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Airplane Conceptual Design Based on Genetic Algorithm

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ABSTRACT

Aircraft design is still a complex engineering process and many decisions are made based upon qualitative choice of the designer. The use of genetic algorithm (GA) as design and optimization methodology for Aircraft can help to reduce the number of qualitative decisions. The Fajr is a super short takeoff (T.O.) and landing (SSTOL) Aircraft, which is designed to fulfill the desire for new short runways such as heliports, center-city-to-center-city travel and carrier on-board delivery (COD) military Aircraft. The objective function for the optimization was a minimization of life-cycle-cost (LCC). Results of the design methodology are discussed, which shows the ability of the GA to perform Aircraft conceptual design. In this approach best SSTOL Aircraft configuration of word, such as a Boeing YC-14 and QSRA is evaluated by GA method and designer can follow a systematic approach to find the most appropriate configuration. Using this approach, the time and the cost of conceptual design can considerably be reduced.

Key Words: Genetic Algorithm, Aircraft Conceptual Design, Optimization

طراحی مفهومی هواپیما براساس الگوریتم ژنتیک

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چکیده

طراحی هواپیما، یک مسأله پیچیده مهندسی است که به مقدار زیاد به ابتکارات فردی و سلیقه‌ای طراحی متکی است. برای کاهش اتکاء به این وابستگی، از تکنیک الگوریتم ژنتیک به عنوان متدولوژی طراحی و بهینه‌سازی هواپیما، استفاده شده است. هواپیمای فجر یک هواپیمای نشست و برخاست فوق کوتاه است که برای تأمین مسافرت‌های کوتاه از مرکز شهر به مرکز شهر، جابجایی و باربری هوایی روی ناو، طراحی شده است. نتایج بدست آمده از این متدولوژی با بهترین هواپیمای همرده موجود دنیا نظیر YC-14 و QSRA مقایسه‌ای رضایت بخش داشته و حکایت از قابلیت این الگوریتم به عنوان متدولوژی طراحی مفهومی یا مقدماتی داشته و قابلیت این الگوریتم را به عنوان روش پیشرفته و سازمان یافته‌ای جهت یافتن ساختارهای مناسب و مقایسه آنها تأیید می‌نماید که با استفاده از خصوصیات این روش، زمان مقایسه طرح‌های مختلف و در نتیجه رسیدن به طرح بهینه کاهش یافته و دقت افزایش می‌یابد.

واژه‌های کلیدی: الگوریتم ژنتیک، طراحی مفهومی هواپیما، بهینه‌سازی

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Introduction

Aircraft (A/C) Life Cycle includes: Research, Development, Test, and Engineering (RDTE), Acquisition, Operating and Disposal. The RDTE phases span the initial part of the A/C program and begin with mission definition and conceptual design, move through trade studies and preliminary design, and conclude with detailed design and flight test. Acquisition consists of A/C manufacturing and delivery to the customer. In this paper, we want to optimize A/C Life-Cycle-Cost (LCC). Many different optimization strategies have been applied to engineering design problems. Recently, the GA has emerged as viable alternative for A/C optimization [1].

For the past few decades, short-commute center-city-to-center-city travel has been a desire. The mission requirements (Table 1) for a Super Short Takeoff (T.O) and Landing (SSTOL) A/C were provided in Air Army of Iranian Navy.

Table 1. Mission Requirements.

Warm up and taxi for 10 minutes
T.O within a ground roll of 300 ft.SL, SA+27°F
Climb at best R/C to best cruising altitude
Cruise at best cruise speed (350 knots), 1500 nm
Descend to SL (no credit for range)
Land with fuel reserves within ground roll of 400 ft
Taxi to gate for 5 minutes
Soldier Capacity – 24 passengers & baggage
Overhead stowage space shall be provided
Weight of soldier and baggage – 200 lbs
Can accommodate priority cargo, soldiers or both
Must be capable of carrying 2 boxes
Wing folding allowed for spot of 60 ft by 29 ft
Maximum payload is 10000 lbs
Technology availability date is 2005

Design requirements for the Fajr included a T.O ground roll of 300 ft and Landing ground roll (L.G.R) of 400 ft, cruise at 350 knots with a range of up to 1500 nm with domestic fuel reserves, payload of 24 passengers and baggage for a commercial version or a military version with a 10,000 lb payload and wing folding allowable to meet spot factor requirement of 60 feet by 29 feet.

Genetic Algorithm Theory

The GA is based upon Charles Darwin's survival of the fittest theory of evolution. It copies the natural selection and reproduction processes of biological populations in order to strengthen the fitness of the overall population.

In biological evolution, the population characteristics or variables are encoded as chromosomes within a string of DNA that completely defines the individual. Over several generations, the population becomes optimal in its environment as defined by their fitness [2].

The GA, as an optimization methodology, is set up in the same manner. That is, individuals are defined by some binary encoding of variables and compete with the rest of their population for survival. The fit individuals reproduce and pass the desired traits on to future generations, while less fit individuals perish. After several generations, the population tends to cluster around the optimum.

The characteristics or design variables, which describe the individuals in a population, are binary encoded into what essentially represents a string of DNA. Once the traits of an individual are defined, a method is needed to determine the relative goodness of individuals. This is accomplished by creating a cost function or fitness function, *F(x)* that depends upon the values of each of the design variables. More weight may be placed on some design variables than others, but each contributes some positive or negative contribution to the overall fitness of the individual. In order to create subsequent generations, the individuals must compete against each other for the rights of procreation. The more fit individuals tend to reproduce more often, while the less fit tend to die out. This exists within the GA as well as in biological populations. The reproduction strategy of tournament selection ranks the population from most to least fit, and begins a random process of selecting parents with the goal of creating children. Two parents are selected to produce two children. Parent individuals, with a high fitness, will be chosen to reproduce more often than individuals with a lower fitness. Over time, the stronger traits will be retained while the weaker traits vanish. The children in most GA techniques replace the parents in the next generation. Some selection techniques, however, allow parents to compete with their children for entry into the next generation. Also, an elitist strategy may ensure that the best individual of the current generation is cloned into the next generation. This prevents the best traits from accidentally dying off. Crossover techniques define the chromosomal make-up of the children by mimicking the natural processes of DNA reproduction. The binary strings of both parents are combined in some way to produce their children. There are two basic types of reproduction: single point and uniform crossover.

After selection and crossover, mutations are also permitted to explore regions of the design space that may have already become extinct or never been explored. A jump mutation swaps two random bits within the child's binary string, and a creep mutation randomly selects a bit to be changed. The standard GA flow that has just been described is shown in the left side of Figure 1. The exit criteria may be set at some given number of generations, or after some measure of convergence has been reached. Eventually, the population will tend to converge to a common point. This would occur if the GA were allowed to run for an extended amount of time. An illustration of this can be seen in human biological evolution. The Europeans and Africans each progressed down separate paths. The Europeans developed pale skin, while the Africans developed dark skin. These isolated populations are said to have converged because each individual, within the separated populations, holds a common trait. The GA, as an optimization tool, can also arrive at this kind of convergence in design within the design The GA should also be run several times to account for this convergence and the inherent random processes. The initial creation of individuals, selection of parents, crossover reproduction, and child mutations are all based on random number draws. Different results can be expected between one initial randomization seed and another. On the other hand, these differences are not guaranteed and different seeds could end with the same results. It is important that several different initialization seeds be performed for any given problem that has some degree of randomization [3]. The GA used for this paper [4] incorporates tournament selection, binary coding, both jump and creep mutation, and either single-point or uniform crossover. Inputs to the GA allowed for variation in the number of variables, bounds on the variables, and numerous other options. Based on the work of others, the population was set at 100 individuals [5], [6]. The uniform crossover rate was 50%, the jump mutation rate 1%, and the creep mutation rate 6%.

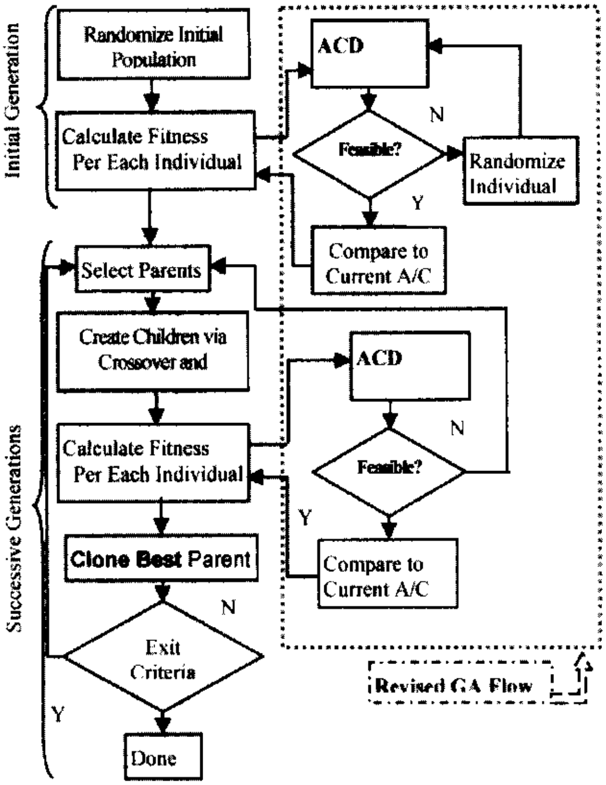

Figure 1- Std and Revised GA Flow For A/C Design.

Design Philosophy and Procedure

A review of current A/C found two A/C, which were similar in size to that expected for the Fajr and had similar ground roll performance capabilities. The first is the Quiet Short-haul

Research A/C (QSRA), which utilizes Upper Surface Blowing (USB) flaps to achieve spectacular short field performance for a fixed wing (F.W) A/C. A second A/C with similar performance is the Canadair CL-84 tilt wing (T.W) at Figure 2. The Fajr designer chose to investigate two designs: a T.W and a F.W A/C with USB flaps. At this paper, at first we explain classical A/C conceptual design and then optimize this design via GA.

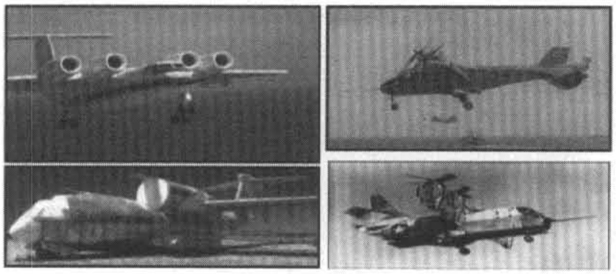

Figure 2- Three view of QSRA, Boeing YC-14, Canadair CL-84,XC-142.

Preliminary Weight and Performance Sizing

Initial weight and performance sizing was performed to calculate the weight, wing area, and installed thrust/power for both design. The weights of both A/C were calculated based on the known mission profile and regression coefficients that relate the empty and takeoff (T.O) weight. This requires the assumption of lift-to-drag ratios, specific fuel consumptions, and propeller efficiencies. The required landing and T.O distances were the only constraints considered in the initial performance constraint sizing. Sizing for the F.W A/C was used to find ranges of the thrust-to weight ratio and the wing loading that met both the T.O and landing requirements. An initial value for wing loading was chosen, and iterations on the thrust-to-weight ratio were conducted until the T.O distance requirement was met. The wing-loading value from the T.O distance computation was used to calculate the landing ground roll , which is approximately independent of the thrust-to-weight ratio [7]. The assumed maximum lift coefficients were based on a review of USB data from the YC-14 [8]. Table 2 summarizes the weight and performance sizing results.

Table 2. Preliminary Weight and Performance Sizing.

Parameter	*F.W*	*T.W*
T.O Weight (lb)	48635	59922
Empty Weight (lb)	25487	34588
Fuel Weight (lb)	12504	14635
Wing Loading	47lb/ ft^2	86lb/ ft^2
T/W or Power Loading	0.60.	5.7 lb/hp
Wing Area	1000 ft^2	700 ft^2
Installed Thrust or power	30000lb	10500hp

Configuration Design

A/C Performance constraints as well as structural and aerodynamic considerations dominated selection of the final configuration. This section describes the fuselage design, wing, empennage, and landing gear.

Fuselage Design

The cockpit was laid out for a two-crewmember configuration. The seating and window layouts were arranged to meet all applicable. The resulting layout (Figure 3) was a two-by-two arrangement of two containers forward, each side-by side, and two containers aft, also side-by-side. A 6" clearance has been provided between the cargo wall and the cargo at all locations, and ample vertical clearance has been included to allow ceiling clearances during loading and unloading. The passenger cabin consists of accommodations for 24 soldiers. The seating arrangement is single aisle, with two seats on each side of the aisle. The seat pitch and width are 32 and 19 inches [9, 10].

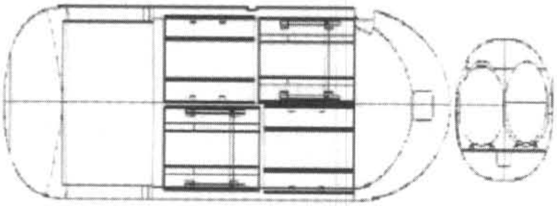

Figure 3- Cargo Layout.

Wing Design

Wing designs for both configurations were severely restricted by geometric constraints - a 29 ft by 60 ft storage requirement for the military version of the A/C. IRAN Navy geometric constraints include a desire for a maximum wingspan of 64 ft, a storage height requirement of 18.5 ft, and, if wing folding is used, a maximum height of 24.5 ft while folding [9]. The high wing design was desirable for the T.W. The F.W configuration utilized both pivoting and wing folding to comply with the geometric constraints. Using this storage method permitts the Navy's maximum desirable wingspan of 64 ft while still meeting all geometric constraints. The T.W configuration also utilized wing pivoting and folding devices. Table 3 summarizes the final geometric parameters for the F.W version.

Table 3. Fixed wing- Wing Geometry.

Wing Parameter	
Wing Area, S_{ref}	1150 ft^2
Span, b	64 ft
Aspect Ratio, AR	3.56
Taper Ratio, λ	0.8
Quarter Chord Sweep, $\Lambda_{c/4}$	5°
Root Chord, c_{root}	19.97 ft
Tip Chord, c_{tip}	15.97 ft
Mean Aerodynamic Chord, MAC	18.04 ft
Average thickness to chord, $(t/c)_{avg}$	14 %
Dihedral, Γ	0°
Incidence Angle, i_w	1°
Twist Angle, ε_t	-3°
Fuel Volume	17,505 lb

High Lift and Powered Lift Design

There are many ways to achieve high lift coefficients using methods such as: USB, leading edge blowing, jet flaps, and circulation control wings. Two different approaches to achieving low T.O and landing speeds and the associated short T.O and landing distances were considered for the Fajr design: USB flaps, and a T.W configuration. By placing the engines in a way that the exhaust is directed over the upper surface of the wing, the USB system provides boundary layer control for the aft part of the wing, which is prone to separation. The flaps also deflect the engine exhaust, providing a vectored thrust component. A review of past A/C designs utilizing USB, such as the Boeing YC-14 [8] and QSRA [10, 11] indicate that lift coefficients of 8 to 12 are possible [12]. Maximum lift coefficients for the Fajr were 4-5 in the T.O configuration and 10- 12 in the landing configuration. The lift coefficients achieved by the QSRA and Fajr for similar flight conditions were within approximately ± 20% [13]. An alternate configuration considered for the Fajr was a T.W A/C. The T.W offers several advantages over a tilt-rotor, such as the Bell/Boeing V-22.

Empennage

Preliminary tail sizes were initially calculated using the volume coefficient method [13]. The unconventional design of the Fajr (large wing chords and relatively low wingspan) made it difficult to obtain reasonable results from this method. Instead of volume coefficients, the horizontal tail sizing used a longitudinal X-plot or scissors plot [14]. The IRAN Navy carrier height requirement coupled with the required upsweep angle required for T.O rotation constrained the span of the vertical tail. The vertical tail area was sized to meet One Engine Inoperative (OEI) minimum control speed requirements. A balancing moment due to the asymmetric thrust and the wind milling drag of the inoperative engine must be generated at 1.2 times the landing stall speed without stalling the vertical tail. Due to the large vertical tail reference area and the height constraint, twin vertical tails placed as end plates on the horizontal tail were used. Table 4 summarizes the relevant horizontal and vertical tail geometry parameters.

Table 4. Empennage Geometry.

Parameter	**H. Tail**	**V. Tail**
Reference Area, S_{ref}	190 ft^2	208 ft^2
Span, b	29 ft	14 ft
Aspect Ratio, AR	4.43	1.88
Taper Ratio, λ	0.8	0.8
Sweep, $\Lambda_{c/4}$	5°	5°
Root Chord, c_{root}	7.28 ft	8.25 ft
Tip Chord, c_{tip}	5.82 ft	6.60 ft
Mean Aero. Chord, MAC	6.58 ft	7.46 ft
Avg thickness to chord, $(t/c)_{avg}$	12 %	10 %
Dihedral, Γ	0°	N/A
Volume Coefficient, $V_{h/v}$	0.2068	0.0617

Landing Gear

To allow the A/C to T.O and land without problems, the longitudinal location of the main landing gear is driven by aerodynamic requirements. The Fajr's upsweep clearance angle was designed to comply with the pitch angle necessary for T.O and landing. Furthermore, the tip-over angle [15] between the aft limit for the C.G and the bottom of the main tires should be greater than the upsweep clearance angle to prevent the C.G of the A/C from traveling aft of the main gear pivot point during T.O rotation. The Fajr design meets these criteria with a minimum longitudinal tip-over angle of 21°. The nose gear must carry enough loads for the A/C to be able to steer while maneuvering on the ground. Therefore, a load percentage for the nose gear of 8%-20% of the A/C weight is required, with values closer to 8% preferred [15]. The nose gear load percentage for the Fajr was 9% for the military version and 15% for the commercial version. The landing gear could not interfere with the cargo space; therefore, it was decided to place the gear in blister fairings on the sides of the fuselage. Furthermore, the turnover angle should be less than 54° for A/C-carrier-based vehicles, and less than 63° for land-based vehicles [15]. The Fajr achieved this clearance with the implementation of kneeling landing gear.

Propulsion Selection & Installation

Propulsion systems were selected for two configurations: the T.W with four turboprop engines [16] and the fixed wing with four turbofan engines. Four turboprop engines geared to two propellers comprise the propulsion installation for the T.O. This configuration eliminates the need for cross shafting between the engines for engine out control in a two-engine configuration. The geometric constraints limit the span of the wing so it must be folded or pivoted. Folding alone did not work for the four-engine configuration because the engines could not fit on the unfolded section of the wing. Instead, the more costly and heavier pivoting wing and wing folding was necessary for the four-engine configuration. The pivoting wing allows the wingspan to be nearly the fuselage length, and thus there was enough space to arrange all four engines.

For the F.W design, either two or four turbofans were considered. Two-engine configurations have the advantage of requiring fewer maintenance hours and slightly higher efficiency compared to the smaller engines that would be used in a four-engine configuration. However, the FAR minimum climb gradients for engine out would require severe over sizing of the engines for the Fajr. Also, the USB flaps depend on engine flow and cross shafting of the engines (as done in the YC-14 [8]) and would be necessary if there was only a single engine on each wing. This would make the engines 'custom' built and relatively expensive. The ALF502 turbofan engine was selected as representative of a high bypass-ratio turbofan engine for the four-engine F.W configuration [17].

The engines for the F.W design were placed far forward of the wing (Figure 4) for USB over the wing. The maximum cruise specific fuel consumption was compared to the maximum efficiency of modern high bypass engines at transonic cruise, which have maximum efficiencies between 34-38% [14]. Figure 5 contains the installed cruise carpet plot for this turbofan engines.

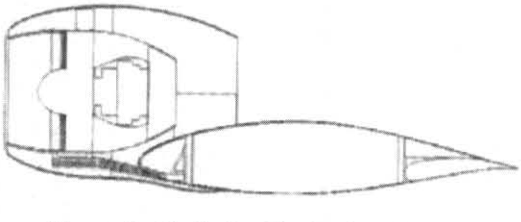

Figure 4 - Turbofan Engine Installation.

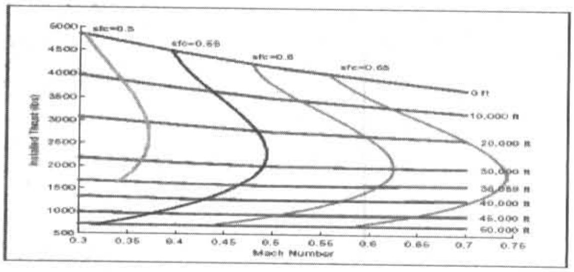

Figure 5- Maximum Cruise Carpet Plot.

Structural Layout

The structural layout was based on structural configurations of existing cargo A/C such as the C-130 [18], and consists of standard frames, longerons, ribs, and spars along with the specialized structural components (Figures 6-7). The wing spars are located at 25% and 70% of chord, which allows the 30% chord flaps and ailerons to be attached directly to the rear spar. For the empennage surfaces, spars are located at 25% and 75% chord with 25% chord rudders and elevators attached to the rear spars. Rib spacing for the wing and empennage surfaces is 24 inches. The fuselage frame depth is 3 inches with spacing of 24 inches. Fuselage longerons are spaced every 12 inches.

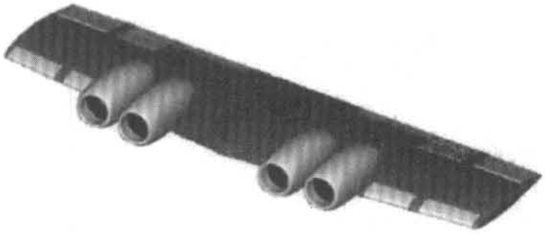

Figure 6- Wing Structural Arrangement.

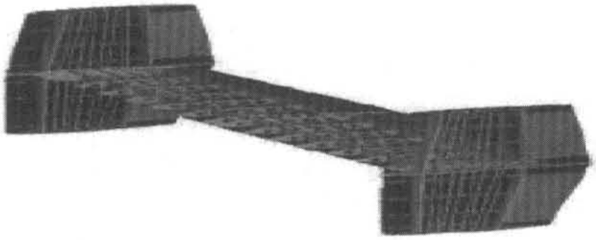

Figure 7- Empennage Structural Arrangement.

Weights and Balance

An estimate of the vehicle loads is the first step in the process of A/C weight calculation. A speed – load factor (V-n) diagram represents the maximum load factor that the A/C would be expected to experience as a function of speed.

The maneuver diagram represents the maximum load factor the plane can achieve aerodynamically. Atmospheric disturbances also exert loads on the airframe. The gust diagram represents the magnitude of these loads. The limit load factor may be read from the plot as the maximum load factor experienced by the A/C and may occur on either the gust or the maneuver line. The ultimate load factor is then 1.5 times the limit load factor as determined from the V-n diagram (Figure 8). The component weights for structural components and systems for the Fajr were calculated using equations based on statistical correlation of existing A/C. These relations included methods from the US Air Force (USAF), US Navy (USN), Torenbeek, and General Dynamics (GD) [18, 19]. Many of the component weights are functions of the T.O weight; therefore, it was necessary to make an initial guess for the T.O weight. Table 5 summarizes the component weight breakdown for the Fajr. The A/C C.G location (and how it moves as the plane is loaded and unloaded) affects landing gear placement, the ability of the A/C to rotate during T.O, and stability/control. The following configurations were analyzed to determine the range over, which the C.G would be expected to change: (a) full fuel with military payload, (b) full fuel with commercial payload, (c) no fuel with military cargo, and (d) no fuel with commercial cargo. The C.G excursion was found to be approximately 5% of the wing MAC and never moves aft of the main gear.

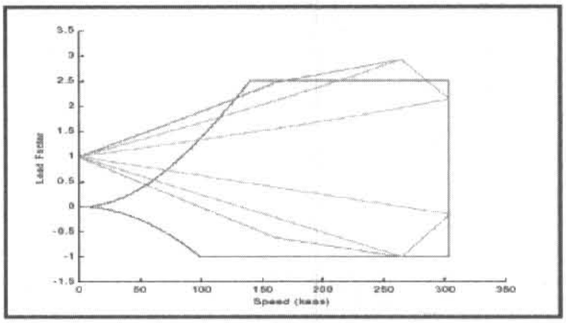

Figure 8- V-n Gust and Maneuver Diagram.

Table 5. Weight Breakdown (lb).

Component	Military	Commercial
Wing	3322	2966
Horizontal Tail	509	509
Vertical Tail	438	438
Fuselage	3457	3457
Nacelles	1125	1125
Nose Gear	274	274
Main Gear	1232	1232
Engines	4334	4334
Fuel System	676	676
Propulsion	374	374
Flight Controls	669	669
Hydraulic	501	501
Inst. & Avionics	853	853
Air Condition & ..	1283	1283
Electrical System	1741	1741
Oxygen	65	65
APU	401	401
Furnishings	223	2056
Baggage Handling	26	26
Auxiliary	255	255
Paint	226	226
Empty	22027	23460
Trapped Fuel & Oil	251	251
Crew	400	600
Fuel	14483	13883
Payload	10000	4920
T.O	46761	43114

Drag Calculation

A standard drag build-up approach was used to calculate the drag polar [14]. Total drag was calculated from three sources: parasite, induced, and compressibility drag. Figure 11 shows the drag polar for the cruise phase.

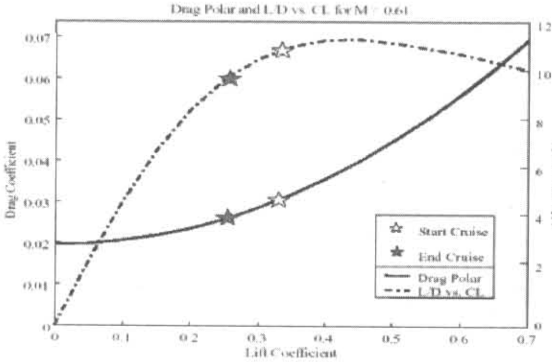

Figure 9- Cruise Drag Polar.

Stability and Control

The stability and control characteristics must comply with the FAR 25 and MIL-8785C for the commercial and military version. These regulations place restrictions on the allowable range of frequencies and damping ratios for the A/C. Roll control and engine out control are also regulated [18,20]. Table 6 summarizes the frequencies, damping ratios, and time constants for landing and cruise. FAR 25 require that the minimum control speed be less than 1.2 times the stall speed in the landing configuration [20]. MIL-F-8785C requires the minimum control speed to be less than or equal to the highest of: (a) 1.1 times the stall speed, or (b) the stall speed plus 10 knots.

Table 6. Frequencies and Damping Ratios.

PARAMETER	Landing Config(0 ft, 55 knots, 33860 lbs)	Cruise Config (37000 ft, 350 knots, 41000 lbs)
Short Period	ω_{nSP}= 2.2 rad/sec	ω_{nSP}= 4.61 rad/sec
	ζ_{SP} = 0.35 (~)	ζ_{SP}= 0.74 (~)
Phugoid	ω_{nP}=0.031rad/sec	ω_{nP}=0.134 rad/sec
	ζ_{nP}= 0.041 (~)	ζ_{nP}= 0.05 (~)
Spiral Const.	T_s = 150.5 sec	T_s= 94.6 sec
Roll Const.	T_r = 1.02 sec	T_r = 0.82 sec
Dutch Roll	ω_{nD}= 1.08 rad/sec	ω_D= 2.63 rad/sec
	ζ_D = 0.21 (~)	ζ_D= 0.0803 (~)

Many of the design requirements for the Fajr involve minimum performance requirements; for example, range, cruise speed, and T.O /L.G.R requirements. The RFP requires that the Fajr have a maximum T.O ground roll of 300 feet and a maximum L.G.R of 400 ft. Due to the stringent T.O and landing distance requirements for the Fajr, Using integral equations for the T.O and landing distances [7]. A simple Euler integration was used to compute the ground rolls. For the variation of thrust with speed for turbofan engines, the performance code implemented a simple correlation between Mach number and the ratio of actual to static thrust [14]. The variation of thrust with speed and rotor angle for the T.W A/C was computed from data in Ref. 7. For the T.W configuration, a force balance was done at each step in the integration to determine whether the plane had taken off. Landing speeds for the T.W were computed by iterating to find a stable unaccelerated descent profile with a flight path angle of no more than -7°. Once the touchdown speed was established, the same method of integration was used to determine the L.G.R. Figure 10 shows that at this weight the T.O ground roll is 289 ft. The maximum T.O weight of the Fajr is 46,761 lb. The L.G.R constraint was imposed at the maximum landing weight which was assumed to be 85% of the maximum T.O weight (39,747 lb), with a resulting ground roll of 273 ft. Using the method outlined in Ref. 7 the climb rate was computed from drag, weight, and propulsion data. The AEO climb performance for various altitudes and Mach numbers is summarized in Figure 11. Range was computed by numerical integration of the specific range from begin cruise weight to end cruise weight. The specific range, or range factor, is defined as the number of nautical miles, which can be flown per pound of fuel. This value was computed for a range of A/C weights, speeds, and altitudes. Figure 12 contains a plot of the specific range for the Fajr over a range of weights at an altitude of 37,000 feet. The range specified does not allow a range credit for descent, and requires adequate remaining fuel reserves after landing. In the case of USN cargo and transport A/C, which was the critical version of the Fajr for sizing purposes, the fuel reserve requirement is the greater of (a) 10% of mission fuel (including one approach, a wave-off, a go-around, a second approach, and trap) or (b) fuel equal to 30 minutes of loiter at sea-level speeds plus 5% of mission fuel [7]. The end cruise weight was iterated to provide adequate reserves, and the resulting range was computed from the known beginning and ending cruise weights. A payload-range diagram was constructed to show the effects of various combinations of payload and fuel loading. Figure 13 shows that at the design payload of 10,000 lbs, the military version of the Fajr has a range of 1,500 nm. The ferry range, representing the maximum range of the A/C, was calculated to be 2,968 nm. Table 7 summarizes the range for various configurations of the Fajr.

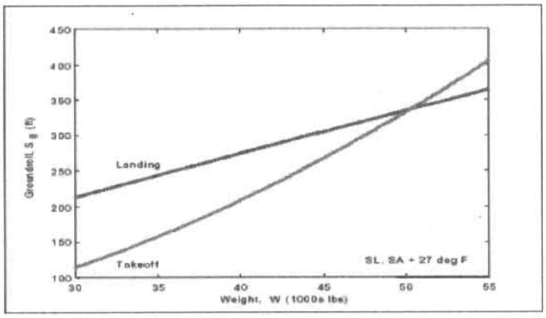

Figure 10- T.O and L.G.R.

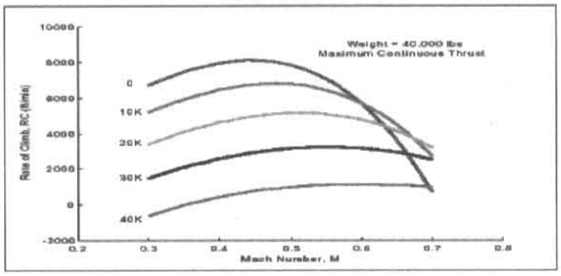

Figure 11- AEO Climb Rate.

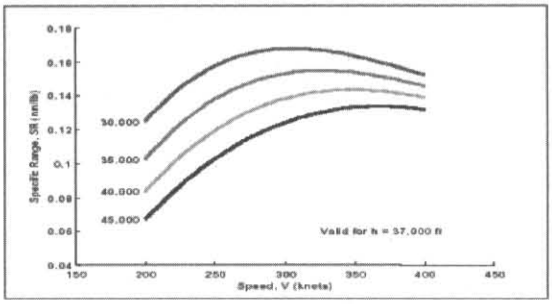

Figure 12- Specific Range.

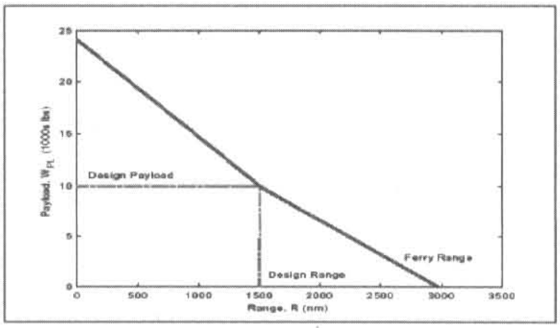

Figure 13- Payload Range.

Table 7. Range of Commercial and Military.

Version	T.O Weight	Payload Weight	Range (nm)
Military	46,761	10,000	1500
Commercial	43,114	4,920	1988
Commercial	42,608	4,920	1500

Cost Calculation

The basic approach to cost calculation consists of a simple cost breakdown - calculating the cost for several A/C program phases, and then summing the estimates to compute LCC [18]. In the cost analysis, the number of A/C played a significant role - many cost numbers, particularly operating cost and LCC, depend heavily on the production run. For the analysis discussed herein, a production run of 750 A/C, of one version (commercial or military), was assumed. For actual operation of this A/C, the production run will be 750 A/C. The total cost of acquisition is calculated as the sum of the manufacturer's cost plus the manufacturer's profit. Program operating cost is the cost associated with the operation of the A/C. This cost accounts for the largest fraction of the LCC. Operating cost consists of two parts: Direct Operating Cost, and Indirect Operating Cost. The operating cost is based on statistical data gathered for many existing A/C [18]. The estimate for this major cost factor takes into account many parameters associated with A/C operations such as mission range, number of years of operation, and number of A/C acquired by the customer. Figures 14 summarizes the LCC (military and commercial version for 750 A/C).

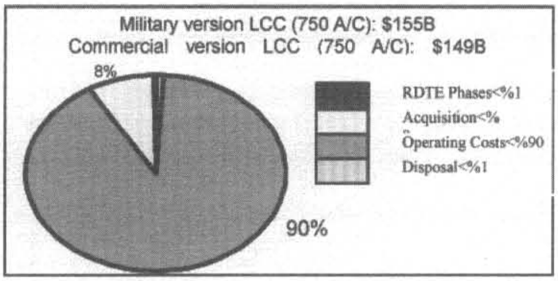

Figure 14- LCC Breakdown.

Design Optimization

The goal of this optimization was to make the best A/C design (ACD). For the Fajr, several design variables, Table 8, were chosen to describe the best design. Each of these design variables describes A/C geometry, performance, or cost metrics. At first, the designer investigates several different A/C designs: two SSTOL A/C (a T.W and a F.W), and one VTOL A/C (also using the T.W configuration). The revised GA flow is given in the right side of Figure 1 (block with dash line) for A/C design optimization. Figure 15 shows a flow chart laid out to simplify the design procedure. The chart shows only feed forward - a concerted effort was made to eliminate feedback, which would require iteration at the subsystem level, rather than overall design iteration at the systems level. The left-hand side shows the design variables. The purpose of constrained optimization is to transform a complex problem into much simpler sub problems that can be solved using GA. Typically, the constrained problem is written as an unconstrained problem with penalty functions for constraints at, near, or beyond their limits. The constrained problem is then converged upon when the limit of a sequence of parameterized unconstrained optimizations is reached. The GA method was implemented in an optimization code written using the Matlab Toolbox. Restrictions on the decision variables were written as constraints, mathematical expressions relating to the decision variable and its bound with inequalities and/or equations. The constraints, summarized in Table 9, were derived from several different areas. Some came directly from the Request for Proposal (RFP), others came from basic engineering guidelines for A/C design, and still others came from FAR. The objective function (*F(x)*) for the optimization was a minimization of LCC. The three baseline designs were studied in both the military and commercial configurations, and then optimized with respect to LCC. For all cases, the optimizer ran successfully (iteration numbers ranged from 196 to 324) and produced the "optimal design" for each configuration. After careful consideration of the cost metrics used to select the best design, the SSTOL F.W configuration shown in Figure 16 was selected. Table 10 summarizes the results for both a vertical and short T.O T.W, and F.W USB version, all for the military design requirements. Although the constraints for the Fajr design were fixed by the RFP, the team felt it useful to show that by relaxing those parameters very slightly, the design would become lighter, less costly, and more efficient. The T.O and landing distance requirements were the most difficult constraints to meet. The Fajr optimal design was heavily influenced by the T.O and landing distances - both were a major design driver. To analyze how significantly the T.O and L.G.R impacted LCC; the constraints were relaxed by 100 ft. The LCC resulting from this constraint relaxation was $130 B. For the optimal design with the original constraints, the LCC was $154 B. A mere 100 ft of runway reduced the LCC by almost $25 B. Figure 17 shows how LCC depends on T.O ground roll (the more difficult of the two constraints to meet). Summary of optimized design (F.W military version) is shown in Table 11, optimized constraint values in Table 12 and cost comparison between initial designs in Table 13.

Table 8. Design Variables.

Group	Variable
Body	Length, diameter
Wing	S_{ref}, span, taper ratio, thickness-to-chord ratio, sweep angle, wing location
Empennage	S_{ref}, span, taper ratio, thickness-to-chord ratio, sweep angle, tail location
Propulsion	Installed thrust/power, engine model (sfc, T_{avail} vs. speed, T_{avail} vs. altitude), engine type, engine numbers
Landing Gear	$\text{distance}_{\text{nose-to-nose gear}}$, $\text{distance}_{\text{nose-to-main gear}}$, lateral position of main gear
Configuration	CFG_{type}
Mission Profile	Cruise altitude, cruise speed, cruse range

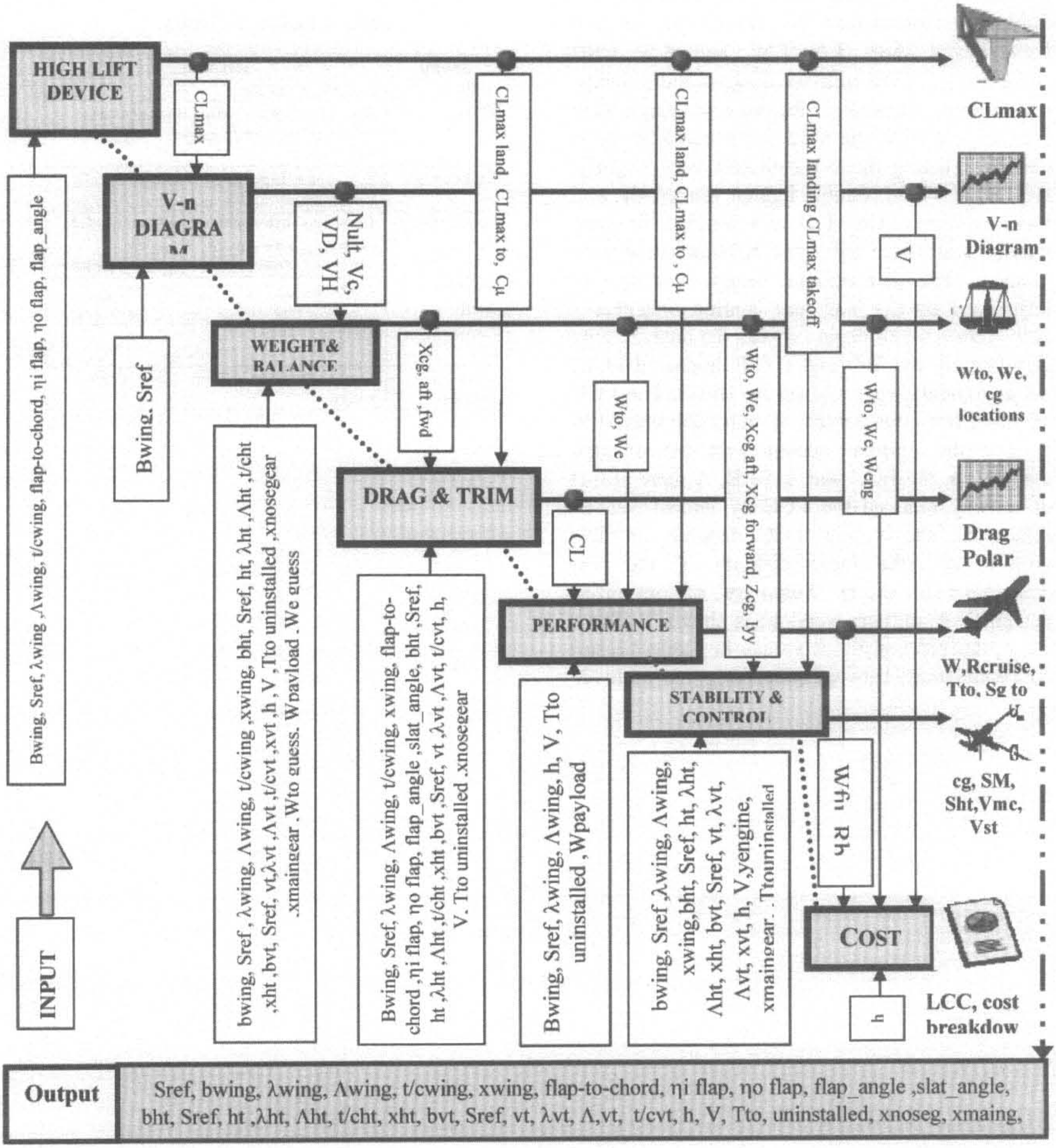

Figure 15- Aircraft Conceptual Design (ACD) Flowchart.

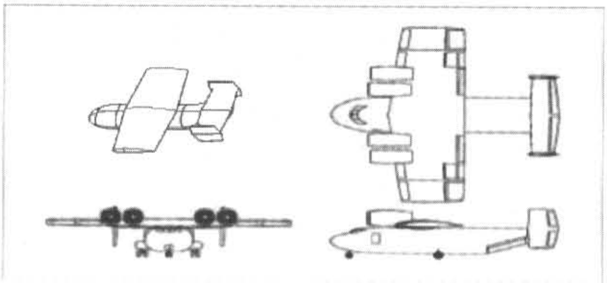

Figure 16- Three-View of Final FAJR Design.

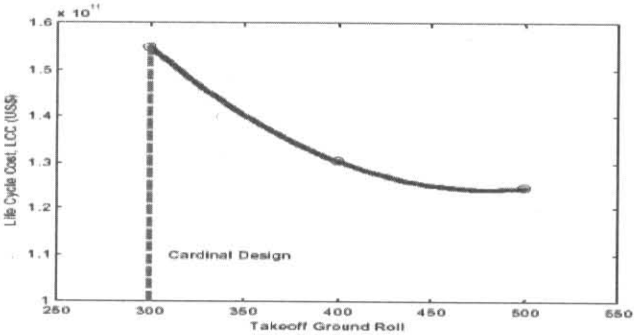

Figure 17- Variation of LCC with T.O G.R Constraint.

Table 10. Design Comparison for Military Version

	Vertical T.O T.W	Short T.O T.w	Short T.O F.W
DOC	\$9.06/nm	\$7.82/nm	\$7.03/nm
IOC	\$1.81/nm	\$1.56/nm	\$1.41/nm
Fuel Price	\$1.20/gal	\$1.20/gal	\$1.20/gal
Engine	\$1.09 M	\$0.81 M	\$0.52 M
AEP	\$20.8 M	\$18.0 M	\$17.1 M
AMP	\$19.7 M	\$17.3 M	\$16.7 M
LCC	\$200.6 B	\$172.1 B	\$154.7 B

Table 11. Summary of Optimized Design (F.W Mil. Version).

Design variable	Initial guess input	Optimized output
Wing Area	1035 ft^2	1150 ft^2
Wing Position	16.5 ft	15.0 ft
Horizontal Tail Area	225 ft^2	190 ft^2
Vertical Tail Area	275 ft^2	208 ft^2
Thrust	33000 lb	22875 lb
Takeoff Weight	46312 lb	46761 lb
Cruise Speed	350 ktas	350 ktas
Cruise Altitude	35000 ft	37000 ft

Table 12. Summary of Optimized Constraint Values.

Constraint	Bound	Initial	Optimal design
Takeoff ground roll	300 ft	184 ft	290 ft
Landing ground roll	400 ft	347 ft	315 ft
Cruise range	1500 nm	960 nm	1500 nm

Table 13. Cos t Comparison Between Initial Designs.

COST METRIC	FIXED-WING	TILT-WING
Operating Cost	\$7.03/nm	\$7.82/nm
Acquisition Cost	\$17.1M	\$18.0 M
Life Cycle Cost	\$154.7B	\$172.1B

Conclusion

To assess which method was the most cost efficient to use, a F.W configuration with USB was designed. Wing and high lift design; propulsion selection and performance characterization, structural layout and design, drag polar buildups, stability and performance analysis, cost calculation and optimization via GA were performed for both designs. Collaborative optimization was then used to minimize (LCC) for the F.W design. A F.W design with USB was selected for its lower LCC. To understand how the design requirements affect the costs, several design studies were conducted. The cost associated with vertical T.O using a T.W A/C was calculated to cost 16% more than the F.W design with short T.O and landing capabilities. Sensitivity analysis showed that increasing the T.O ground roll requirement by 100-200 ft would decrease LCC by 15-20%. The airplane price of Embraer ERJ-145 A/C is 15.5 USM\$ and Canadair Challenger A/C is 20USM\$ which shows that the airplane price of Fajr A/C (17.1 USM\$) seems reasonable.

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