aedr}	10^6 hrs	0.121	0.356	0.305	0.391	0.457	0.466	0.439	0.497	0.563
C_{aedr}	10^6 US\$	9.275	27.161	23.265	29.846	34.920	35.625	33.572	38.004	43.015
C_{dstr}	10^6 US\$	1.607	4.970	4.440	5.516	6.559	6.207	5.924	7.201	7.642
C_{fta}	10^6 US\$	0.338	1.021	0.436	1.970	1.475	1.556	1.553	2.808	2.051
MHR_{tlgr}	10^6 hrs	0.331	0.796	0.758	0.872	1.014	1.040	0.976	1.101	1.248
C_{tlgr}	10^6 US\$	16.656	40.023	38.137	43.839	51.017	52.310	49.089	55.363	62.755
MHR_{labr}	10^6 hrs	0.394	1.030	0.853	1.125	1.303	1.164	1.089	1.411	1.389
C_{manr}	10^6 US\$	14.236	37.189	30.775	40.619	47.045	42.036	39.300	50.921	50.141
C_{qcr}	10^6 US\$	1.851	4.835	4.001	5.280	6.116	5.465	5.109	6.620	6.518
C_{mme_r}	10^6 US\$	2.653	6.046	5.377	6.563	7.525	5.055	5.626	8.101	5.957
C_{rdte}	10^6 US\$	64.474	162.079	138.614	186.429	207.321	199.073	189.704	233.915	239.115
ESTIMATION OF C_{prodn}										
$MHR_{aedprod}$	10^6 hrs	0.183	0.516	0.499	0.518	0.664	0.764	0.720	0.722	0.923
$C_{aedprod}$	10^6 US\$	13.956	39.428	38.138	39.605	50.691	58.400	55.034	55.169	70.513
$C_{ftaprod}$	10^6 US\$	30.000	40.000	40.000	30.000	40.000	40.000	40.000	40.000	40.000
$MHR_{tlgprod}$	10^6 hrs	0.629	1.463	1.554	1.480	1.865	2.131	2.000	2.023	2.557
$C_{tlgprod}$	10^6 US\$	31.614	73.575	78.158	74.431	93.786	107.204	100.603	101.775	128.610
$MHR_{labprod}$	10^6 hrs	5.072	12.400	12.874	11.507	15.686	17.585	16.441	16.979	20.976
$C_{manprod}$	10^6 US\$	183.085	447.634	484.762	415.408	566.266	634.813	593.507	612.926	757.227
C_{qcp}	10^6 US\$	23.801	58.193	60.419	54.003	73.615	82.526	77.156	79.680	98.439
$C_{mmeprod}$	10^6 US\$	138.459	287.028	333.271	247.270	357.261	332.113	369.660	384.594	391.370
C_{intr}	10^6 US\$	0.011	0.037	0.034	0.049	0.056	0.052	0.056	0.074	0.061
C_{avion}	10^6 US\$	0.520	0.928	0.956	1.037	1.247	1.125	1.300	1.378	1.404
C_{pplant}	10^6 US\$	0.981	1.641	1.752	2.066	2.176	2.191	2.247	2.330	2.601
C_{pgram}	10^6 US\$	1124.510	2565.160	2754.310	2356.950	3353.250	3378.390	3481.180	3623.750	4042.380
C_{prodn}	10^6 US\$	1428.130	3232.270	3461.880	2965.780	4209.270	4249.420	4370.930	4545.350	5075.760
C_{cacalc}	10^6 US\$	4.975	8.486	9.001	10.507	11.042	11.121	11.402	11.948	13.287
$C_{cacquot}$	10^6 US\$	2.850	9.000	7.800	10.400	12.300	11.500	11.600	14.500	12.200
% error	-	74.6	-5.7	15.4	1.0	-10.2	-3.3	-1.7	-17.6	8.9

Table F.3: C_{acq} estimation for nine contemporary twin-turboprop aircraft

and market perceptions.

F.3 *DOC* estimation sub-module

Though various methodologies for estimation of *DOC* of civil aircraft are proposed in literature, there is no general agreement on even what exactly the term *DOC* represents ! For instance, in some methods, only the costs related to the actual flight of the aircraft are considered as a part of *DOC*; the costs related to the ownership of the aircraft are accounted in the *IOC*. The first attempt to generalise *DOC* was the formula proposed by Air Transport Association of America in 1944, which was last updated in 1967 [161]. Since then, many *DOC* estimation procedures have been proposed ; by aircraft manufacturers such as Boeing [162], by researchers such as [33] & [163] and by airline associations such as [164]. Most airlines also have their own methods of calculating & reporting *DOC*.

All these methods are quite similar in breakdown, but differ in detailed assumptions. Their main disadvantage is the lack of suitable definition of detail when attempting to model maintenance & overhaul costs, which in these methods are usually assumed to be functions of a gross parameter such as airframe weight or installed engine thrust. But this shortcoming is acceptable when a comparative evaluation of a series of aircraft is desired, as in the present study. Most of these methods have been developed with medium to large capacity turbofans in mind, and hence were not directly applicable to the low capacity twin-turboprop aircraft.

The sub-module for estimating *DOC* in the present study is based on the AEA method [164], but certain terms have been modified to make them more relevant to the twin-turboprop short-range aircraft. The following aircraft & mission related parameters are required as input to this sub-module:

1. Take-off mass M_{TO} (kg)
2. Max. Take-off Power SHP_{TO} (HP)
3. Propulsion group mass M_{prgr} (kg)
4. Stage length X_{stage} (m)
5. Stage time T_{stage} (sec)
6. Aircraft acquisition cost C_{acq} (US \$)
7. Reference year I_{year}

8. Number of passengers N_{pax}
9. Total mission fuel consumption $M_{fu_{main}}$ (kg)
10. Number of (equi-distant) stages in a mission N_{stage}

DOC is usually broken down into the following components:

1. Standing Charges C_{stand}
2. Crew cost C_{crew}
3. Fuel cost C_{fuel}
4. Maintenance cost C_{maint}
5. Landing Charges C_{land}
6. Navigational Charges C_{nav}
7. Handling Charges C_{handl}

C_{stand} includes the cost of depreciation of the aircraft (C_{depr}), cost of repayment of the interest payable on the capital borrowed to acquire the aircraft (C_{intr}), and the cost of insuring the aircraft hull & passengers (C_{insr}). The various steps involved in the estimation of DOC are explained below:

1. Calculation of Block Time (T_{blk})

Block time is the total elapsed time between *chocks off* (as the aircraft departs from the first airport) and the *chocks on* (as the aircraft reaches the destination). Apart from the time required for the climb, cruise and descent phases, it includes the *manoeuvre allowance* for the time spent in engine starting & taxi-out, take-off, initial acceleration, approach, landing and taxi-in. From the flight performance manuals of contemporary twin-turboprop, an average figure of 9 minutes was chosen for the manoeuvre allowance. Thus, the Block Time (in minutes) was calculated as:

$$T_{blk} = \frac{T_{stage}}{3600} + 0.15 \quad (F.24)$$

2. Calculation of Annual Utilisation (U_{ann}) & Flights per annum (N_{ann})

Annual utilisation depends mainly on the number of routes flown and the frequency offered by the operator, which is itself a function of the demand for travel. To maximise the returns on the investment, the operator would like to

have as high a utilisation as possible, but it is limited by the turn-around time and the scale of operations. Short-range aircraft usually have lower levels of utilisation compared to the long range ones, due to the much higher number of take-off & landings per flight hour. Since DOC is a strong function of U_{ann} , it was decided to use a realistic figure of 3600 for the total hours available for flight operations per annum⁵. Note that this is lower than the figure of 3750 recommended in the AEA method [164], which was considered too high for this class of aircraft. If the total number of flight hours required to meet the demand levels were lower than 3600, it was assumed that the aircraft would be used on other routes or for freight operations during the off-peak hours, to meet this requirement. An average turn-around time of 30 minutes was considered which is appropriate for the kinds of aircraft under consideration. Thus:

$$U_{ann} = T_{blk} \cdot \frac{3600}{T_{blk} + 0.50} \quad \& \quad N_{ann} = \left(\frac{U_{ann}}{T_{blk}} \right) \quad (F.25)$$

3. Calculation of C_{depr}

The cost of equipped aircraft to the operator includes the costs related with procuring and storing adequate amount of spares related to the airframe & the power-plant. Assuming a 80% - 20% split between the airframe & power-plant for spare requirements (as suggested in [164]), the cost of equipped aircraft can be estimated as:

$$C_{ac_{equip}} = C_{acq} \cdot \left[0.80 \cdot (1 + F_{sp_{af}}) + 0.20 \cdot (1 + F_{sp_{pp}}) \right] \quad (F.26)$$

where,

$$F_{sp_{af}} = \text{Airframe Spares cost factor} = 0.15$$

$$F_{sp_{pp}} = \text{Power-plant Spares cost factor} = 0.35$$

C_{depr} can then be calculated based on assumptions regarding the useful life of the aircraft & the residual value at the end of its life as:

$$C_{depr} = C_{ac_{equip}} \cdot \frac{(1 - F_{resval})}{(N_{ann} \cdot F_{life})} \quad (F.27)$$

where,

$$F_{resval} = \text{Aircraft residual value as a fraction of original } C_{ac_{equip}}$$

$$F_{life} = \text{useful operational life of the aircraft (years)}$$

⁵This figure is affected by the time lost due to aircraft not being air-worthy, closure of airport due to bad weather or other reasons, curfews imposed on night-time flights due to noise and community annoyance considerations etc.

4. Calculation of C_{intr}

The average book-value of the aircraft is considered for calculation of C_{intr} , hence:

$$C_{intr} = 0.50 \cdot C_{ac_{equip}} \cdot \frac{F_{inter}}{N_{ann}} \quad (F.28)$$

Where F_{inter} is the annual rate of interest on borrowed capital.

5. Calculation of C_{insur}

$$C_{insur} = C_{ac_{equip}} \cdot \frac{F_{insur}}{N_{ann}} \quad (F.29)$$

Where F_{insur} is the annual rate of insurance for hull & passengers, which is usually around 0.5% for long-range aircraft operated by established airlines. A higher figure of 1.5 % was assumed in the present study, since these short-range aircraft are likely to be used by start-up or small airlines on un-established routes. Hence, C_{stand} can be calculated using:

$$C_{stand} = C_{depr} + C_{intr} + C_{insur} \quad (F.30)$$

6. Calculation of C_{crew}

C_{crew} consists of annual costs related to the salary & allowances of the flight crew & cabin attendants, and the costs associated with their training. One cabin attendant per 35 passengers was assumed, as recommended in [164]. Further, it was assumed that the total annual costs associated with each flight crew were twice the hourly pay-rate, and the costs associated with each cabin attendant were one fifth of the flight crew costs. Hence:

$$C_{crew} = T_{blk} \cdot F_{crew} \cdot (2 + 0.2 \cdot N_{fa}) \quad (F.31)$$

where,

F_{crew} = Hourly pay-rate of flight crew

N_{fa} = Number of cabin attendants in passenger cabin

7. Calculation of C_{maint}

C_{maint} can be broken down under two main constituents, C_{maint_a} related to the airframe (which includes propeller, instruments & avionics) and C_{maint_e} which relates to the power-plant. C_{maint_a} & C_{maint_e} can further be subdivided into costs associated with labour & material, and both these terms have a component per flight hour, per trip and a constant term per annum⁶. For C_{maint_e} , an additional cost term related to the periodic overhaul of the engine is to be considered, which is usually carried out at a manufacturer approved

⁶This term is also called the *maintenance burden* and it takes into consideration the overheads.

organisation. To keep the maintenance costs down, some operators prefer to sub-contract part or whole of the maintenance, especially if the level of flight operations is not large enough to justify setting up a separate maintenance department.

In the present study, it was decided to base these cost terms on the data of a contemporary aircraft, rather than use some outdated or un-reliable coefficients. The detailed breakdown of the various cost terms related to C_{maint_a} & C_{maint_e} for Dash-8-300 aircraft [165] were obtained, since it can be considered as a good representative aircraft for the types under consideration. For estimating C_{maint_a} & C_{maint_e} of any generic aircraft, the relevant cost terms related to this aircraft were scaled with the square root of M_{TO} & SHP_{TO} , respectively. Thus:

$$C_{maint_a} = \sqrt{\frac{M_{airf}}{10124}} \cdot [F_{ampt} + F_{alpt} \cdot F_{mhr} + T_{blk} \cdot (F_{ampfh} + F_{mhr} \cdot F_{alpfh})] \quad (F.32)$$

where,

M_{airf} = Airframe mass of the aircraft (kg)

10124 = Airframe mass of Dash-8-300 (kg)

F_{ampt} = Cost of material for airframe maintenance per trip (US \$)

F_{alpt} = Man-hours per trip for airframe maintenance (hrs)

F_{mhr} = Man-hour rate for airframe maintenance (US \$ /hr)

F_{ampfh} = Cost of material for airframe maintenance per flight hour (US \$)

F_{alpfh} = Man-hours per flight hour for airframe maintenance (hrs)

and,

$$C_{maint_e} = \sqrt{\frac{SHP_{TO}}{2380}} \cdot [F_{empt} + F_{eopt} + F_{elpt} \cdot F_{mhr} + T_{blk} \cdot (F_{empfh} + F_{eopfh} + F_{mhr} \cdot F_{elpfh})] \quad (F.33)$$

where,

SHP_{TO} = Engine Power at Max. Take-off rating (HP)

2380 = Engine Power at Max. Take-off rating for Dash-8-300 (HP)

F_{empt} = Cost of material for engine maintenance per trip (US \$)

F_{elpt} = Man-hours per trip for engine maintenance (hrs)

F_{eopt} = Man-hours per trip for engine overhaul (hrs)

F_{mhr} = Man-hour rate for engine maintenance (US \$ /hr)

- F_{empfh} = Cost of material for engine maintenance per flight hour (US \$)
 F_{eopfh} = Cost of material for engine overhaul per flight hour (US \$)
 F_{elpfh} = Man-hours per flight hour for engine maintenance (hrs)

8. Calculation of C_{land}

The charges levied towards landing fee depend on the policy in force at the airport, and vary from country to country, and sometimes even from airport to airport within a country. In the present study, C_{land} (in Indian Rupees ⁷ was estimated using the following formula, which is applicable for operation of domestic flights within India [166]:

$$C_{land} = \begin{cases} 46 \cdot \frac{M_{TO}}{1000} & \text{If } M_{TO} \leq 10000 \\ 460 + 82 \cdot \left(20 - \frac{M_{TO}}{1000}\right) & \text{If } 10000 \text{ kg} < M_{TO} < 20000 \text{ kg} \\ 1280 + 162 \cdot \left(\frac{M_{TO}}{1000} - 20\right) & \text{If } M_{TO} > 20000 \end{cases} \quad (\text{F.34})$$

9. Calculation of C_{nav}

C_{nav} (in Indian Rupees) was estimated using the following formula applicable for domestic operations in India [166]:

$$C_{nav} = \begin{cases} 6 \cdot \frac{M_{TO}}{1000} & \text{If } M_{TO} \leq 10000 \text{ kg} \\ 60 + 11 \cdot \left(20 - \frac{M_{TO}}{1000}\right) & \text{If } 10000 \text{ kg} < M_{TO} < 20000 \text{ kg} \\ 167 + 21 \cdot \left(\frac{M_{TO}}{1000} - 20\right) & \text{If } M_{TO} > 20000 \text{ kg} \end{cases} \quad (\text{F.35})$$

10. Calculation of C_{handl}

Like C_{land} , C_{handl} is also a function of the local policies in force at the airport. For domestic flight in India, the handling charge is included in C_{nav} , hence it was not considered separately in the present study.

Thus, DOC for one trip can be calculated using:

$$DOC_{trip} = C_{stand} + C_{crew} + C_{fuel} + C_{maint} + C_{land} + C_{nav} + C_{handl} \quad (\text{F.36})$$

A useful *figure of merit* for comparing the aircraft operating cost is the DOC per seat per nautical mile. This is obtained using:

$$DOC_{snm} = \frac{DOC_{trip}}{N_{pax} \cdot X_{stage}} \quad (\text{F.37})$$

DOC_{snm} is usually evaluated in cents per seat per nautical mile, and is frequently quoted in Air-Transport literature.

⁷35 Indian Rupees = 1 US \$.

F.3.1 Estimation of IOC

The IOC (Indirect Operating Cost) of an airline is a function of various non-technical and commercial factors such as the commission paid to sales agents, staffing levels and overhead expenses, kind and extent of service provided, type of catering, and the budget allocated for sales-promotion, advertisement etc. It is therefore very difficult to have a generic methodology for estimation of IOC . Usually, the start-up or “no-frills” airlines have much lower IOC compared to the established ones. It is general practice to consider IOC as a percentage (between 20% to 50%) of DOC . In the present module IOC was included indirectly in TOC by multiplying DOC by a factor F_{IOC} to arrive at an estimate of TOC . Thus:

$$TOC = F_{IOC} \cdot DOC \quad (F.38)$$

F.4 Estimation of DOC of some contemporary twin-turboprop aircraft

As a demonstration of this sub-module, DOC_{trip} and DOC_{snm} for a stage length of 200 nm was estimated for nine contemporary twin-turboprop aircraft. The DOC breakdown of these aircraft is shown in Table F.4. T_{stage} , $M_{fu_{main}}$ & M_{empty} for these aircraft were obtained from the respective performance manuals ([114],[116], [117], [136] & [139]). It may be noted that the AVMARK quoted values from [160] for C_{acq} have been used for the calculation of DOC . It can be seen that the standing charges (C_{stand}) form the largest component of DOC_{trip} for all aircraft except DO-228-212, followed by C_{crew} , C_{fuel} , C_{maint_e} , C_{maint_a} , C_{land} & C_{nav} . Owing to low C_{acq} , C_{stand} for Do228-212 aircraft are quite low, even lower than C_{crew} ! For S-340B & Do-328 aircraft, C_{fuel} & C_{maint_e} are almost equal, but for larger aircraft, C_{maint_e} are higher than C_{fuel} . Though DOC_{trip} for the 19 seater Do228-212 is lower than even C_{stand} for CN235-100 & larger aircraft, it has a much larger DOC_{snm} compared to these aircraft. As expected, the largest aircraft i.e. ATR-72-210 has the lowest value of DOC_{snm} .

AIRCRAFT	Units	Do228-212	S-340B	Do328	CN235-100	Dash8-300	ATR42-320	F50-100	ATR72-210	SAAB-2000
INPUT DATA										
N_{pax}		19	33	30	44	50	46	50	66	52
C_{acq}	10 ⁶ US\$	2.85	9.00	7.80	10.40	12.30	11.50	11.60	12.20	12.20
$SHPTO$	HP	776	1750	2180	1396	1777	1567	1866	3089	3740
M_{TO}	Kg	6400	13155	13640	15100	18897	16700	19990	21500	22000
$M_{fuelmain}$	Kg	278.27	415.00	460.00	500.00	569.00	494.00	566.00	560.00	689.00
M_{empty}	Kg	3258	7810	8480	9000	11338	9885	11459	12040	12965
T_{stage}	mins	70.9	56.0	57.5	66.0	57.0	59.0	57.0	54.0	48.0
DOC CALCULATION										
T_{blk}	mins	79.9	65.0	66.5	75.0	66.0	68.0	66.0	63.0	57.0
U_{ann}		2618	2464	2481	2572	2475	2498	2475	2439	2359
N_{ann}		1965	2274	2238	2057	2250	2204	2250	2322	2483
$C_{ac,eqip}$	10 ⁶ US\$	3.39	10.71	9.28	12.38	14.64	13.69	13.80	14.52	14.52
C_{depr}	US\$	103.56	282.59	248.85	360.99	390.32	372.55	368.11	375.14	350.82
C_{intr}	US\$	86.30	235.49	207.37	300.83	325.27	310.46	306.76	312.62	292.35
C_{insur}	US\$	21.76	59.37	52.28	75.84	82.00	78.27	77.33	78.81	73.70
C_{stand}	US\$	211.61	577.44	508.50	737.66	797.59	761.27	752.20	766.57	716.87
C_{mainta}	US\$	41.01	56.51	58.71	68.93	71.35	67.76	71.52	67.93	65.32
C_{mainte}	US\$	80.49	102.60	116.56	102.59	104.62	100.57	107.21	133.05	135.64
C_{crew}	US\$	292.97	238.33	243.83	300.00	264.00	272.00	264.00	252.00	228.00
C_{fuel}	US\$	69.57	103.75	115.00	125.00	142.25	123.50	141.50	140.00	172.25
C_{land}	US\$	8.41	20.53	21.67	25.09	33.99	28.84	36.55	43.51	45.83
C_{nav}	US\$	1.10	2.71	2.86	3.32	4.51	3.82	4.85	5.67	5.97
DOC_{trip}	US\$	705.15	1101.87	1067.14	1362.59	1418.30	1357.76	1377.82	1408.40	1369.87
DOC_{nm}	c/pax-nm	18.56	16.70	17.79	15.48	14.18	14.76	13.78	10.67	13.17

Table F.4: DOC estimation for nine contemporary twin-turboprop aircraft

Appendix G

Far-field Noise estimation module

A step-by-step procedure for estimation of Far-field noise of propellers is presented in [99]. This empirical procedure was developed by Hamilton Standard division of United Technologies Corporation on the basis of available test data, and its accuracy is acceptable for preliminary design studies. This method was also employed in [47], but the propeller was assumed to be four bladed, hence only the relevant curves were used. In the present module, all the curves provided in [99] were used, to develop a module for estimation of far-field noise of a typical propeller having 2 to 8 blades. Furthermore, the procedures used to approximate some of the curves were also better than those used in [47], as explained later.

The procedure for estimation of far-field noise levels listed in [99] consists of the following 8 steps :

1. Calculation of Rotational Tip Mach Number (RTMN)

$$RTMN = \frac{\pi n D_{prop}}{V_a}, \quad (G.1)$$

where,

$$\begin{aligned} n &= \text{Propeller rotational speed (rps)} \\ D_{prop} &= \text{Propeller diameter (m)} \\ V_a &= \text{Speed of sound (m/s)} \end{aligned}$$

2. Partial noise level based on RTMN & Power input (FL1)

Curves for estimation of FL1 as a function of power input to the propeller are provided, for 6 RTMN values between 0.4 to 0.9. In the present work,

the following formula listed in [47] was used, which was found to be a good approximation of these curves.

$$FL1 = 37.5 \cdot RTMN + 15.75 \cdot \log_{10}(SHP_{To}) + 17.0 \quad (G.2)$$

3. Partial noise level based on blade count & D_{prop} (FL2)

Curves for estimation of FL2 as a function of propeller diameter for 2, 3, 4, 6 & 8 bladed propellers are provided. Curves for 5 & 7 bladed propellers were obtained using linear interpolation, resulting in the following expressions :

$$FL2 = \begin{cases} 16.541 - 20.7448 \cdot \log_{10} D_{prop} & n_{blade} = 2 \\ 13.618 - 20.3871 \cdot \log_{10} D_{prop} & n_{blade} = 3 \\ 10.195 - 20.0295 \cdot \log_{10} D_{prop} & n_{blade} = 4 \\ 8.906 - 20.2083 \cdot \log_{10} D_{prop} & n_{blade} = 5 \\ 7.271 - 19.6718 \cdot \log_{10} D_{prop} & n_{blade} = 6 \\ 6.195 - 20.0295 \cdot \log_{10} D_{prop} & n_{blade} = 7 \\ 4.695 - 20.0295 \cdot \log_{10} D_{prop} & n_{blade} = 8 \end{cases} \quad (G.3)$$

4. Partial level due to atmospheric absorption & spherical spreading (FL3)

Sound pressure level falls off roughly by 6 dB for every doubling of the distance between the source & the observer. A curve to estimate FL3 is provided, which was approximated by the following expression :

$$FL3 = 44.42 - 20.5 \cdot \log_{10} L \quad (G.4)$$

where L is the distance of the source from the propeller centre (m).

5. Correction for the directivity pattern (DI)

The noise level is dependent on the azimuth angle θ_{azim} between the source and the observer, where $\theta_{azim} = 0$ on the propeller axis in the forward direction. A curve for estimating the directivity index (DI) for θ_{azim} between 20 deg. & 160 deg. is given; the values for DI at every 20 degree interval were read from this curve, and the values at any intermediate θ_{azim} were obtained using linear interpolation.

6. Correction for number of propellers (NC)

A correction NC to the overall sound pressure level is to be applied, based on the number of propellers n_{prop} as follows :

$$NC = \begin{cases} 0 & n_{prop} = 1 \\ 3 & n_{prop} = 2 \\ 6 & n_{prop} = 4 \end{cases} \quad (G.5)$$

7. Perceived Noise Level Adjustment (*PNLA*)

Curves for *PNLA* as a function of propeller diameter for various Helical Tip Mach Number (HTMN) are listed for 2,3,4,6 & 8 bladed propellers. In [47], the curves for 4 bladed propeller only were approximated using Chebyshev polynomial fit. The fits so obtained was quite good, except at low and high propeller diameters, at which the *PNLA* values decreased and increased asymptotically for all HTMN values. This could lead to numerical instability and errors in some cases, especially when the module is coupled to an optimiser. An inspection of the nature of all these curves revealed that they could be approximated without much loss in accuracy by a Two-Line fit, with a change in slope at a propeller diameter of 15 ft (4.57 m). As an example, Figure G.1 compares the Chebyshev Polynomial fit for *PNLA* for the 4 bladed propeller that was used in [47] with the Two-line fit used in the present work. The curves for the 5 bladed propeller were obtained by linear interpolation between the curves for the 4 bladed & the 6 bladed propeller. Further, the curves for the 6 & 8 bladed propeller were assumed to apply for the 7 bladed propeller also, in the absence of any detailed data. The Two-Line fits for *PNLA* were obtained for all such curves listed in [99].

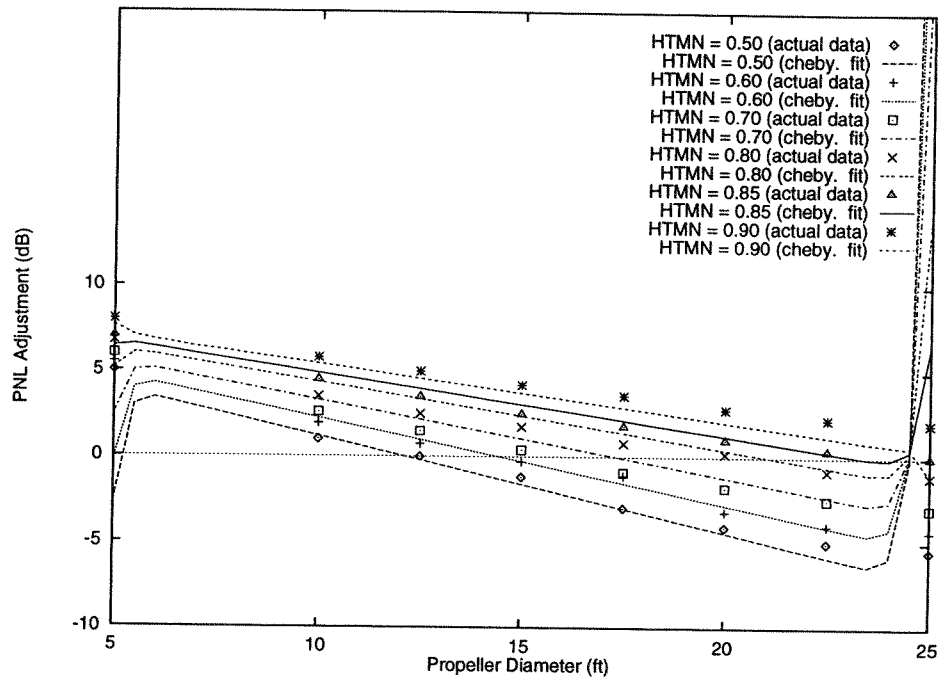
Thus, the Total Far-field Noise Level (*TFNL*) can be calculated as :-

$$TFNL = FL1 + FL2 + FL3 + DI + NC \quad (G.6)$$

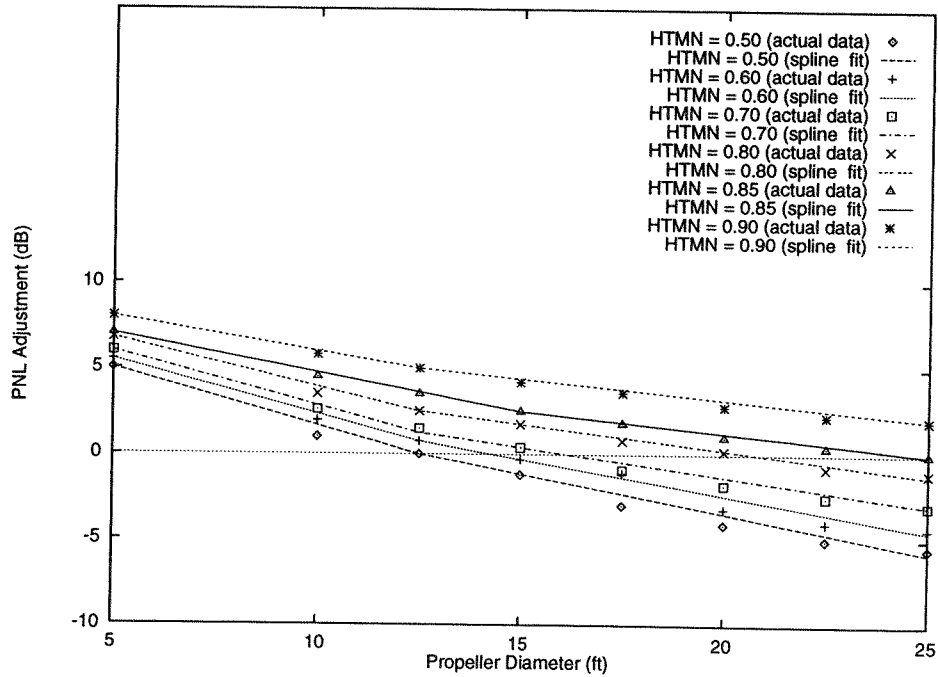
Finally, to estimate the *EPNdB* value during take-off, 4 is subtracted from *TFNL*, i.e. $EPNdB = TFNL - 4$.

Using the above procedure, the *EPNdB* at any far-field location from an n bladed propeller can be calculated, where $2 \leq n \leq 8$.

PNLA Curves for 4 Bladed Propeller



CHEBYSHEV POLYNOMIAL FIT



TWO-LINE FIT

Figure G.1: Comparison of Chebyshev & Two-Line fit for PNLA curves

Appendix H

Description of CASTOR & CRAGER codes

H.1 Introduction

This appendix provides brief description of the computer code CASTOR (Commuter Aircraft Synthesis & Trajectory Optimisation Routine) developed by Simos & Jenkinson at Loughborough University [47], and its modified version CRAGER (Commuter & Regional Aircraft Generalised-cost Estimation Routine) developed by the author, as discussed in Chapter 9. Both these codes are in FORTRAN, and have the same basic architecture; their versions¹ discussed below are applicable to twin-engined turboprop aircraft of conventional configurations. In the description that follows, the differences between CASTOR & CRAGER shall be highlighted, and the modified features and new modules of CRAGER shall be discussed. For ease in understanding, the variables or modules that are used only in CASTOR are labelled as α , while those that are used only in CRAGER (or have been modified) are labelled as γ . The variables and modules common to both the codes are labelled as β .

Both the codes have two distinct components, the Analysis and the Optimisation. In CASTOR, the gradient based optimiser RQPMIN optimiser is used, which is replaced by the Simulated Annealing code SIMANN in CRAGER. However, the architecture of both the codes is such that any optimiser can be easily coupled to the analysis part of the code, if the user so desires.

¹Version 1b for CASTOR & Version f for CRAGER

H.2 Classification of parameters

The various parameters used in both these codes can be classified under three different categories as follows :

- **Design Variables**

These are the parameters related to the configuration and flight-profile of the aircraft, whose optimum values are to be determined. The 24 Design Variables in CASTOR & 20 in CRAGER are shown in Table H.1. Upper and lower limits that these parameters can take are supplied as input, which ensure that the various assumptions made within the design synthesis are not violated. These limits could be narrowed down based on previous experience or problem specific knowledge. In CRAGER, a new methodology has been developed to estimate the value of D_{prop} , hence it has been removed from the list of Design Variables. The three Design Variables related to the diversion mission (i.e. the cruise fraction, speed & altitude in the diversion phase) are also removed, since diversion is considered as an additional stage with the same parameters as the main mission. Further, the cruise Mach number (M_{cr}) is optimised in CRAGER rather than cruise speed (V_{cr}) as in CASTOR, to avoid inappropriate combinations of cruise altitude (H_{cr}) & V_{cr} leading to large number of infeasible cases. Finally, BFL is considered as a Design Variable (rather than a Design Constraint as in CASTOR) in CRAGER, since its optimum value for minimum C_{gen} is desired.

- **Design Constraints**

Certain parameters are specified as (equality or inequality) constraints, and a configuration that does not meet these constraints is termed infeasible. Table H.2 lists the 13 Design Constraints that have to be specified in CASTOR. The first two of these constraints arise from the the air-worthiness regulations which the aircraft have to meet before they can be certified. The next four are either due to the desirable features of the aircraft, or from the point of view of operational limitations under which the aircraft have to operate. The remaining seven are also used to make the design synthesis “single-pass” as discussed in Chapter 5. In CRAGER, the constraint on Landing Field Length (LFL) is not considered since its effect is automatically considered while determining the minimum runway length requirement². The constraint on the cruise throttle during diversion is also removed, as the diversion stage is not to be optimised. Finally, since BFL has been moved to the list of Design Variables as explained above, the number of Design Constraints in CRAGER is reduced to 10.

²In CRAGER, the runway length required for safe operation of the airport is considered to be the greater of BFL and $(LFL - 180\text{m})$, assuming the air distance during landing to be 180 m, which is flown over the runway protection zone and offset.

Variable	Symbol	Units	Description	Label
CONFIGURATION RELATED				
ARW	AR_w	-	Wing aspect ratio	β
SREF	S_w	M^2	Wing area	β
TRW	λ	-	Wing taper ratio	β
TCW	τ	-	Wing thickness ratio	β
FL3	L_{fus_r}	-	Rear fuselage length factor	β
FLN	L_{fus_w}	-	Wing location factor	β
DFDTO	$\delta_{f_{TO}}$	deg.	Takeoff flap deflection	β
XMTO	M_{TO}	kg	Take-off mass	β
XMFUEL	M_{fu}	kg	Total fuel mass	β
SHPTO	P_{TO}	HP	Engine power at max. Take-off rating	β
DPROP	D_{prop}	m	Propeller diameter	α
TQTHP	-	-	Engine scaling factor	α
XBFL	BFL	m	Balanced field length	γ
TRAJECTORY RELATED				
THROA	Π_{cl}	-	Engine throttle at climb	β
THROCS	Π_{id}		Initial descent throttle	β
THROCF	Π_{fd}		Final descent throttle	β
VAIAS	V_{cl}	kt	Climb speed	β
VBIAS	V_{cr}	kt	Main stage cruise speed	α
CRUZMA	M_{cr}	-	Cruise Mach number	γ
VCIAS	V_{de}	kt	Descent Speed	β
HCRUZ	H_{cr}	m	Cruising altitude (main mission)	β
SB1	SB_1	-	Main stage cruise fraction	β
SB2	SB_2	-	Notional stage cruise fraction	β
SB3	SB_3	-	Diversion cruise fraction	α
VBIAS3	V_{dv}	kt	Diversion cruise speed	α
HCRUZ3	H_{dv}	m	Diversion cruise altitude	α

Table H.1: Design Variables in CASTOR & CRAGER

Variable	Constraint on	Type	Value assigned	Label
GRAMIN	WAT climb gradient	>	2.4%	β
EPNDB	Sideline noise level	<	94 EPNdB @ 450 m	β
MINMRG	Static Margin	=	5% MAC	β
RODLIM	Max. Rate of Descent	<	2.54 m/s (un-pressurised aircraft)	β
BFLMAX	Balanced Field Length	<	User specified value	α
LFLMAX	Landing Field Length	<	User specified value	α
MTOCAL	Calculated T.O. Mass	=	XMTO	β
MFUCAL	Calculated Fuel Mass	=	XMFU	β
THROB1	Main Cruise Throttle	<	100%	β
THROB3	Diversion Cruise Throttle	<	100%	α
CSTAGEM	Main Stage Length	=	Σ (climb, cruise & descent stage)	β
CSTAGEN	Notional Stage Length	=	Σ (climb, cruise & descent stage)	β
CSTAGED	Diversion Stage Length	=	Σ (climb, cruise & descent stage)	β

Table H.2: Constraints imposed in CASTOR & CRAGER

- **Design Constants**

Design Constants are those parameters whose values are not varied during the estimation of C_{gen} . This includes parameters related to the fuselage sizing, type & geometry of the horizontal tail, vertical tail & nacelle, engine RPM during various segments, power plant, wing aerodynamics, airframe roughness factors, mission parameters, and parameters related to cost estimation. Table I.2 in Appendix I provides a description of the Design Constants in CRAGER, and the values assigned to them in the case studies carried out with CRAGER discussed in Chapter 10 & Appendix I.

H.3 Penalty Function in CRAGER

In CRAGER, a penalty-function approach is used to provide the information related to the extent and severity of the violated constraints to the optimiser. The tolerance on each constraint (i.e. the extent by which violation of a constraint can be considered as acceptable) has to be specified by the user. The violated constraints are identified using:

$$iv_i = \begin{cases} 1 & \text{if } constr_i > tol_i \\ 0 & \text{if } constr_i \leq tol_i \end{cases} \quad (H.1)$$

where,

$$\begin{aligned} iv_i &= \text{Code to check if the } i\text{th constraint is violated} \\ constr_i &= \text{Value of the constraint function for } i\text{th constraint} \\ &= \pm(\text{specified value} - \text{actual value}) \text{ of } i\text{th constraint} \\ tol_i &= \text{user specified tolerance for } i\text{th constraint} \end{aligned}$$

The absolute value of $constr_i$ is to be used in Equation H.2 for equality constraints. For inequality constraints, the negative sign is to be used if the actual value of the constraint should be less than the specified value, and vice versa.

The following formula is used to build the penalty function for violated constraints :

$$Penalty = \sum_{i=1}^{nconstr} iv_i \cdot iact_i \cdot w_i \cdot constr_i \quad (H.2)$$

where,

- $nconstr$ = Number of possible constraints
= 10 in present version of CRAGER
- $iact_i$ = Code number to determine if the i th constraint is active
= 1 if active and 0 if inactive
- w_i = User specified *weight* for i th constraint
= high value if constraint is considered severe

In Equation H.2, the absolute value of $constr_i$ is to be used for equality constraints. For inequality constraints, the negative sign is to be used if the actual value of the constraint should be less than the specified value, and vice versa.

H.4 Subroutines & Functions in CRAGER

Table H.3 lists the major & minor subroutines and functions that are common to CASTOR and CRAGER and the new ones developed for CRAGER. The major subroutines correspond to a specific module, while the minor subroutines and functions are used to carry out a specific task within the major subroutines, and sometimes in the main program. To distinguish between the major & minor subroutines of CRAGER, only the major subroutines have been numbered in Table H.3.

H.5 Parameters related to SIMANN Optimiser in CRAGER

In the present form of CRAGER, the SIMANN optimiser is used, and the parameters related to this optimiser are listed in Table H.4. At present, any one of the following four parameters can be considered as the objective function to be minimised viz. :

No	Name	Purpose	Label
1	INPUT	Read Design Constants (during first call only)	β
2	BPARK	Ball-park the engine in the database	γ
	READAT	Read appropriate input data for ball-parking engine	γ
	GENDAT	Generate power-plant data for the ball-parked engine	γ
	FITVAL	Interpolate the data related to ball-parked engine	γ
3	DHMASS	Mass Estimation Module	γ
4	AERO1	Aerodynamics Module	γ
	FLAPS1	Calculate Flap factors independent of δ_f	β
	FLAPS2	Calculate Flap factors dependent of δ_f	β
	T2X	Second order T-function for Chebyshev polynomial fit	β
	T3X	Third order T-function for Chebyshev polynomial fit	β
	BLEND	Fairing of functions to ensure continuous derivatives	β
5	HPROP	Calculate propeller characteristics	γ
6	ASTAGE	Mission performance module	β
	SEGMNT	Estimate aircraft performance in a mission segment	β
	RO	Estimate atmospheric density	β
	VISC	Estimate kinematic viscosity of air	β
	THFRAC	Estimate fuel-flow at a specific throttle setting	γ
7	CROSK	Aircraft acquisition cost estimation module	γ
	CEF	Estimate Cost Escalation factor	γ
	AFMHR	Estimate Airframe Mfg. Labour man-hour rate	γ
	ENGMHR	Estimate Engineering Labour man-hour rate	γ
	TLGMHR	Estimate Tooling & QC man-hour rate	γ
	FLIN	Linear interpolation routine	γ
8	JSDOC	<i>DOC</i> estimation module	γ
9	APICAO	Airport Cost estimation module (ICAO regulations)	γ
10	GCOST	Generalised Cost estimation module	γ
11	NOISE	Far-field Noise level estimation module	γ
	PNLA	Estimate Perceived Noise Level Adjustment	γ

Table H.3: New and modified Subroutines & Functions in CRAGER

PARAMETER	DESCRIPTION
IOBJ	Code for objective function
NDV	Number of Design Variables (20)
NCONSTR	Number of Design Constraints (10)
IV	Status of each constraint (active/inactive)
WI	Weight assigned to each constraint
DESVAL	Desired value of each constraint
IWRITE	Code for extent of analysis related output desired
IPRINT	Code for extent of optimisation related output desired
MAXEVL	Upper limit on number of objective function evaluations
TINT	Initial Annealing Temperature
EPS	Tolerance parameter for termination criterion
NEPS	Number of iterations for termination criterion
RT	Annealing temperature reduction parameter
NT	Number of cycles before annealing temperature reduction
NS	Number of cycles before step length adjustment

Table H.4: SIMANN related parameters in CRAGER

1. Maximum Take-off mass (M_{TO})
2. Mission fuel mass ($\dot{M}_{fuel_{mis}}$)
3. Direct operating cost per seat-nm (DOC_{snm})
4. Generalised cost per passenger (C_{gen})

The flow chart of CRAGER is shown in Figure H.1.

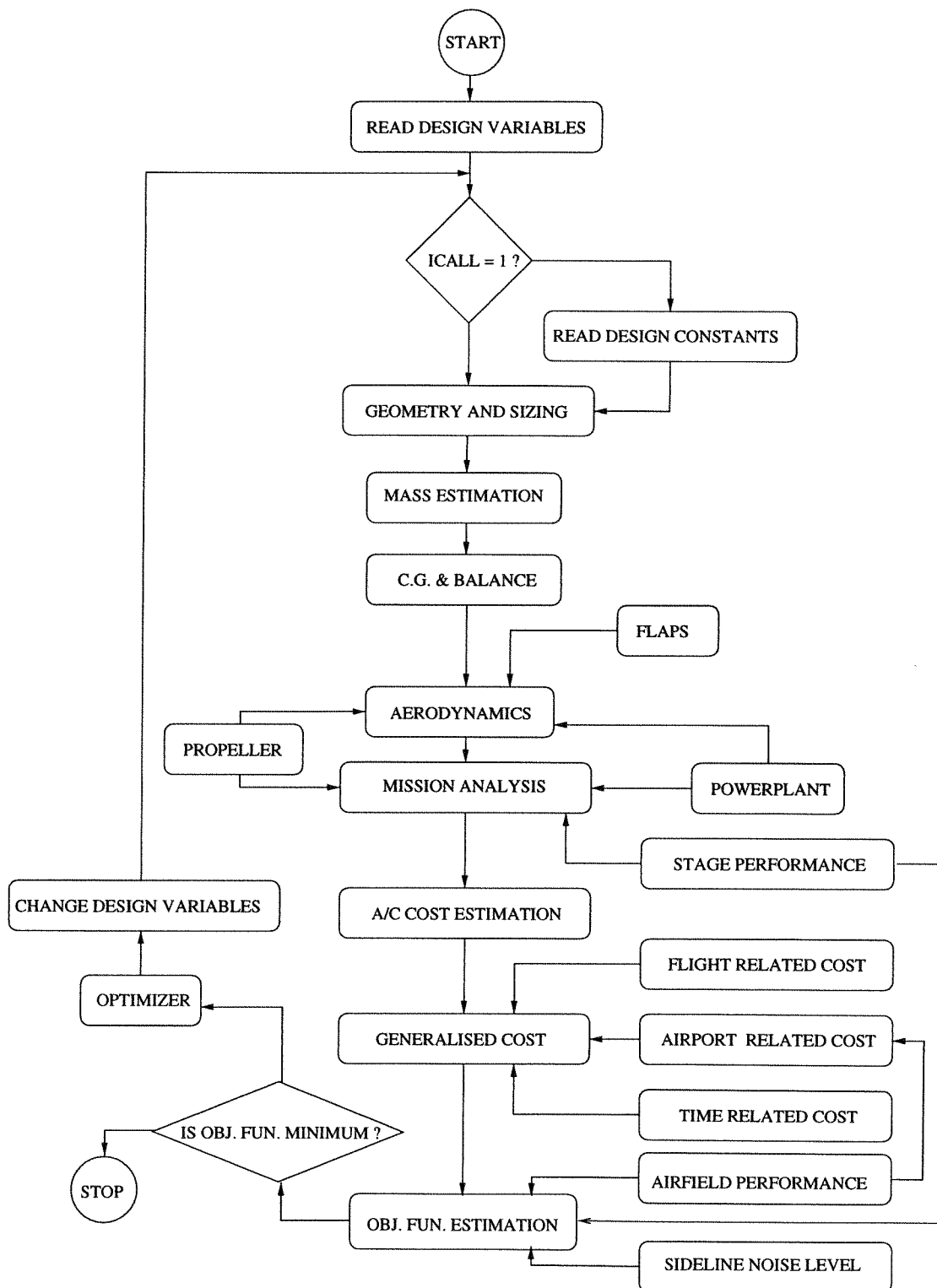


Figure H.1: Flow chart of CRAGER

Appendix I

Details of case studies with CRAGER

As discussed in Chapter 10, this Appendix describes in the details results obtained in the case studies carried out with CRAGER. It is divided under the following sections :

- Comparison of C_{gen} of optimum 19, 30, 50 & 70 seater aircraft determined by CRAGER for 100, 200 & 400 nm stage lengths
- Comparison of minimum C_{gen} and minimum DOC configurations
- Sensitivity analysis of C_{gen} terms on the optimum configurations
- Comparison of pressurised and un-pressurised 15 seater aircraft
- Comparison of C_{gen} of a few existing and the optimum 50 seater aircraft determined by CRAGER for 100, 200 & 400 nm stage lengths

The nomenclature of naming the aircraft discussed in Chapter 10 is also followed here.

I.1 CRAGER as system cost analysis tool

A comparative analysis of 19, 30, 50 & 70 seater aircraft for operation in India over stage lengths of 100, 200 & 400 nm was carried out to demonstrate the applicability of CRAGER as a system cost analysis tool. A hypothetical city having a population

of 50,000 literate people above six years of age and very high business potential, located 400 nm from a metropolitan city was considered as the baseline. It was also assumed that these two cities are not very well connected by other means of transportation, and a relatively small amount of traffic exists due to other factors. For this city-pair, the annual one-way travel demand predicted by Equation D.1 of Appendix D is approx 18000 passenger-trips, assigning suitable values to the slack variables viz. $C = 2$, $B = 3$, & $T = I = G = 1$. Although the annual demand reduces with reduction in stage length according to Equation D.1, the same value was used for stage lengths of 200 & 100 nm, to enable a fair comparison of the C_{gen} of various aircraft. Table I.1 lists the main differences in the input parameters of these four aircraft, which were decided based on a survey of existing aircraft.

AIRCRAFT CAPACITY	-	19	30	50	70
Fuselage Diameter	m	1.6	2.5	2.7	3.0
Pax. per row	-	2	3	4	4
Pax. cabin length	m	8.10	8.10	10.53	14.60
Limit Differential pressure	bar	0.35	0.4	0.4	0.4
Flap Type	-	SS ¹	DS ²	SSF ³	DSF ⁴
¹ = Single Slotted					
² = Double Slotted					
³ = Single Slotted Fowler					
⁴ = Double Slotted Fowler					

Table I.1: Main geometrical design constants for the various aircraft

I.1.1 Description of parameters related to CRAGER

The upper and lower limits to the 20 design variables were assigned using the corresponding values using the database of existing commuter & regional aircraft (Ref. Appendix A) as a guideline. As discussed in Appendix H, CRAGER consists of a large number of Design Constants, whose values are assigned as inputs by the user. Table I.2 lists these Design Constants and the values assigned to them in this study, for the baseline cases.

NAME	UNITS	DESCRIPTION	VALUE
GEOMETRY AND CONFIGURATION RELATED			
FINCID	deg.	Fuselage incidence angle w.r.t. wing zero-lift line	0.0
IWING		Code for wing type, 0 = low wing, 1=high wing	1
ARH		Horizontal tail aspect ratio	5.0
TRH		Horizontal tail taper ratio	0.5
TCH		Horizontal tail thickness/chord ratio	0.12

NAME	UNITS	DESCRIPTION	VALUE
VH		Horizontal tail volume coefficient	1.05
ITAIL		Code for horizontal tail type, 0 = fuselage mounted, 1 = T-tail	1
QHQQ		Ratio of tail-plane & free-stream dynamic pressure	0.95
ARV		Vertical tail aspect ratio	1.6
TRV		Vertical tail taper ratio	0.5
TCV		Vertical tail thickness/chord ratio	0.12
VV		Vertical tail volume coefficient	0.1
VSWEPTD	deg.	Vertical tail sweep-back at quarter chord	30
PCLEAR	m	Propeller to fuselage clearance	0.5
IPROP		Code number for propeller type, 1 = Hartzell 5 bladed propeller 2 = Hamilton Standard 6 bladed propeller	1
POWER-PLANT MODEL RELATED			
IENG		Number of engines in the database	8
IALT		Number of altitude steps	7
IVEL		Number of fwd. speed steps	8
IRD		Rating for ball-parking the engine	
		0 = Max. Take-off rating	
		1 = Max. Climb rating	
		2 = Max. Cruise rating	0
DALT	ft	Altitude for ball-parking the engine	0.0
DVEL	kt	Fwd. speed for ball-parking the engine	0.0
AERODYNAMICS RELATED			
C1A	/rad.	Aerofoil lift curve slope	6.1
C1MAX		Aerofoil max. Lift coefficient	1.6
C1DES		Aerofoil design Lift coefficient	0.3
CMACW		Aerofoil pitching moment coefficient	-0.08
TCRTCW		Ratio of t/c wing root to average wing t/c	1.0
BFOB		Ratio of flap span to wing span	0.7
CFOC		Ratio of flap chord to wing chord	0.3
DFDLAN	deg.	Landing flap deflection	40
MAXOVO		Ratio of increment in $C_{l_{max}}$ due to flap deflection to increment in C_l due to flap deflection at zero AOA	1.0
DC1MAX		Sectional $C_{l_{max}}$ increment due to landing flap Calculated, if input value = 0	0
RUFW		Wing & tail aerodynamic roughness factor	1.2
RUFF		Fuselage aerodynamic roughness & shape factor	1.2
RUFN		Nacelle aerodynamic roughness & shape factor	1.8
XXWIW		Factor on wing weight	1
XXFUW		Factor on fuselage weight	1
XXTAW		Factor on empennage weight	1
XXNAW		Factor on nacelle weight	1
MISSION & PERFORMANCE RELATED			
VDIVE	kt.	Design diving speed (EAS)	128.61
DIVERS	nm	Diversion Stage length	100
HOLDMN	min	Hold time	45

NAME	UNITS	DESCRIPTION	VALUE
INHSEG		Number of height segments in which each climb & descent phase is split in the flight profile module	
INCSEG		Number of distance segments in which each cruise phase is split in the flight profile and analysis module	3
IMLAND		Code for estimation of aircraft landing weight, 1 = max. Takeoff Mass 2 = mass at the end of main mission 3 = mass at the end of total mission, 4 = mass at the end of first stage, any other integer values represent % of Takeoff Mass	2
WATISA	^o C	Temperature deviation from ISA for WAT climb gradient estimation	20
WATH	m	Airfield elevation above mean sea-level for WAT climb gradient estimation	1524
DISLAT	m	Lateral distance from Runway centerline, for sideline noise estimation	450
TAMB	^o C	Ambient air temperature	15
AZIMUTH	deg.	Azimuth angle between the noise source and the observation point	90
AIRCRAFT ACQUISITION & OPERATING COST RELATED			
QPROTO		Number of aircraft prototypes built	2
QSTAT		Number of airframes built for static testing	0
RPROTO	/month	Rate of fabrication of prototype(s)	0.25
RPRODN	/month	Rate of fabrication of production aircraft	3.33
IYEAR		Reference year for RDT&E cost estimation	1996
IPRODN		Number of production aircraft for cost amortisation	400
FDIFF		Factor for judging the & complexity of the aircraft	1
FMAT		Factor for judging the type of materials used for manufacture	1
FOBS		Factor for judging the aircraft stealth & observability characteristics	1
FCAD		Factor for judging the CAD capability employed in the design & manufacturer	1
FTSF		Factor for judging special test set-up requirements	0
FINTR	US \$	Cost of cabin furnishings per passenger	1000
FPROF		Factor for profit for the manufacturer	0.1
FINT		Rate of interest on the money borrowed for financing RDT&E phase	0.1
FSPARE		Airframe spares cost as a fraction of the aircraft acquisition cost	0.15
FENGINE		Engine spares cost as a fraction of the aircraft cost	0.35
FLIFE	years	Number of years of useful service of the aircraft	15

NAME	UNITS	DESCRIPTION	VALUE
FRESVAL		Residual value of the aircraft as a fraction of aircraft cost	0.1
FINTER		Rate of interest on the capital investment for aircraft purchase	0.1
FINSUR		Rate of insurance premium for hull and passenger insurance	0.015
AIRCRAFT & ENGINE MAINTENANCE COST RELATED			
FAMPT	US \$	Airframe material cost per trip for line maintenance	14.32
FALPT	hours	Manhours per trip for airframe line maintenance	0.70
FEMPT	US \$	Engine material cost per trip for line maintenance	7.24
FEOPT	us &	Engine & associated rotables overhaul cost per trip	18.67
FELPT	hours	Manhours per trip for engine line maintenance	0.04
FMHR	US\$/hr	Manhour rate for line maintenance per trip	18.8
FAMPFH	US \$	Airframe material cost per flight hour for major maintenance	21.49
FALPFH	hours	Manhours per flight hour for airframe major maintenance	1.05
FEMPFH	US \$	Engine material cost per flight hour for major maintenance	10.86
FEOPFH	US \$	Engine & associated rotables overhaul cost per flight hour	74.69
FELPFH	hours	Manhours per flight hour for engine maintenance	0.015
OTHER DOC TERMS RELATED			
FCREW	US\$/hr	Manhour rate for pilots	100
NCCPP		Number of passengers per each cabin attendant	35
FFCOST	US\$ /lit	Cost of aviation fuel	0.20
FFDENS	Kg/lit	Density of aviation fuel	0.8
FLANDC		Factor for estimating Landing Charges	5
FHANDL	US\$	Handling charge at airport, per passenger	1.56
FYEAR		Baseline year for DOC estimation	1996
FNOW		Reference year for DOC estimation	1996
DOL2RS		Coverison rate between US\$ & Indian Rupee	35.0
FIOC		Factor to consider Indirect Operating Costs	0.75
AIRPORT & GENERALISED COST RELATED			
IPAXAN		Annual passenger travel demand	18000
VOTIME	Rs/hr	Value of time of passengers	100
AXSVEL	KMPH	Average speed of access to airport	40
FLANC		Fraction of land costs accounted in estimating Airport setting-up cost	1
APDEPR		Number of years over which airport setting-up costs are recovered	20
APRINT		Annual interest rate on capital borrowed for setting up the airport	0.10
IOPRYR		Average number of days in a year when the airport is operational	300

Table I.2: List of Design Variables in CASTOR and their values

The values assigned to the 10 Design Constraints and other parameters related to the Penalty Function¹ are listed in Table I.3.

NO.	CONSTRAINT ON	WEIGHT	TOLERANCE	TYPE	DESIRED VALUE
1	Static Margin	1.0E+5	0.0001	=	0.05
2	Calculated T.O. Mass	1.0E+3	0.05	=	0.0
3	Calculated Fuel Mass	1.0E+3	0.01	=	0.0
4	WAT climb gradient	1.0E+5	0.0	>	0.024
5	Main Stage Length	1.0E+1	1.0	=	user specified
6	Notional Stage Length	1.0E+1	1.0	=	user specified
7	Diversions Stage Length	1.0E+1	0.01	=	185000
8	Main Cruise Throttle	0.5E+6	0.0	<	1.0
9	Max. Rate of Descent	1.0E+4	0.0	<	2.54
10	Sideline noise level	1.0E+1	1.0	<	94.0

Table I.3: Design Constraints and Penalty Function related parameters

I.1.2 Description of parameters related to SIMANN

Table I.4 lists the 8 control parameters in SIMANN which have to be assigned suitable values assigned, based on recommendations, past experience, trial runs, and problem specific knowledge, as explained below. As discussed in Chapter 3, Simulated

NO.	SYMBOL	DESCRIPTION
1	T_{int}	Initial annealing temperature
2	R_T	Temperature reduction factor
3	N_T	Number of cycles before annealing temperature reduction
4	$\mathbf{V}$	Starting step sizes for n design variables
5	$\mathbf{c}$	Step size reduction criterion
6	N_S	Number of cycles before step size reduction
7	N_{eps}	Number of cycles for checking convergence criteria
8	eps	Minimum reduction in f acceptable before termination

Table I.4: SIMANN related parameters in CRAGER

Annealing has been mathematically proven to converge to the global optimum irrespective of the starting values. However, the number of computations (and hence the computational time) required for the mathematical global optimum to be achieved is almost infinite. From practical considerations, it is necessary to specify a limit on the number of function evaluations. Moreover, since the present study falls within

¹Refer Appendix H for details about the Penalty Function used in CRAGER.

the realm of conceptual design, it is sufficient if a reasonable level of convergence is achieved, rather than waiting for the absolute optimum. The four main parameters that govern the number of function evaluations and the globalness of the optimum solution are T_{int} , R_T , N_T & N_S .

Since $\mathbf{V}$ are progressively altered as the optimisation proceeds, a good estimate for their starting values was half the range of each of the n Design Variables. T_{int} in each case was determined by trial runs as suggested by Goffe et al. [90], in which T_{int} was set to unity and R_T was set to 1.5, and by identifying the annealing temperature T^* at which the step lengths $\mathbf{V}$ covered the entire range for all the n Design Variables. A value slightly higher than T^* so determined was assigned to T_{int} for the actual runs, which for most cases was 10^7 . N_{eps} & eps were heuristically assigned a values of 4 and 1.0, respectively.

The values recommended by Corana et al. [88] for R_T , c & N_S (i.e. 0.85, 2.0 & 20, respectively) were used, since they were found to be suitable based on previous experience. For N_T , they have suggested a value of $\max(100, 5 \cdot n)$ for optimising a function of n Design Variables. Trial runs with the recommended N_T value revealed that the execution time required for each run was of the order of 6-8 hours on a network of SUNSPARK workstations. Due to the stochastic nature of the optimiser, it was necessary to carry out few runs with different starting points for each case, to ensure that the results were free from random number effects. The matrix of test cases was very large², hence it was not feasible to allow so much execution time for each run.

I.1.3 Revised optimisation strategy

An inspection of the progression of the optimisation process revealed that all randomly chosen starting points corresponded to an infeasible solution, since the objective function was very severely constrained. In fact, it was almost impossible to specify a feasible starting point, unless it was obtained as the output of a previous optimisation run. Further, it was seen that in each run, most of the iterations were utilised to arrive at a feasible solutions, and then the feasible solutions were improved upon in the remaining iterations. The improvement in the objective function during the last few iterations before convergence was very less, since it was achieved by very slight changes to the values of the design variables which had little practical significance.

In view of the above observation, the following strategy was followed to arrive at good "Engineering" optimum solutions within reasonable computational time. After

²Four different aircraft capacities at three different stage lengths, and two different objective functions i.e. DOC & C_{gen} plus several other cases to determine the sensitivity of C_{gen} terms

determining a suitable T_{int} value as described above, several runs were initiated from different starting points determined randomly, with far lower N_T values (e.g. 25 or 30) compared to the value recommended by Corana et al. (i.e. 100). The aim of these runs was to quickly identify promising regions of the objective function subspace, rather than giving the optimiser enough time to converge to the actual optimum. The computational time for these runs was reduced in the same proportion as the reduction in N_T . From the best of the solutions so determined, a few longer runs were then initiated with $N_T = 100$. This strategy enabled a reduction in the total computational time required for each case, while the large number of small runs ensured that the function domain was explored in reasonable detail and provided increased confidence in the globalness of the optimum solution.

I.1.4 Optimum C_{gen} configurations for various stage lengths

Tables I.5, I.6, I.7 & I.8 list the design variables and some important output parameters related to the minimum C_{gen} aircraft for various stage lengths. The optimum configuration & flight profiles for the main mission of the various aircraft are compared in Figure I.1 & I.2. It can be seen that 70-OG-200 & 70-OG-200 aircraft violate the Side-line noise constraint; this constraint was made inactive when these aircraft were optimised, assuming that that this requirement could be met by using advanced noise suppression systems. Table I.9 lists the breakdown of C_{gen} and its components for the various aircraft at the three stage lengths. Figure I.3 shows the breakdown of C_{gen} for the various aircraft at stage lengths of 100, 200, & 400 nm.

I.2 Comparison of minimum DOC & C_{gen} configurations

Having determined the minimum C_{gen} configurations for the four aircraft as described above, it was decided to obtain the minimum DOC configurations of the same aircraft, with a view to investigate how C_{apt} & C_{time} affect the optimum. In most cases, it was found that the minimum DOC and minimum C_{gen} configurations were quite similar. This is due to the fact that C_{flt} is the largest fraction of C_{gen} for all aircraft, followed by C_{time} & C_{apt} , as can be seen in Table I.9, hence parameters values that tend to minimise C_{flt} also, in general, result in lower C_{gen} . Another possible reason for this is the fact that the calculated C_{acq} of all the aircraft were found to be higher than the industry estimates, and hence had to be corrected to ensure realistic values for the various DOC terms³.

³Refer Appendix F for further details

OPTIMISED DESIGN VARIABLES					
Parameter	Symbol	Units	19-OG-100	19-OG-200	19-OG-400
Wing aspect ratio	AR_w	-	9.98	8.26	8.47
Wing area	S_w	m ²	33.16	26.75	26.89
Wing taper ratio	λ	-	0.73	0.51	0.73
Wing thickness ratio	τ	-	0.18	0.16	0.15
Rear fuselage length factor	L_{fus_r}	-	2.16	2.20	2.33
Wing location factor	L_{fus_w}	-	0.507	0.501	0.496
Takeoff flap deflection	δ_{fTO}	deg.	20	20	20
Takeoff mass	M_{TO}	kg	7824.3	7325.6	7503.1
Mission fuel mass	M_{fu}	kg	1352.8	1054.4	1018.4
SHP max. TO rating	SHP_{TO}	HP	1032.4	1140.1	1294.0
Engine throttle at climb	Π_{cl}	-	0.96	0.98	0.96
Climb speed	V_{cl}	KIAS	168.9	173.5	166.9
Cruise Mach no.	M_{cr}	-	0.347	0.354	0.374
Descent speed	V_{de}	KIAS	249.5	224.0	230.9
Cruising altitude	H_{cr}	m	3968.5	4671.0	5112.9
Main stage cruise fraction	$\bar{s}_m$	-	0.517	0.732	0.873
Notional stage cruise fraction	$\bar{s}_n$	-	0.584	0.761	0.768
Balanced field length	BFL	m	1019.1	1047.1	981.7
IMPORTANT OUTPUT PARAMETERS					
Parameter	Symbol	Units	19-OG-100	19-OG-200	19-OG-400
GEOMETRY & LOADINGS					
Wing span	b_w	m	18.20	14.86	15.01
Fuselage length	L_{fus}	m	15.08	15.13	15.35
Wing loading	w/s	kg/m ²	235.93	273.90	279.00
Power loading	p/w	kw/kg	0.197	0.232	0.257
AIRPORT RELATED					
ICAO classification number	$IACN$	-	2	2	2
ICAO classification letter	$IACL$	-	B	A	B
Land area	AP_{area}	acres	140.771	141.274	141.272
Setting-up costs	C_{setup}	10 ⁶ Rs.	35.465	35.001	35.129
FLIGHT RELATED					
Block time	T_{blk}	min	34.2	54.9	92.3
Block speed	V_{blk}	KTAS	175.61	218.51	260.02
Average specific mission fuel	M_{fu}	kg/nm	2.706	2.636	2.546
Break-even load factor	$BELF$	-	70.17	64.80	59.55
AIRWORTHINESS RELATED					
Second stage climb gradient	γ	%	3.21	3.57	5.65
Sideline noise level	SNL	EPNdB	87.5	87.9	88.4

Table I.5: Design Variables and output related to optimised 19 seater aircraft

OPTIMISED DESIGN VARIABLES					
Parameter	Symbol	Units	30-OG-100	30-OG-200	30-OG-400
Wing aspect ratio	AR_w	-	11.35	9.54	8.91
Wing area	S_w	m ²	46.99	50.16	48.69
Wing taper ratio	λ	-	0.56	0.55	0.50
Wing thickness ratio	τ	-	0.19	0.15	0.17
Rear fuselage length factor	L_{fus_r}	-	2.49	2.31	2.51
Wing location factor	L_{fus_w}	-	0.484	0.482	0.469
Takeoff flap deflection	δ_{fto}	deg.	20	20	20
Takeoff mass	M_{TO}	kg	11973.4	11806.8	11739.0
Mission fuel mass	M_{fu}	kg	1595.7	1293.7	1311.9
Engine power max. TO rating	$SH_{P_{TO}}$	HP	1330.3	1364.8	1434.9
Engine throttle at climb	Π_{cl}	-	0.96	0.99	0.97
Climb speed	V_{cl}	KIAS	168.2	173.3	181.8
Cruise Mach no.	M_{cr}	-	0.333	0.341	0.341
Descent speed	V_{de}	KIAS	232.0	250.0	249.9
Cruising altitude	H_{cr}	m	4097.4	3956.9	3638.8
Main stage cruise fraction	$\bar{s}_m$	-	0.330	0.708	0.855
Notional stage cruise fraction	$\bar{s}_n$	-	0.410	0.735	0.217
Balanced field length	BFL	m	1172.8	1073.2	1054.5
IMPORTANT OUTPUT PARAMETERS					
Parameter	Symbol	Units	30-OG-100	30-OG-200	30-OG-400
GEOMETRY & LOADINGS					
Wing span	b_w	m	23.10	21.87	20.83
Fuselage length	L_{fus}	m	19.82	19.37	19.87
Wing loading	w/s	kg/m ²	254.81	235.37	241.10
Power loading	p/w	kw/kg	0.168	0.173	0.182
AIRPORT RELATED					
ICAO classification number	$IACN$	-	2	2	2
ICAO classification letter	$IACL$	-	B	B	B
Land area	AP_{area}	acres	159.337	148.112	146.196
Setting-up costs	C_{setup}	10 ⁶ Rs.	45.052	41.819	41.193
FLIGHT RELATED					
Block time	T_{blk}	min	35.9	57.6	104.2
Block speed	V_{blk}	KTAS	166.98	208.33	230.39
Average specific mission fuel	M_{fu}	kg/nm	1.996	1.970	2.060
Break-even load factor	$BELF$	-	57.89	53.46	51.73
AIRWORTHINESS RELATED					
Second stage climb gradient	γ	%	3.09	3.02	2.55
Sideline noise level	SNL	$EPNDB$	89.3	89.5	89.9

Table I.6: Design Variables and output related to optimised 30 seater aircraft

OPTIMISED DESIGN VARIABLES					
Parameter	Symbol	Units	50-OG-100	50-OG-200	50-OG-400
Wing aspect ratio	AR_w	-	12.62	11.65	10.75
Wing area	S_w	m ²	54.33	53.96	50.90
Wing taper ratio	λ	-	0.61	0.51	0.65
Wing thickness ratio	τ	-	0.19	0.15	0.17
Rear fuselage length factor	L_{fus_r}	-	2.38	1.39	2.17
Wing location factor	L_{fus_w}	-	0.495	0.541	0.504
Takeoff flap deflection	δ_{fTO}	deg.	20	20	19
Takeoff mass	M_{TO}	kg	17715.6	18062.3	17365.2
Mission fuel mass	M_{fu}	kg	1904.9	1701.6	1516.3
SHP max. TO rating	SHP_{TO}	HP	1972.4	2450.8	2209.6
Engine throttle at climb	Π_{cl}	-	0.95	0.97	0.98
Climb speed	V_{cl}	KIAS	167.4	213.1	169.4
Cruise Mach no.	M_{cr}	-	0.344	0.378	0.345
Descent speed	V_{de}	KIAS	238.4	192.1	226.8
Cruising altitude	H_{cr}	m	3599.6	3476.7	3923.2
Main stage cruise fraction	$\bar{s}_m$	-	0.387	0.614	0.853
Notional stage cruise fraction	$\bar{s}_n$	-	0.446	0.643	0.368
Balanced field length	BFL	m	1375.5	1212.6	1331.3
IMPORTANT OUTPUT PARAMETERS					
Parameter	Symbol	Units	50-OG-100	50-OG-200	50-OG-400
GEOMETRY & LOADINGS					
Wing span	b_w	m	26.19	25.07	23.40
Fuselage length	L_{fus}	m	22.91	20.23	22.34
Wing loading	w/s	kg/m ²	326.08	334.75	341.16
Power loading	p/w	kw/kg	0.166	0.202	0.190
AIRPORT RELATED					
ICAO classification number	$IACN$	-	3	3	3
ICAO classification letter	$IACL$	-	C	C	B
Land area	AP_{area}	acres	215.67	194.194	192.298
Setting-up costs	C_{setup}	10 ⁶ Rs.	72.382	65.600	67.202
FLIGHT RELATED					
Block time	T_{blk}	min	35.5	55.1	102.9
Block speed	V_{blk}	KTAS	168.87	217.81	233.30
Average specific mission fuel	M_{fu}	kg/nm	2.292	2.468	2.290
Break-even load factor	$BELF$	-	48.77	44.01	41.67
AIRWORTHINESS RELATED					
Second stage climb gradient	γ	%	3.16	3.09	3.62
Sideline noise level	SNL	EPNDB	92.0	93.1	92.7

Table I.7: Design Variables and output related to optimised 50 seater aircraft

OPTIMISED DESIGN VARIABLES					
Parameter	Symbol	Units	70-OG-100	70-OG-200	70-OG-400
Wing aspect ratio	AR_w	-	12.80	10.49	12.94
Wing area	S_w	m^2	75.51	79.25	67.10
Wing taper ratio	λ	-	0.53	0.52	0.56
Wing thickness ratio	τ	-	0.20	0.17	0.19
Rear fuselage length factor	L_{fus_r}	-	2.30	2.06	2.62
Wing location factor	L_{fus_w}	-	0.491	0.486	0.500
Takeoff flap deflection	δ_{fro}	deg.	16	13	20
Takeoff mass	M_{TO}	kg	24132.5	24067.1	23954.3
Mission fuel mass	M_{fu}	kg	2408.9	2004.9	2078.8
SHP max. TO rating	SHP_{TO}	HP	2638.7	2948.7	2990.4
Engine throttle at climb	Π_{cl}	-	0.95	0.97	0.99
Climb speed	V_{cl}	KIAS	154.7	190.4	145.6
Cruise Mach no.	M_{cr}	-	0.345	0.355	0.356
Descent speed	V_{de}	KIAS	184.9	206.2	233.3
Cruising altitude	H_{cr}	m	3874.4	4356.0	3552.0
Main stage cruise fraction	$\bar{s}_m$	-	0.324	0.562	0.889
Notional stage cruise fraction	$\bar{s}_n$	-	0.373	0.591	0.400
Balanced field length	BFL	m	1491.3	1365.0	1444.0
IMPORTANT OUTPUT PARAMETERS					
Parameter	Symbol	Units	70-OG-100	70-OG-200	70-OG-400
GEOMETRY & LOADINGS					
Wing span	b_w	m	31.09	28.83	29.47
Fuselage length	L_{fus}	m	27.44	26.72	28.41
Wing loading	w/s	kg/m^2	319.59	303.68	357.02
Power loading	p/w	kw/kg	0.163	0.183	0.186
AIRPORT RELATED					
ICAO classification number	$IACN$	-	3	3	3
ICAO classification letter	$IACL$	-	C	C	C
Land area	AP_{area}	acres	233.97	217.429	228.299
Setting-up costs	C_{setup}	10^6 Rs.	88.991	82.553	86.455
FLIGHT RELATED					
Block time	T_{blk}	min	37.9	56.9	101.7
Block speed	V_{blk}	KTAS	158.11	210.99	236.03
Average specific mission fuel	M_{fu}	kg/nm	2.848	2.875	3.153
Break-even load factor	$BELF$	-	47.48	41.17	38.43
AIRWORTHINESS RELATED					
Second stage climb gradient	γ	%	3.23	2.83	3.70
Sideline noise level	SNL	$EPNDB$	93.9	94.5	94.7

Table I.8: Design Variables and output related to optimised 70 seater aircraft

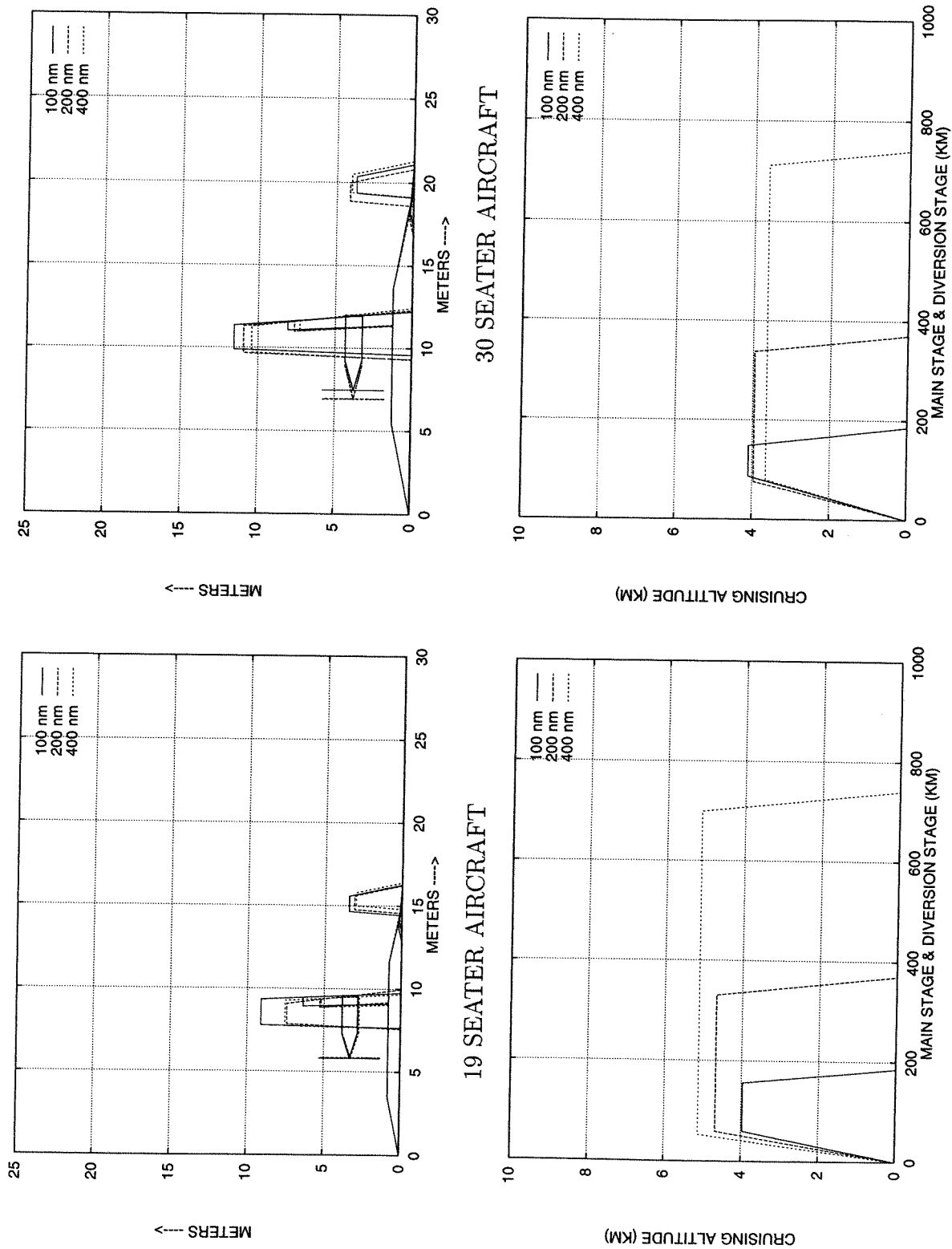


Figure I.1: Min. C_{gen} configurations & mission profiles of 19 & 30 seater aircraft

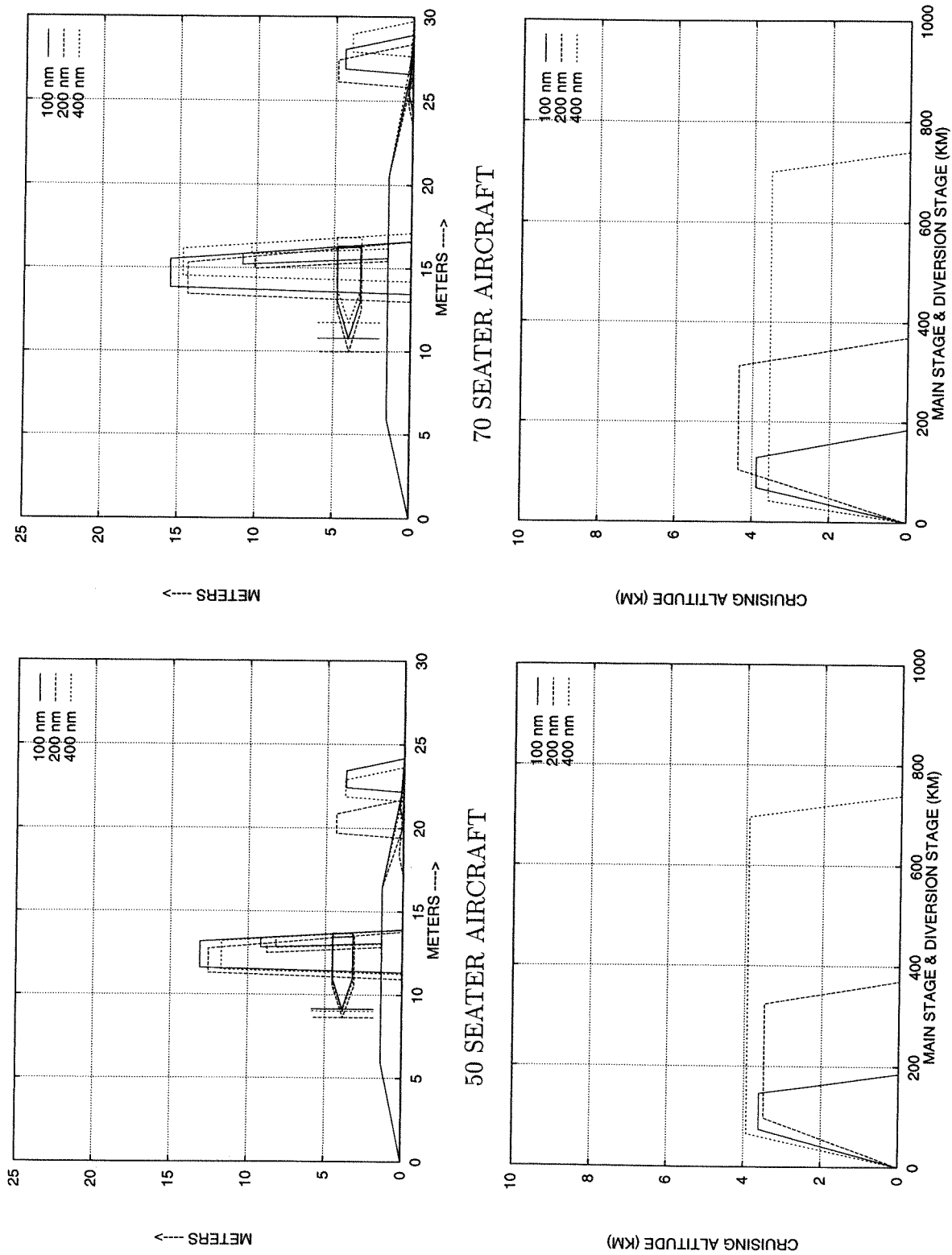


Figure I.2: Min. C_{gen} configurations & mission profiles of 50 & 70 seater aircraft

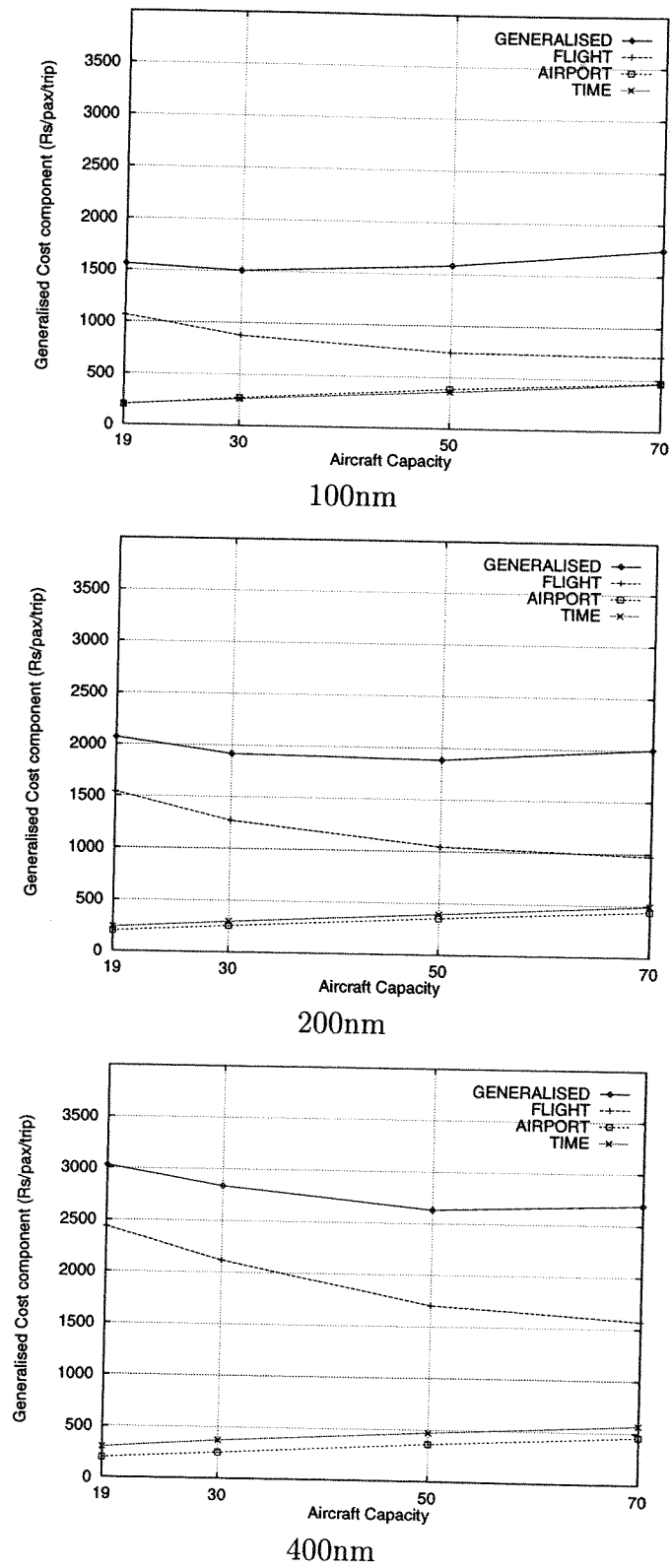


Figure I.3: C_{gen} breakdown of various aircraft at the three stage lengths

Aircraft	N_{paz}	C_{time}	C_{flt}	C_{apt}	C_{gen}	DOC_{snm}	$C_{flt_{snm}}$	$C_{gen_{snm}}$
Units	-	Rs/seat	Rs/seat	Rs/seat	Rs/seat	c/snm	Rs/snm	Rs/snm
STAGE LENGTH = 100 NM								
19-OG-100	19	201.95	1066.78	196.69	1560.43	22.86	10.67	15.60
30-OG-100	30	259.89	880.03	270.97	1505.89	18.86	8.80	15.06
50-OG-100	50	359.22	741.35	387.99	1583.56	15.89	7.41	15.84
70-OG-100	70	463.25	721.80	470.32	1750.37	15.47	7.22	17.50
STAGE LENGTH = 200 NM								
19-OG-200	19	236.53	1540.29	197.16	2068.98	16.50	7.7	10.34
30-OG-200	30	296.01	1270.63	255.32	1916.97	13.62	6.35	9.58
50-OG-200	50	391.82	1046.06	353.44	1886.32	11.21	5.23	9.43
70-OG-200	70	494.79	976.64	438.30	2004.73	10.46	4.88	10.02
STAGE LENGTH = 400 NM								
19-OG-400	19	298.83	2436.05	196.81	3026.69	13.05	6.09	7.57
30-OG-400	30	373.62	2115.88	252.41	2836.91	11.34	5.29	7.09
50-OG-400	50	471.45	1704.60	362.74	2633.79	9.13	4.26	6.58
70-OG-400	70	569.47	1572.02	458.11	2694.59	8.42	3.93	6.74

Table I.9: Comparison of C_{gen} terms of various aircraft optimised for 100, 200 & 400 nm stage lengths

In some cases, however, the optimum DOC configurations were quite different from the optimum C_{gen} ones. For e.g., Table I.10 compares the salient features of the the minimum C_{gen} aircraft 30-OG-400 & the minimum DOC aircraft 30-OD-400. The % change in the values of the parameters for 30-OD-400 relative to 30-OG-400 is also listed. For e.g., Table I.10 shows that 30-OD-400 tries to lower C_{flt} (hence DOC) by reducing the mission fuel and mission time. This is achieved by spending a smaller fraction of time & fuel in the climb stage and cruising at lower altitude & higher Mach number. The reduction in Block Time T_{blk} and Mission Fuel is, however, only 3% & 1%, respectively, hence the reduction in C_{flt} is only around 2%.

30-OG-400 is seen to have a 26% lower wing loading and 4% higher power loading compared to 30-OD-400, both of which lead to a 22% reduction in BFL , which is the main parameter that affects C_{apt} . However, the reduction in BFL is also accompanied with a reduction in ICAO Aerodrome Code Number⁴ from 3 to 2, due to which the runway width and the Approach surface area are also reduced. All these factors lead to a 30% reduction in C_{apt} .

The largest component of C_{time} is T_{defer} , which is not an optimisable parameter and has a fixed value for a specific aircraft. C_{time} does get affected to a very small extent by the Block Time (T_{blk}), which depends on the value of some mission related design variables. Thus a 3% increase in T_{blk} for 30-OG-400 results in only 1% increase in C_{time} . The configuration & mission profile of these two aircraft are compared in

⁴Classification of airports as per ICAO regulations is discussed in Chapter 7.

Parameter	Units	30-OG-400	30-OD-400	% diff.
Calculated Aircraft Acq. Cost	US \$	9.95	9.71	-2
Corrected Aircraft Acq. Cost	US \$	6.00	6.00	0
Wing Area	m ²	48.69	38.03	-22
Max. Take-off Power	HP	1434.92	1439.50	0.3
Max. Takeoff Mass	kg	11739.00	11524.50	-2
Wing Loading	kg/m ²	241.10	303.00	26
Power Loading	HP/kg	0.24	0.25	4
Mission Fuel Mass	kg	1311.00	1300.00	-1
Climb Speed	KIAS	181.80	177.20	-3
Climb Fuel	kg	120.50	91.80	-24
Climb Time	min	12.70	9.42	-26
Cruise Mach Number	-	0.34	0.36	6
Cruise Time	min	79.08	79.15	0.1
Descent Speed	KIAS	250.00	246.00	-2
Cruising Altitude	m	3639.00	3393.00	-7
Diversion Fuel	kg	212.00	207.00	-2
Holding Fuel	kg	240.00	241.00	0.4
Balanced Field Length	m	1054.50	1282.80	22
ICAO Aerodrome Code Letter	-	B	B	-
ICAO Aerodrome Code No.	-	2	3	-
Runway Width	m	23	30	30
Airport Width	m	450.09	453.25	1
Approach Surface Area	acres	7.78	13.34	71
Airport Area	acres	146.20	183.80	26
Runway Construction Cost	10 ⁶ Rs	19.45	30.54	57
Airport Set-up Cost	10 ⁶ Rs	41.19	56.02	36
Block Time	min	113.17	110.05	-3
Airport Cost	Rs/pax	252.41	327.20	30
Time Cost	Rs/pax	373.60	368.40	-1
Flight Cost	Rs/pax	2115.88	2064.83	-2
Generalised Cost	Rs/pax	2836.91	2855.45	1
Specific Flight Cost	Rs/s-nm	5.29	5.16	-2
Specific Generalised Cost	Rs/s-nm	7.09	7.14	1

Table I.10: Comparison of Min. DOC & Min. C_{gen} 30 seater aircraft for 400 nm stage

Figure I.4.

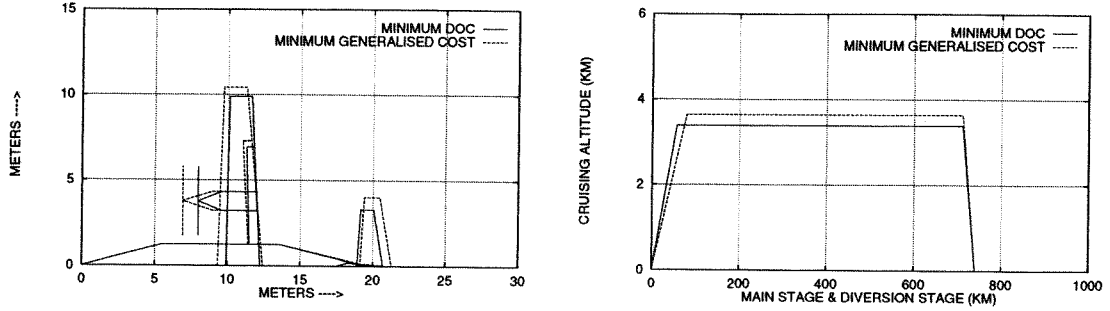


Figure I.4: Configuration & mission profile of min. DOC & min. C_{gen} 30 seater aircraft for 400 nm stage

I.3 Sensitivity analysis of C_{gen} terms

Having determined the optimum C_{gen} configurations for the various aircraft, it was decided to investigate the effect of changing the magnitude of two components of C_{gen} viz. C_{time} & C_{apt} on the optimum configurations. As discussed in Chapter 7 and 8, the largest component of C_{apt} is the land cost (C_{land}). Two other factors that affect C_{apt} for a given annual demand and aircraft size are the depreciation period AP_{depr} and the interest rate on the capital borrowed for setting-up the airport R_{int} . Therefore, effect of high C_{apt} was simulated by assuming high C_{land} , low AP_{depr} & high R_{int} , and vice versa. Similarly, high C_{time} was simulated by assuming a high value of time ($\mathcal{V}$) and increase in access time (T_{acc}), and vice versa.

I.3.1 Effect of very high Airport Cost, ignoring Time cost

As discussed above, C_{apt} forms only a small fraction of C_{gen} , which is dominated by C_{flt} . To investigate the effect of very high C_{apt} without considering C_{time} , the airport land cost was assumed to increase by ten times from the baseline value of Rs 50 per sq. m., the AP_{depr} was reduced to 10 years, and $\mathcal{V}$ was assumed to be zero. This assumption ensured that C_{apt} would constitute the major fraction of C_{gen} , hence the optimum solution would be mainly driven by the parameters that directly affect C_{apt} , rather than C_{flt} . The results showed that reduction in C_{apt} is obtained mainly by reduction in the airport land area, and to a smaller extent by reduction in the construction cost of airside area⁵. However, a reduction in airport land area can be achieved by adopting two different strategies, depending on whether or not a

⁵The airside area consists of the runway, taxiway & apron pavements.

reduction in ICAO Airport Code Letter or Number can be achieved in the process. These two strategies are discussed below with the aid of two examples.

Table I.11 compares some important parameters of 70-OG-400 aircraft and the optimum solution that resulted with the above assumption i.e. 70-ZVHA-400 aircraft.

Parameter	Units	70-OG-400	70-ZVHA-400	% diff.
Balanced Field Length	m	1444.01	1291.91	-11
Wing Span	m	29.47	28.79	-2
Fuselage Length	m	28.41	24.14	-15
Max. Take-off Power	HP	2990.44	2949.38	-1
Wing Loading	kg/m ²	357.02	301.57	-16
Power Loading	HP/kg	0.249	0.245	-2
ICAO Aerodrome Code Letter	-	C	C	-
ICAO Aerodrome Code No.	-	3	3	-
Taxiway Width	m	15	15	0
Taxiway-Apron separation	m	90	90	0
Apron-Terminal Bld. separation	m	24.5	24.5	0
Airport Width	m	521.66	516.97	-1
Airport Length	m	1564.01	1411.91	-10
Airport Area	acres	228.30	207.05	-9
Runway Construction Cost	10 ⁶ Rs	52.02	46.64	-10
Flight Cost	Rs/pax	1572.02	1582.53	1
Using land cost = Rs 50 per sq. m. & $AP_{depr} = 20$ for both				
Airport Land Cost	10 ⁶ Rs	23.10	20.95	-9
Airport Set-up Cost	10 ⁶ Rs	86.46	78.73	-9
Airport Cost	Rs/pax	458.11	419.25	-8
Flight Cost + Airport Cost	Rs/pax	2030.13	2001.78	-1
Using land cost = Rs 500 per sq. m. & $AP_{depr} = 10$ for both				
Airport Land Cost	10 ⁶ Rs	230.98	209.48	-9
Airport Set-up Cost	10 ⁶ Rs	294.34	267.26	-9
Airport Cost	Rs/pax	2315.14	2104.27	-9
Flight cost + Airport Cost	Rs/pax	3887.16	3686.8	-5

Table I.11: Effect of high C_{apt} and zero C_{time} on 70-OG-400 aircraft

Both the aircraft have the same ICAO Airport Classification Number & Letter. The reduction in BFL leads to a 10% reduction in airport length and runway construction cost. The airport width is also reduced due to a reduction in fuselage length, but only by 1%. Thus, the airport land area is reduced mainly by reduction

in the airport length. The reduction in wing span, though small, helps in reducing the width of the apron, hence its construction cost.

If the the baseline land cost (Rs 50 per sq. m) is assumed for the airport associated with both these aircraft, a 9% reduction in Airport setting-up cost and C_{apt} is seen, which leads to a 1% reduction in C_{gen} (with $C_{time} = 0$). On the other hand, if higher land cost is considered, the reduction in C_{gen} is 5%. It is interesting to note that this reduction is achieved at the cost of only 1% increase in C_{flt} . The configuration and flight profile of these two aircraft are compared in Figure I.5. It may be noted that the horizontal tail for 70-ZVHA-400 is much larger compared to 70-OG-400, due to the increase in wing area and decrease in fuselage length. When

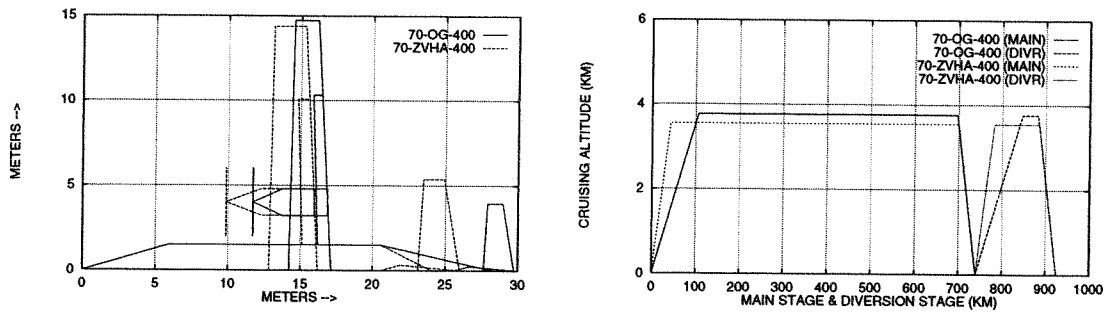


Figure I.5: Configuration & mission profile of 70-OG-400 & 70-ZVHA-400 aircraft

the same assumption about high land cost was applied to 50-OG-100 aircraft, the reduction in C_{apt} was achieved adopting a different strategy. Table I.12 compares the main parameters of 50-OG-100 aircraft and 50-ZVHA-100 aircraft.

In this case, the reduction in wing span results in a reduction in the ICAO Aerodrome Code Letter from C to B, which results in large reductions in the taxiway width, taxiway-apron separation & apron-terminal building separation. This (and a reduction in fuselage length) leads to 10% reduction in airport width. BFL is decreased by a large increase in power loading (which is marginally offset by an increase in wing loading); this leads to a reduction in airport length, but by only 5%. In this case, the 12% reduction in airport land area is achieved mainly by reducing the airport width and to a lesser extent by reducing the airport length.

In this case too, a 1% reduction in reduction in C_{gen} is seen for the baseline case, though C_{flt} increases by 2.5%. With higher land cost and lower AP_{depr} , however, the reduction in C_{gen} is around 7%. The configuration and flight profile of these two aircraft are compared in Figure I.6. The above two examples show that in situations where airport land cost is very high (e.g. airports located near or within the limits of a city, such as London City Airport), reduction in C_{apt} can be achieved without very heavy penalty on C_{flt} , leading to a net reduction in C_{gen} . It can also be concluded that large reductions in C_{apt} occur in cases where :

Parameter	Units	50-OG-100	50-ZVHA-100	% diff.
Balanced Field Length	m	1375.45	1302.88	-5
Wing Span	m	26.19	22.71	-13
Fuselage Length	m	22.91	21.77	-5
Max. Take-off Power	HP	1972.37	2453.79	24
Wing Loading	kg/m ²	326.08	343.30	-5
Power Loading	HP/kg	0.222	0.267	20
ICAO Aerodrome Code Letter	-	C	B	-
ICAO Aerodrome Code Number	-	3	3	-
Taxiway Width	m	15	10.5	-30
Taxiway-Apron separation	m	90	52	-42
Apron-Terminal Bld. separation	m	24.5	16.5	-33
Airport Width	m	511.40	461.16	-10
Airport Length	m	1495.45	1422.87	-5
Airport Area	acres	215.67	188.83	-12
Runway Construction Cost	10 ⁶ Rs	41.77	40.37	-3
Flight Cost	Rs/pax	741.35	759.96	2
Using land cost = Rs 50 per sq. m. & $AP_{depr} = 20$ for both				
Airport Land Cost	10 ⁶ Rs	21.82	19.10	-12
Airport Set-up Cost	10 ⁶ Rs	72.38	67.24	-7
Airport Cost	Rs/pax	387.99	361.10	-7
Flight Cost + Airport Cost	Rs/pax	1129.34	1121.06	-1
Using land cost = Rs 500 per sq. m. & $AP_{depr} = 10$ for both				
Airport Land Cost	10 ⁶ Rs	218.20	191.04	-12
Airport Set-up Cost	10 ⁶ Rs	268.76	239.18	-11
Airport Cost	Rs/pax	2116.43	1885.22	-11
Flight Cost + Airport Cost	Rs/pax	2857.78	2645.18	-7

Table I.12: Effect of high C_{apt} and zero C_{time} on 50-OG-100 aircraft

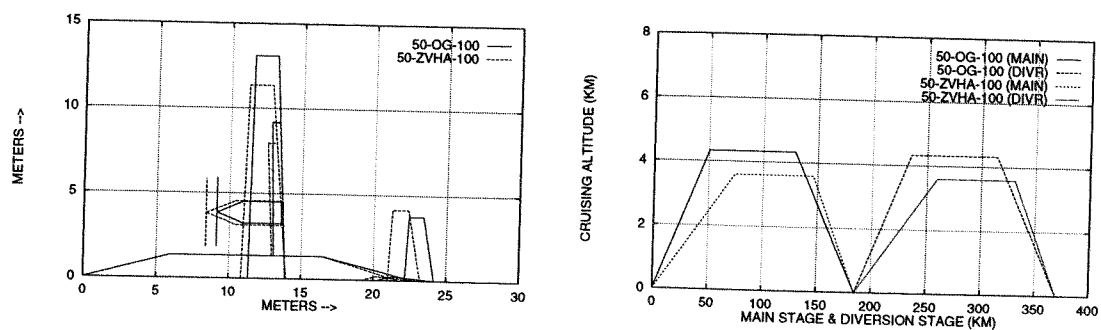


Figure I.6: Configuration & mission profile of 50-OG-100 & 50-ZVHA-100 aircraft

- Reduction of wing span leads to lower ICAO Aerodrome Code Letter, as in 50-ZVHA-100 aircraft
- Reduction of BFL leads to lower ICAO Aerodrome Code Number, as in 30-OG-400 aircraft

I.3.2 Effect of excessively high Time cost, ignoring Airport cost

To investigate the effect of very high C_{time} , optimum configurations of 19 and 30 seater aircraft for operation over 400 nm stage were obtained assuming $\mathcal{V}$ of 1500 Rs/hour, ignoring C_{apt} . This ensured that the C_{time} terms would be even larger than the C_{flt} terms, hence the optimum solution would be driven by C_{flt} related parameters. As mentioned earlier, a large fraction of C_{time} is due to the Defer Time⁶ (T_{defer}), which changes only if the capacity of the aircraft is changed. Hence T_{defer} was ignored in this analysis. The optimum configurations so obtained were designated as 19-HVZA-400 & 30-HVZA-400, respectively.

Table I.13 compares some important parameters of these aircraft with the corresponding aircraft optimised for C_{gen} . Since the study was limited to conventional turboprop aircraft, excessive reductions in the Block Time (T_{blk}) were not possible. However, Table I.13 shows that for both the aircraft, the assumption of high $\mathcal{V}$ lead to a reduction in T_{blk} , with an associated reduction in C_{flt} .

The configuration and mission profile of these aircraft is shown in Figure I.7

I.4 Comparison of pressurised and un-pressurised 19 seater aircraft

Two additional design variables and a constraint have to be considered in CRAGER and CASTOR for un-pressurised aircraft. These are the initial and final throttle employed during the descent phase, and the upper limit on the rate of descent. Figure I.8 compares the configuration & mission profile of an un-pressurised and pressurised 19 seater aircraft optimised for 400 nm stage. While the optimum cruising altitude for the pressurised aircraft is just above 5000 m, the un-pressurised aircraft tends to cruise at the lowest permissible altitude of 1000 m. The descent profile of the two aircraft are also quite different. Due to the limit on the rate of descent that was imposed on the un-pressurised aircraft, it descends quite slowly with the throttle

⁶The concept of Defer Time is discussed in Chapter 1.

Parameter	Units	19-OG-400	19-HVZA-400	% Diff.	30-OG-400	30-HVZA-400	% Diff.
Max. Take-off Mass	kg	7503.8	7576.5	1.0	11739.0	11772.6	0.3
Mission Fuel Mass	kg	1018.4	1023.640	0.5	1311.9	1309.9	-0.1
Max. Take-off Power	HP	1294.0	1428.0	10.4	1434.9	1408.0	-1.9
Cruise Mach No.	-	0.374	0.38	0.4	0.341	0.350	2.8
Balanced Field Length	m	981.7	988.5	0.7	1054.5	1270.2	20.5
Wing Loading	kg/m ²	279.00	309	10.7	241.10	289.60	20.1
Power Loading	HP/kg	0.345	0.38	9.3	0.244	0.239	-2.2
Block Time	mins	92.3	91.7	-0.7	104.2	103.0	-1.2
Defer Time	mins	57	57	0	90	90	0
Airport Setup Cost	million Rs	35.13	37.68	7.3	41.19	56.13	36.3
Flights per year	-	948	948	0	600	600	0
C_{apt}	Rs/seat	196.81	209.16	6.3	252.41	326.99	29.5
C_{flt}	Rs/seat	2436.05	2433.17	-0.1	2115.88	2099.12	-0.8
With $\mathcal{V} = 100$ Rs/hr and including C_{apt}							
C_{time}	Rs/seat	298.83	297.83	-0.3	373.61	371.69	-0.5
C_{gen}	Rs/seat	3026.70	3035.16	0.3	2836.90	2892.80	2.0
With $\mathcal{V} = 1500$ Rs/hr but excluding C_{apt}							
C_{time}	Rs/seat	3057.50	3042.50	-0.5	3354.17	3325.42	-0.9
C_{gen}	Rs/seat	5588.55	5570.67	-0.3	5565.05	5519.54	-0.8

Table I.13: Effect of very high C_{time} on 19-OG-400 and 30-OG-400 aircraft

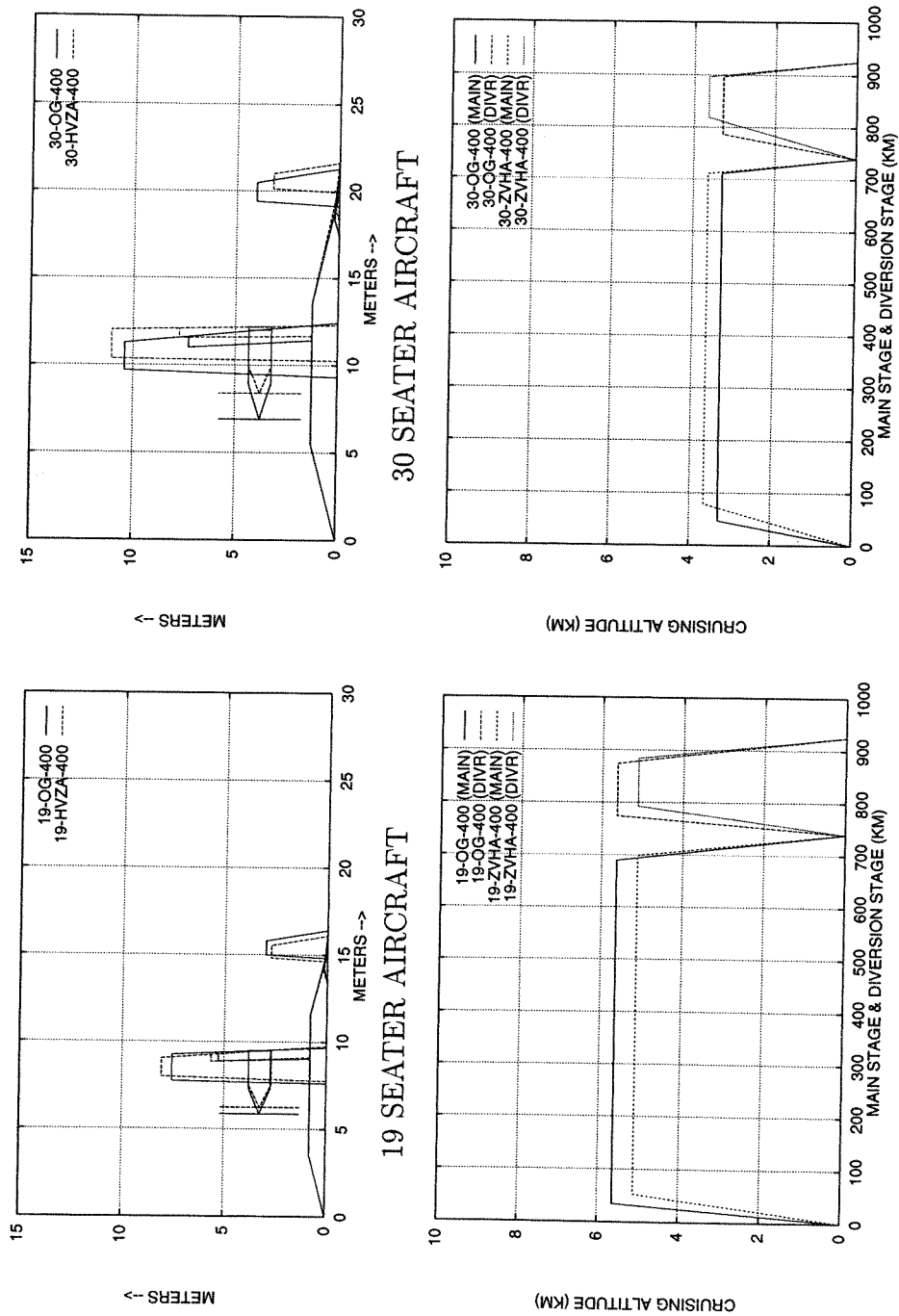


Figure I.7: Effect of high C_{time} on configuration & mission profile of 19 & 30 seater aircraft

varying between 27.5% to 20 %. Further, it can be seen that the un-pressurised aircraft covers a much larger horizontal distance during descent, compared to the pressurised one. As a result of a much lower cruising altitude and lesser cruise stage fraction, the un-pressurised aircraft has a higher performance requirement.

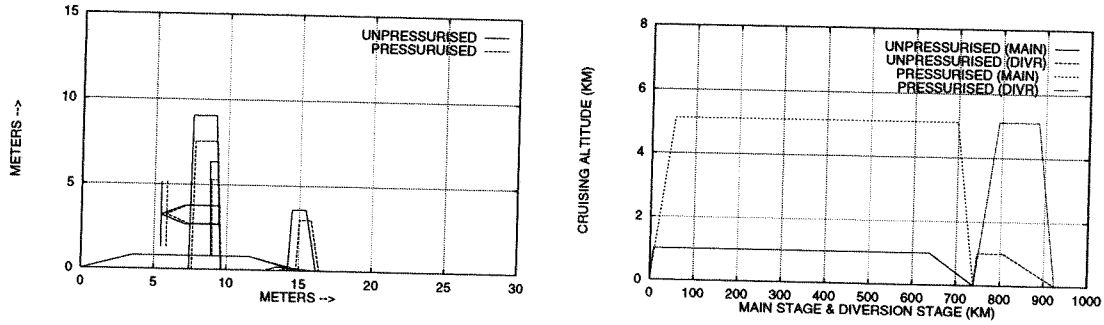


Figure I.8: Configuration & mission profile of 19 seater pressurised & un-pressurised aircraft

I.5 CRAGER as an aircraft evaluation tool

The aim of this section is to demonstrate the applicability of CRAGER as a powerful tool for comparative analysis of commuter & regional aircraft for a specific route. A case study was carried out in which the C_{gen} of a few existing 50 seater aircraft, and the optimum 50 seater aircraft obtained by CRAGER was evaluated and compared. Three stage lengths were considered, viz., 100, 200 & 400 nm and cost terms applicable in India in 1996 were used.

The aircraft parameters of 5 present day regional aircraft with passenger capacity ≈ 50 seats was obtained from [139] for stage lengths of 100, 200 & 400 nm. This data is listed in Table I.14, and was supplied as input to the Cost Estimation Module (Refer Appendix F) to estimate the acquisition cost (C_{AAC}) of these aircraft. DOC_{snm} of these aircraft for operation over stage lengths of 100, 200 & 400 nm was then estimated. It may be noted that though the values of C_{AAC} & DOC_{snm} for these aircraft have been quoted in [139], they were not used in this comparative analysis, since the formulae and assumptions for DOC estimation were not applicable for the present case study. Table I.14 also includes the relevant data for the optimum (i.e. minimum C_{gen}) 50 seater aircraft obtained by CRAGER for these three stage lengths.

Table I.15 lists the M_{fuel} & T_{blk} for the actual and optimised 50 seater aircraft for the three stage lengths. It may be noted that for the optimum aircraft determined by CRAGER (i.e. 50-OG-XXX), the data in Table I.15 corresponds to the three different

Aircraft	N_{pax}	M_{TO}	P_{TO}	BFL	b_w	D_{fus}	L_{fus}	OEM	LFL
Units	-	kg	kW	m	m	m	m	kg	m
ATR42-320	46	16700	1567	1090	24.57	2.87	22.67	10290	940
CN235-100	40	15100	1396	1475	25.81	2.90	21.40	9800	1520
DASH8-300	50	18997	1777	1180	27.43	2.69	25.68	11658	1175
FOKKER 50	50	19990	1866	1200	29.00	2.70	25.25	12520	1160
SAAB 2000	52	22000	3100	1360	24.76	2.31	27.03	13500	1280
50-OG-100	50	17716	1972	1375	26.19	2.70	22.91	10261	1391
50-OG-200	50	18062	2451	1213	25.07	2.70	20.23	10811	1393
50-OG-400	50	17365	2209	1331	23.39	2.70	22.34	10299	1412

Table I.14: Input data related to actual and optimised 50 seater aircraft

Aircraft name	100nm		200nm		400nm	
	M_{fuel}	T_{blk}	M_{fuel}	T_{blk}	M_{fuel}	T_{blk}
Units	kg	min	kg	min	kg	min
ATR42-320	299	35	584	59	868	102
CN235-100	312	39	500	66	878	115
DASH8-300	348	35	569	57	1019	98
FOKKER 50	354	37	566	57	1001	100
SAAB-2000	433	31	689	48	1152	82
50-OG-XXX	231	36	494	55	884	101

Table I.15: Block Fuel & Block Time for actual and optimised 50 seater aircraft

aircraft listed in Table I.14. Table I.16 compares the various terms of C_{gen} for all the aircraft at the three stage lengths. The C_{time} (and hence the C_{gen}) of the optimum 50 seater aircraft determined by CRAGER are slightly higher than the values quoted earlier in Table I.9, since in this analysis, no upper limits were enforced on C_{acq} for all the aircraft, to ensure uniformity. The optimum aircraft obtained by CRAGER have the lowest C_{gen} per seat-nm for stage lengths of 100 & 200 nm. For the 400 nm sector, however, SAAB-2000 & DASH8-300 are seen to be slightly superior to 50-OPT-400.

AIRCRAFT	N_{par}	C_{time}	C_{flt}	C_{apt}	C_{gen}	DOC	DOC_{snm}	$C_{gen_{snm}}$
Units	-	Rs/seat	Rs/seat	Rs/seat	Rs/seat	\$/seat	c/s-nm	Rs/s-nm
COMPARISON OF ALL AIRCRAFT FOR STAGE LENGTH = 100NM								
ATR42-320	46	351.33	927.63	267.26	1641.72	914.38	19.88	16.42
CN235-100	40	315.00	1077.28	361.13	1784841	923.38	23.08	18.48
DASH8-300	50	358.33	920.70	299.18	1673.21	986.47	19.73	16.73
FOKKER-50	50	361.67	971.62	367.58	1795.87	1041.03	20.82	17.96
SAAB-2000	52	361.67	933.50	410.87	1801.04	1040.18	20.00	18.01
50-OG-100	50	359.22	789.68	387.99	1631.89	846.08	16.92	16.32
COMPARISON OF ALL AIRCRAFT FOR STAGE LENGTH = 200NM								
ATR42-320	46	378.33	1307.31	267.26	2047.90	1288.63	14.01	10.24
CN235-100	40	360.00	1513.04	388.46	2356.50	1296.89	16.21	11.78
DASH8-300	50	395.00	1246.45	299.18	2035.63	1335.48	13.35	10.18
FOKKER-50	50	395.00	1276.15	367.58	2133.73	1367.30	13.67	10.67
SAAB-2000	52	390.00	1211.44	410.87	2107.31	1349.89	12.98	10.54
50-OG-200	50	391.82	1125.96	353.40	1966.19	1206.38	12.06	9.83
COMPARISON OF ALL AIRCRAFT FOR STAGE LENGTH = 400NM								
ATR42-320	46	450.00	1929.60	267.26	2741.86	1902.03	10.34	6.85
CN235-100	40	440.83	2307.70	361.13	3204.66	1978.03	12.36	8.01
DASH8-300	50	463.33	1862.13	299.18	2719.64	1995.13	9.98	6.80
FOKKER-50	50	465.83	1919.47	367.58	2847.89	2056.58	10.28	7.12
SAAB-2000	52	446.67	1756.36	410.87	2708.90	1957.09	9.41	6.77
50-OG-400	50	468.67	1778.45	380.17	2722.29	1905.48	9.53	6.81

Table I.16: Comparison of C_{gen} terms of actual and optimised 50 seater aircraft

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