OPTIMIZATION OF REGIONAL AIRCRAFT CONFIGURATIONS FROM PASSENGERS' PERSPECTIVE

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Abstract. This paper outlines the methodology for integration of overall system cost (***OSC***) in conceptual design and optimization of civil aircraft for short-haul business travel. The ***OSC*** consists of the generalised cost of travel incurred by the passenger, which includes cost terms related to access, flight, and setting-up and operating the airport. The optimum configuration and trajectory of a commuter/regional aircraft and the associated airport infrastructure that meets the expected level of travel demand at the least possible ***OSC*** is determined.

As a case study, the above methodology was applied for estimating the ***OSC*** related to operation of twin-engined propeller driven regional aircraft for business air-travel in India. Optimum configurations of 15, 20, 30 & 60 seater aircraft were determined for operation over stage lengths of 100 nm to meet the annual one-way passenger demand of 18000. Sensitivity of ***OSC*** of these configurations to change in demand levels, time costs & and the cost terms related to the infrastructure was determined. The 20 & 30 seater aircraft appeared to be the best compromise solutions for low & medium annual passenger demand.

Introduction

During the conceptual design stage, the optimum configuration of a civil aircraft is generally obtained by minimizing a single/mixed objective function, within the constraints imposed. Examples of such objective functions are the Direct Operating Cost, Life Cycle Cost or Gross Weight, with the constraints imposed on field length requirement, one-engine-operative climb gradients etc. From the passenger's perspective, however, the optimum aircraft configuration is the one that minimizes the net amount of money spent for the total journey. A passenger pays for air-travel (or any mode of public transportation) in direct terms, in the form of the Fare F, and in indirect terms, in the form of the money equivalent of time spent in travel (C_{time}). Further, if the aircraft is to be operated in a region not yet connected by air, an extra term appears in the cost equation due to the investment (C_{ap}) which is needed for setting-up and operating the airports and associated infrastructure. In conventional air-transportation studies, only a part of C_{ap} is included in F in the form of landing charges and handling charges or airport tax. This is because the infrastructure associated with air travel (e.g. airports) is either already existing to meet other needs, or is financed by government grants or loans. From the point of view of the airline, it is sufficient to minimize F alone, since it is very closely related to the total flight costs (C_{flt}) incurred by them to provide the service. However, if the overall system costs connected with setting up the air-network are to be minimised, then C_{ap} assumes a large significance, and can become a major driver. From the passengers' perspective, C_{time} also assumes a lot of importance, especially for business travel on short stages, where other modes of travel offer very stiff competition to air-travel.

At first, reduction in C_{ap} may not seem important from the passenger's point of view. In the long run, however, it is in their own interest that out of proportion investment on the infrastructure is not made and ***OSC*** is minimised. The general expression for ***OSC*** can thus be considered as :-

$$OSC = C_{flt} + C_{ap} + C_{time}$$

In a previous study, a methodology was presented for incorporating ***OSC*** and operational aspects in aircraft conceptual design, and a case study was carried out to arrive at the optimum configuration of an Air-Taxi aircraft for a hypothetical network in India.[1] This paper outlines extension of that methodology to determine the optimum commuter / regional aircraft configuration and the associated airport infrastructure that meets the expected level of travel demand for a network at the least possible ***OSC***. It is evident that such an aircraft-airport combination would be the optimum from the passengers' perspective too, since it shall best meet their aspirations in the long run.

Value of time

The concept of "Value-of-Time" (*VOT*) has been discussed widely in transportation research literature, especially in road & rail transport. Simply stated, *VOT* represents the perceived money equivalent of a unit of time spent by the passenger in travel. However, it is very difficult to arrive at a number that represents average *VOT* 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 in how to determine its value ; thumb-rules for *VOT* range from 94 % to 167 % of the average gross hourly income[2]. The perceived *VOT* is usually higher for the waiting and loading/unloading time spent in baggage & security check-in and collection, since it seems to be wholly unproductive from the point of view of passengers. A systematic estimation of *VOT* of business & leisure air-travellers in Australia (based on actual survey of passengers) revealed that there is a great difference in the *VOT* for leisure and business passengers, and that *VOT* for domestic business travel is much higher than that for international travel for business trips[3]. Another time factor that has to be considered is the defer time, which is the average time by which the passenger has to postpone the 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. Defer time can be estimated as one quarter of the average time between flights given by the ratio of the hours of operation to the number of flights per day [4]. Finally, the access time 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 & defer times assume a great importance, since they are usually of the same order of magnitude at the actual journey time.

Commuter Aircraft & 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 and field length requirements. They do suffer from a poor passenger appeal and lower perceived safety levels, especially in the developed countries, but they still quite popular as they offer a major cost advantage. Many small commuter aircraft are unpressurized, 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 [5].

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 less number of flights with larger aircraft from the operating cost point of view. But this results in low frequency, which adversely affects the defer time. 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 lower. 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[6]. As is evident, the optimum aircraft/airport combination is greatly affected by the demand for air-travel, which, in turn is greatly affected by the availability of seats.

The flight profiles of aircraft over short routes are dominated by climb & descent phases, with little or no cruise segment. This offers a challenging task to the aircraft designer of not only arriving at the optimum configuration of the aircraft, but also the optimum trajectory that it should follow during its flight. One such methodology is CASTOR, which is described briefly in the next section.

Brief description of CASTOR

CASTOR[7,8] (Commuter Aircraft Synthesis & Trajectory Optimization Routine) is a computer program (in FORTRAN) for integrated preliminary design and flight profile optimization of twin-engined propeller driven aircraft of conventional layout. It utilizes 22 design variables, of which 10 are design, or "sizing variables" and 12 are flight profile variables (Ref. Table 1).

Configuration related	*Trajectory related*
1. Wing Aspect Ratio	1. Climb Throttle
2. Wing Area	2. Initial Descent Throttle
3. Wing Taper Ratio	3. Final Descent Throttle
4. Wing Thickness Ratio	4. Climb Speed
5. Wing L.E. location	5. Main Stage Cruise Speed
6. Rear Fuselage Length	6. Descent Speed
7. Takeoff Flap Deflection	7. Cruising Altitude (Main mission)
8. Take-off Mass	8. Main Stage Cruise Fraction
9. Total Fuel Mass	9. Notional Stage Cruise Fraction
10. Shaft Horse Power	10. Diversion Cruise Fraction
	11. Diversion Cruise speed
	12. Diversion Cruise Altitude

TABLE 1 - Design Variables of CASTOR

There is a provision in CASTOR to analyse 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 utilize 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 of CASTOR 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. The program uses 12 user-defined constraints to control the optimization in terms of design & operational limitations and to satisfy certain aspects of the methodology used, as shown in Table 2.

Static Margin	= 5 % MAC
Calculated T.O. Mass	= Specified T.O Mass
Calculated Fuel Mass	= Specified Fuel Mass
Balanced Field Length	< BFL_{max}
WAT climb gradient	> 2.4 %
Landing Field Length	< LFL_{max}
Main Stage Length	= climb + cruise + descent stages
Notional Stage Length	= climb + cruise + descent stages
Diversion Stage Length	= climb + cruise + descent stages
Main Cruise Throttle	< 100 %
Diversion Cruise Throttle	< 100 %
Max. Rate-of-Descent	< Specified value

TABLE 2 - Constraints imposed in CASTOR

A peculiar feature of CASTOR is that if the total distance covered during Main, Notional or Diversion stage is more than the specified stage length, the constraint is deemed as violated. The same applies to the constraint on Static Margin, i.e. the constraint is met only for an aircraft having a static margin of 5%, within a small tolerance. Take-off Mass & Fuel Mass are also used as equality constraints. Unpressurized configurations can be analysed by specifying a suitable upper limit on the maximum Rate of Descent. To ensure that the optimum configurations do not have unrealistically large field length requirements, upper limits on the Balanced Field Length and the factored Landing Field Length are also applied.

User defined input values are read for all parameters which are not to be optimised (design constants). CASTOR consists of two distinct modules, the Analysis module and the Optimization module. In the Analysis module, the value of the user-defined Objective Function (which could be Direct Operating Cost, Max. Take-off Mass, or Total Fuel Mass) 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 Optimizer 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. A proprietary multivariate optimization routine MVO[9] was employed for this purpose, which is a conventional gradient based method. Such methods are very sensitive to the starting configuration and are prone to getting trapped at the local minima, hence multiple runs of the optimizer from different starting points are needed before one can be sure of reaching the global minimum. In the present work, the optimization was carried out using a stochastic multi-variable optimization technique called Simulated Annealing. In a comparative evaluation of 5 different gradient based & stochastic optimization methods for aircraft parametric design carried out at Lockheed Aeronautical Systems[10], the best results were obtained with modified Genetic Algorithms & Simulated Annealing methods. Several other researchers have also commented on the superiority these optimization techniques over the gradient-based methods for tackling multi-modal objective functions[11,12,13].

Optimization by Simulated Annealing (SA)

SA was introduced by Metropolis et al.[14] and is based on the thermodynamical analogy of annealing of metals. When molten metal is allowed to anneal (cool slowly), it eventually arrives at a low energy state. If, on the other hand, it is quenched (cooled suddenly), it assumes a high energy state. SA tries to minimise some analogue of the energy in a manner similar to annealing to achieve the global minima. It was first proposed by Kirkpatrick et al [15] for optimization 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).

Details of the SA algorithm. In the present work, the SA algorithm developed by Goffe et al.[13] based on the methodology proposed by Corona et al.[11] for objective functions involving continuous variables was employed. The algorithm starts with a high initial value of temperature T_{init} and a starting set of design variables. Trial sets are then generated using random numbers from the set [-1,1] and initial step length for each design variable v_i. If the function value for the trial set is lower than that for the previous one, the trial set is accepted. Acceptance of a trial set yielding higher function value is random, with a probability decreasing exponentially with the temperature. After N_S steps through all design variables, their step lengths are adjusted, to ensure that roughly half of all the moves are accepted using a varying criterion c_i, in line with the approach followed by Metropolis et al[14]. A 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. After carrying the above loop N_T times, the temperature is gradually reduced employing a geometric schedule governed by the parameter r_t. The algorithm is stopped when the reduction in the function value in N_e successive cycles is less than a small number e.

As with all general purpose optimization methods, some control parameters in S.A. have to be "tuned" to suit the objective function, and to ensure that the optimizer performs efficiently. A bad choice for these parameters can make the algorithm extremely inefficient and may even result in failure to arrive at the global optimum. There are 8 such parameters related to the SA viz. T_{init}, v_i, N_S, c_i, N_T, r_t, N_e and e. Values of 1.0, 20, 2.0, 20 and 0.001 were assigned for v_i, N_S, c_i, N_e and e respectively, as recommended by Corona et al.[11], and based on experience. The most suitable values of the remaining 3 parameters viz. T_{init}, N_T and r_t were determined by numerical experimentation, as in a previously reported study[12,13].

In short, SA explores the entire domain of the function and tries to optimize it while moving both uphill and downhill, enabling it to escape from the local optima. Unlike conventional methods, it is independent of starting values. The change in the step length as the algorithm proceeds provide an insight into the sensitivity of the design variables with the objective function, since large step lengths indicate that the objective function is quite flat in that design variable and vice versa.

Case study for short range business air travel

To bring out the aspects of ***OST*** discussed above, a case study was carried out for short range business travel in India. Even though only about 1% of the total population of India currently travel by air, the demand for domestic air travel has been steadily growing in the last two decades by 10%, and it 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 [16,17,18].

In keeping with the general policy of economic liberalisation, the domestic air-travel segment was partially deregulated by the Indian government in 1994 under the "open-sky policy". This has resulted, till date, in the creation of 8 privately operated scheduled airlines, and 25 air-taxi operators, with many more such projects in the pipeline[17]. To ensure that these new airlines do not operate only on a select few commercially attractive (but already saturated) trunk routes between major cities, certain restrictions were imposed on their route structure. The routes were divided under three categories in the decreasing order of commercial attractiveness, and certain proportion of the total ASM (Available Seat Miles) flown in Cat-I routes had to be in Cat-II & Cat-III routes. The rationale for these restrictions seems to be to ensure that the airlines fulfilled 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.

The National Airports Authority of India (NAA) has budgeted a sum of Rs 150 billion (US $ 477 million) during the next 5-year plan and Rs 320 billion (US $ 10 billion) for 1997-2002 for development of airport infrastructure, most (if not all) of which will have to be generated from self-financed projects[16,17]. NAA is keen to adopt the BOT (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 project on infrastructure development 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.

The present case study is based on a hypothetical scenario and tries to arrive at the minimum ***OST*** solution for setting up an air-network in India between a metropolis and a town located at distance of 100 nm (185 KM), essentially aimed at business travel. Such a short range may seem improper for air-travel, but presence of geographical barriers and lack of adequate infrastructure for surface transportation (such as in some Cat-II & III routes in Northern & Western India) may make air-travel worthwhile. Since the market is new and untested, the expected travel demand is unlikely to be very high, hence only twin-engined turboprop aircraft are considered. For the baseline case, an annual passenger load of 18000 passengers was considered, which translates to 60 passengers per day, assuming flights on 300 days in an year. It is assumed that a well-equipped airport is already existing at one end, so the costs related with setting up a suitable airport at the other end only are estimated. A constant access cost C_{access} of Rs 95 (and corresponding access time T_{access} of 30 minutes) was considered. Thus, the expression for ***OSC*** turns out to be :-

$$OSC = C_{access} + VOT(T_{access}+T_{block}+T_{defer}) + C_{flt} + C_{ap},$$

where

VOT = Average Value of Time of passengers
T_{block} = Block time for the flight (Trip Time + 9 mins. for Take-Off & Landing)
T_{defer} = Defer time
C_{flt} = Total Flight cost per passenger
C_{ap} = Cost of setting-up & running the airport, per trip per passenger.

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. Thus, the average duration of the time period during which demand for travel can be assumed to exist is 12 hours in a day. Commuter 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 is assumed that the flights are scheduled at equal intervals during the daytime, with a constant passenger load factor of 0.85. T_{defer} is then directly dependent on the total number of flights scheduled per day.

Optimum configurations of 15, 20, 30 & 60 seaters of conventional configuration with minimum DOC for 100 nm range were obtained using CASTOR, as shown in Table 3. All aircraft were able to fly 5 stage lengths of 100 nm without refuelling, which is a desirable operational feature to reduce their turn-around time and to reduce the infrastructural requirements at the newly set-up airport. The constraint on BFL and LFL was relaxed as the aircraft size increased, since all the aircraft are assumed to have conventional aerodynamics. In all the cases, the powerplant seemed to get sized to meet the BFL and OEI climb gradient constraint. The optimum 20 seater aircraft, in fact, needs lesser engine power than the 15 seater, and hence flies slower, and has lower overall fuel requirement. All aircraft, except the 60 seater, were unpressurized, hence the optimum cruising altitude was near the lower permissible limit of 1500 m, to meet the constraint of 500 fpm on the max. rate of descent.

Parameter	*Units*	*15 seater*	*20 seater*	*30 seater*	*60 seater*
MTOW	kg	8481	9447	14265	23958
Wing Area	sqm	48.36	57.34	68.02	76.89
W/S	kg/m^2	175.37	164.75	209.72	311.59
W_{empty}	kg	5529	6111	9561	15350
$W_{fuel\ total}$	kg	1374	1297	1655	2087
$W_{fuel\ mission}$	kg	200	203	232	314
$W_{payload}$	kg	1578	2040	3050	6520
T.O. Power	HP	1274	1137	1717	3000
Power Loading	HP/kg	0.300	0.241	0.241	0.250
V_{cruise}	m/s	106	98	114	118
$L_{fuselage}$	m	20.55	22.08	28.67	31.80
$D_{fuselage}$	m	1.60	1.60	2.50	3.00
b_{wing}	m	25.05	27.02	29.74	31.56
Abreast		2	2	3	4
BFL	m	850	900	1100	1450

TABLE 3 - Optimum aircraft configurations obtained by CASTOR

Estimates for unit costs of these aircraft were obtained based on their sizing data & performance, using a standard method[19], for an assumed fleet size of 350. If, however, the cost estimates so obtained for these low capacity aircraft exceeded the industry estimates, an upper limit of 200,000 US $ per seat was employed, to make them realistic. The Trip operating costs were obtained based on realistic cost assumptions for various cost elements such as depreciation, interest, insurance, maintenance, crew and fuel for present day Indian conditions[18,19].

This airport is assumed to be financed by capital borrowed at an interest rate applicable for long term projects R_{int} (say 8%). Thus, apart from the costs related to operating the airport, the costs involved in setting up the airport (C_{setup}) are also to be recovered from the passengers utilizing it, over a reasonable period of time AP_{depr} (say 20 years). Hence, if the annual cost of operating the airport are C_{oper}, and the only revenue earned by the airport is through the Landing Charge L_{fee} for each of the N_{trip} annual trips to meet the annual demand of Ann_{pax}, the expression for total airport costs C_{ap} is :-

$$C_{ap} = \left\{ C_{oper} + C_{setup} \cdot \left[\frac{1}{AP_{depr}} + \frac{R_{int}}{2} \right] - L_{fee} \cdot N_{trips} \right\} \cdot \left\{ \frac{1}{Ann_{pax}} \right\}$$

Details of the Airport Model

The aim of the model is to arrive at the configuration and cost of setting-up and running a regional airport based on FAA or ICAO recommendations, given the details of the most critical aircraft, and the expected traffic levels of all aircraft that will be operated from it. Though it is mainly developed for sizing & cost estimation of small regional airports (suitable for operation of twin-turboprop aircraft up to 75 seat capacity) the airside sizing & land area estimation can be carried out even for larger airports.

The three Levels of airports

A database of the aeronautical equipment and facilities available at all currently operational domestic airports in India was developed[20,21]. Using this database, the airports were classified under three levels in the increasing order of cost of investment (Ref. Table 4). The airport level is increased as the number of movements and the duration for which the airport is operational increases, and appropiate amount of aeronautical equipment is provided at the airport. The number of taxiways and aprons are assumed to increase by one with increase in level of the airport. Thus, level-1 airport has only one apron & and additional aprons & taxiways are added along the direction of the length of the runway as the airport level increases.

Airport Level	1	2	3
Investment	Low	Medium	High
Navigational Aids+ Lighting	Tower + NDB + VHF Radio	+ VHF Radio+ Beacon	+Approach Lights + Runway Lights
ATC service	AIS only	Tower Control	Tower+ Approach
Operations	day VFR	day VFR	VFR + IFR
Hours Open	As Required	8 hours	12 hours

TABLE 4 The 3 levels of airport

Geometric sizing of the airfield

The first step in the geometric design of the airport is the estimation of number of runways required and their configuration, followed by their sizing, i.e. estimation of dimensions of the runway pavement, safety area, object free area, obstacle free zone, protection zone, and threshold approach surface. The next step is to determine the runway to taxiway separation, and the taxiway dimensions, followed by separation & sizing of the apron. The geometric sizing of the airport is carried out based on the guidelines provided by FAA & ICAO regulations, which list the minimum recommended dimensions for all of the above, after classifying the airport[22,23,24]. FAA classifies the airports based upon the 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). ICAO also classifies airport using a two-element code, consisting of a *aerodrome code number* (based on the reference field length) and *aerodrome code letter* (based on the wing span & outer main gearwheel span). The Reference Field Length 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. For geometric sizing of the airfields on Indian airports, the ICAO regulations were used.

Passenger terminal sizing

For this, the cost breakdown for the proposed civil enclave at an Indian airport (designed for 400 pax., 200 arriving & 200 departing) is used as the baseline[20]. Such an airport is considered as an upper limit for a regional airport operating twin-turboprop aircraft, so a methodology was developed to scale down the costs related to this enclave, in consultation with architects & approved quantity surveyors. The terminal building is assumed to have a floor area of approx. 14 m^2 per passenger, and is assumed to be constructed in blocks, each suitable for handling 50 passengers. The length to width ratio of the terminal building is assumed to be 4:1, and additional blocks are assumed to be added along it's length. The control tower was assumed to be a part of the passenger terminal building, for which 50 m^2 additional area was provided. The above methodology was used to estimate costs of Passenger Termini of various sizes. It was found that between the block sizes of 50 & 250 passengers, their costs increased linearly with increasing number of passengers.

Estimation of land area

For estimation of the total land area required for the airport, a typical airport layout with one runway is considered. The dimensions & distances between runway, apron, terminal building and approach surface areas are calculated from the ICAO specifications. The distance of the airport boundary fence on the far-side (opposite the terminal building) is kept as 320 m (7:1 slope for 150 ft obstacle). For ICAO regulations, the dimensions of the runway clear zone (below the approach surface) are estimated using guidelines similar to FAA criteria.

Table 5 gives the details of the geometrical sizing, of the airports associated with the four aircraft.

Aircraft capacity	15	20	30	60
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
CLASSIFICATION				
ICAO Code No	2	2	2	3
ICAO Code Letter	C	C	C	C
SEPARATION				
Runway-Taxiway	54.0	54.0	54.0	93.0
Taxiway-Apron	24.5	24.5	24.5	24.5
Fire Category	4	4	5	5
RUNWAY SIZING				
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				
No. of Taxiways	3	2	2	1
Total Length	156	104	104	93
Width	15	15	15	15
APRON SIZING				
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
PAX. TERMINAL				
Pax. Capacity	50	50	50	100
Width	13.23	13.23	13.23	18.71
Length	52.92	52.92	52.92	74.83
LAND AREA				
Airport Width	458.83	460.52	467.76	521.12
Airport Length	970	1020	1220	1570
Runway Clear Zone Area (acres)	14.46	7.784	7.784	13.35
Total Airport Land Area (acres)	138.90	131.64	156.59	228.89

TABLE 5- Geometrical Sizing of the Airports
Note: All dimensions in meters, unless stated

Estimation of airport setting-up costs

Cost of aeronautical equipment

Approximate cost estimates for setting up the infrastructure & equipment and for each level of the airport were obtained from vendors of airport equipment and from the National Airports Authority of India[20].

Runway, taxiway(s) & Apron(s) Construction cost

The budgetary cost estimates for extension of 150 ft wide runway by 1500 ft at 2 Indian airports are used for this purpose, both of which have a runway with LCN of 40. Both these airports have flexible pavements suitable for operation of B-737-200 aircraft. Using LCN charts and B737-200 tyre pressure data[25], LCN 40 was converted to PCN, and thickness of flexible material that would be required for various sub-grade CBR values were evaluated using the ACNFLEX computer program[26] Since the actual subgrade CBR at these airports is not known, average thickness were obtained by calculating the pavement thickness at all the 4 subgrade CBRs, which turned out to be 56 cm. Assuming a cost split of 73 % for material & 27 % for labour for Indian conditions[20], the cost of material and labour for a flexible pavement per m^3 could be estimated.

Land cost

One of the largest components of airport setting up cost is the cost associated with the acquisition and site-preparation of the land. Since land prices show a large variation, a representative value of Rs 50 per sq. m. was chosen in this study[20]. For the level 3 airport, 50% higher costs were assumed, to take into consideration the much larger site preparation costs involved with installing the Runway & Approach lighting, and also due to provision of extra facilities for longer hours of operation and larger number of movements.

Estimation of airport operating costs

Estimates for the annual staffing & running costs for the three levels of airports were made, based on data related to staffing requirements and current salary levels of various categories of airport staff in Indian airports[20]. The staffing at Level 3 airport includes extra staff required due to the extended hours of operations. Based on the fuselage overall length & diameter, the Fire & Rescue category of the airport is determined as per ICAO recommendations[24]. The number and type of equipment, fire-tender & firemen required to man the fire station could be obtained, hence costs involved in setting up the fire-station, and the annual recurring expenses associated with it could be estimated.

The breakdown of airport setting-up and operating costs is given in Table 6. The single largest cost element is seen to be the land cost, varying from 64% of the total set-up costs for 15 seater aircraft to 43% for the 60 seater aircraft. The total set-up costs of the airport for the 15 seater & 30 seater aircraft are quite similar, this is because the higher runway costs for the 30 seater are almost offset by the higher land costs for the 15 seater aircraft. In fact, the land costs 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. The annual gap between income and expenditure of the airports is seen to decrease as the aircraft capacity increases.

Aircraft size	*15 seater*	*20 seater*	*30 seater*	*60 seater*
Airport Level	3	2	2	1
Runway Cost	13.35	15.10	23.03	51.75
Taxiway Cost	1.70	1.21	1.51	1.77
Apron Cost	1.27	1.01	1.80	1.27
Pax. Terminal Cost	2.20	2.20	2.20	3.88
Equipment Cost	2.2	0.80	0.80	0.55
Fire station Cost	2.7	2.7	2.9	2.9
Set-up Cost (without Land cost)	23.43	23.02	33.23	62.12
Land Cost	42.15	26.63	31.68	46.51
Total Set-up Cost	65.58	49.65	63.92	108.63
Staffing Cost	0.80	0.64	0.64	0.41
Consumables	0.30	0.20	0.20	0.10
No. of Firemen	9	9	11	11
Fire station Costs	0.50	0.50	0.61	0.61
Operating cost	1.60	1.34	1.45	1.12
Annual Movements	1200	900	600	300
L_{fee} per trip (Rupees)	339.25	377.89	1208.6	1668.1
Annual Income	0.41	0.34	0.73	0.50
Annual Shortfall	1.19	1.00	0.72	0.62

TABLE 6- Breakdown of Airport related Costs
Note:- All cost terms in 10^6 Rupees, unless stated

Table 7 compares the ***OSC*** of the 4 aircraft-airport combinations to meet the annual passenger demand of 18000. It can be seen that the aircraft unit price for all except the 60 seater aircraft had to be corrected to match industry expectations. The DOC was calculated to reflect realistic fleet utilization levels, since the use of these aircraft is not assumed to be limited to this sector alone. The operating cost per seat-mile are seen to reduce with increase in aircraft size, as expected. A *VOT* of Rs 100 per hour was assumed in the absence of any clear-cut estimates for Indian business travellers. This represents approximately 85% of the average gross income of the travellers, as suggested by Hensher(3). The total C_{ap} for the 60 seater aircraft was seen to be almost equal to C_{flt}, due to very high values of T_{defer}. On the other hand, C_{ap} values are quite low if only the airport operating cost C_{oper} to be recovered from the passengers (as airport tax or passenger handling fee). C_{ap} increases between 3 and 10 times if the airport setting up costs (excluding the land costs) are also to be recovered. However, if land cost is also to be included, C_{ap} increases drastically, between 5.5 times for the 20 seater and nearly 17 times for the 60 seater ! The lowest C_{ap} is seen for the 20 seater aircraft.

The lowest ***OSC*** for was seen for the 20 seater aircraft, but only marginally lower than that for the 30 seater. When C_{time} is ignored (by considering zero *VOT*), but the total C_{ap} is considered, the 30 seater aircraft has the lowest ***OSC***. Only in the case when C_{flt} & C_{oper} alone are considered, the 60 seater aircraft has lower ***OSC*** than the 30 seater. Hence the 30 seater aircraft is the best overall compromise solution for this scenario.

***OSC** Estimation (In Rs., unless stated)*	*15 seater*	*20 seater*	*30 seater*	*60 seater*
Aircraft Price (10^6 US $)	3.00	4.00	6.00	11.06
Annual Utilization (hours)	2076	2120	2054	1987
Total Annual Flights	3049	2960	3092	3226
DOC (cents per seat mile)	14.48	12.78	10.87	9.97
Flight Cost	703.41	621.06	527.88	403.54
Flight Time (minutes)	41	43	40	37
Number of flights per day	4	3	2	1
Defer Time (minutes)	45	60	90	180
Time Cost (*VOT*=100 Rs)	193.08	221.64	266.42	411.58
C_{ap} (operating cost only)	65.99	55.27	39.99	34.14
C_{ap} (partial set-up cost)	183.14	170.39	201.15	344.73
C_{ap} (total set-up cost)	393.91	303.57	359.57	576.30
TOTAL ***OSC***	1385.41	1241.27	1248.87	1486.21
OSC with *VOT* = 0	1192.33	1019.63	982.45	1074.63
OSC with partial C_{ap} only	1174.63	1108.09	1090.45	1254.65
Ranking as per C_{oper} only	4	3	2	1
Ranking with partial C_{ap}	3	2	1	4
Ranking with Total ***OSC***	3	1	2	4
Ranking with *VOT* = 0	4	2	1	3

TABLE 7 - ***OSC*** Comparison for the 4 aircraft for Annual Passenger Load = 18000

Figure 1 shows the variation of various cost terms as the passenger capacity increases for the baseline case.

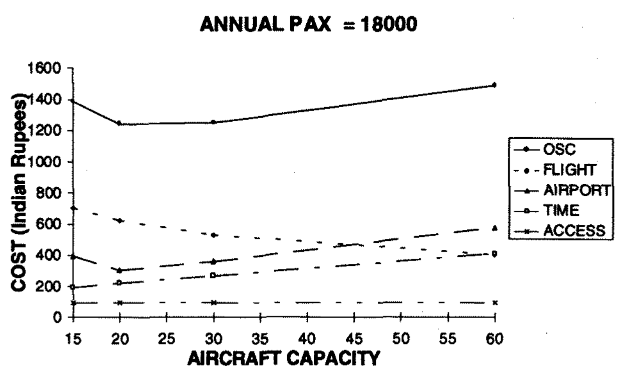

Figure 1 - ***OSC*** breakdown for baseline case

Sensitivity analysis

It is fairly obvious that as the number of passengers that use the air-network increase, C_{ap} 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 ***OSC*** 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 ***OSC*** to changes in demand was carried out by studying the effect of doubling, tripling, halving, and quartering the annual passenger load.

Figure 2 shows the effect of doubling the annual passenger load on ***OSC***.

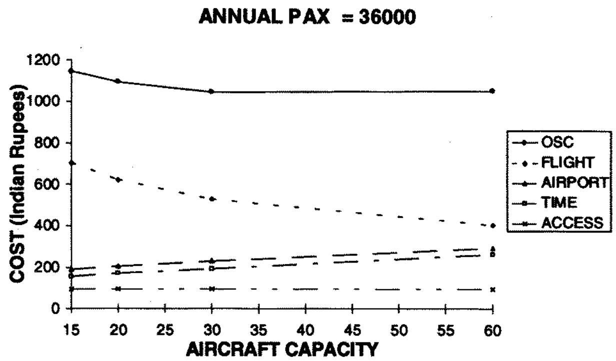

Figure 2 - Effect of doubling Ann. Pax. Load on ***OSC***

The 30 seater aircraft has the lowest ***OSC*** for this case, with 60 seater not very far behind. For the 60 seater aircraft, the increase in C_{ap} and C_{time} slightly offset the decrease in C_{flt}.

For annual passenger load of 54000, however, the 60 seater has the lowest ***OSC***, as shown in Figure 3

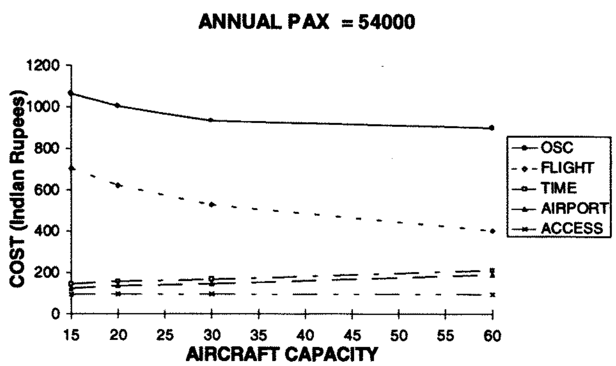

Figure 3 - Effect of tripling Ann. Pax. Load on ***OSC***

This is because C_{ap} & C_{time} are now much smaller components of ***OSC***, and it thus follows the trend of C_{flt}. The difference in the ***OSC*** 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 ***OSC***. This trend may not be the same for ever increasing aircraft sizes, since beyond a certain point, the airport requirements may increase much beyond what a level 3 airport provides, hence C_{ap} may increase drastically, altering the whole picture.

The situation is completely reversed for lower passenger loads. Figure 4 shows the ***OSC*** breakdown for an annual passenger load of 9000 passengers. In this case, the decrease in C_{flt} is overcome by increase in C_{time} itself, hence ***OSC*** follows the trend of C_{ap} itself.

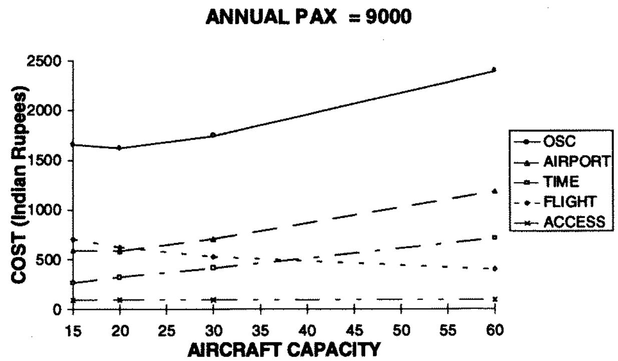

Figure 4 - Effect of halving Ann. Pax. Load on ***OSC***

The 20 seater aircraft has the lowest ***OSC*** for this case, closely followed by the 15 seater. For the 60 seater aircraft, C_{ap} and C_{time} are seen to be even larger than C_{flt}.

Finally, Figure 5 shows the effect of very low passenger loads (only 4500 per year) on ***OSC***.

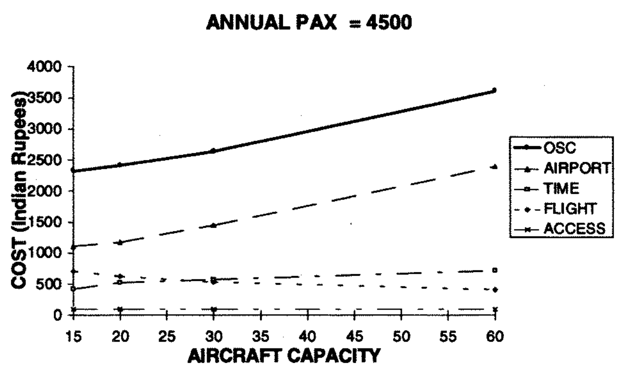

Figure 5 - ***OSC*** breakdown for very low demand

It can be seen that ***OSC*** is dominated by C_{ap} for this case and is excessively high for 30 and 60 seater aircraft. higher passenger capacity. The 15 seater aircraft is the clear winner in this case, but the magnitude of ***OSC*** is quite high. In all the above figures, C_{access} is constant, but is included in the figures to provide a quick visual comparison of the magnitude of ***OSC*** for each case.

Conclusions

The case study revealed that for low passenger loads, C_{time} and C_{ap} are the most dominant terms in ***OSC***, hence low capacity aircraft were seen to have low ***OSC***. 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 ***OSC*** for all the passenger loads. Within the limitations of the case study, it can thus be concluded that small to medium capacity aircraft are more suitable for short-haul travel when ***OSC*** is considered, since the inherently lower seat-mile costs of larger aircraft are more than offset by the increase in costs related to time and the airport infrastructure.

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