Diesel engine application on AEW&C turboprop effectiveness-cost assessment

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Abstract

Purpose – The purpose of this paper is to perform a technical and economical analysis on the conversion of a regional turboprop platform for Airborne Early Warning and Control (AEW&C) missions by supposing installation of supplementary diesel turbo-charged engines.

Design/methodology/approach – The problem has been approached by considering all issues related to conversion to AEW&C platform. Class II methods have been used for weight and drag estimations. Flight performances have been evaluated by using standard equations of flight mechanics. Costs have been evaluated by using a model developed by the authors.

Findings – As far as performances are concerned, it is possible to increase aircraft service ceiling of about 4,400 ft by installing auxiliary diesel engines in separate wing-nacelles. The low specific fuel consumption (SFC) of diesel engines balances the reduction of mission endurance caused by the aerodynamic drag increment (i.e. additional drag of AEW radar antenna and new nacelles). The proposed solution is shown to have the best Effectiveness-Cost performance in comparison with other AEW&C aircraft-systems.

Practical implications – To convert regional turboprops to AEW&C platform by employing turbocharged diesel engines could be an interesting future perspective for aerospace companies interested in creating a new AEW&C market segment.

Originality/value – The proposed solution gives the possibility to reduce operating costs in the AEW&C mission field. The issue is actual due to typical high operating costs of AEW&C missions.

Keywords Aircraft engines, Operating costs, Airborne Early Warning and Control (AEW&C), Diesel engine application, Effectiveness-cost analysis, Direct operating cost

Paper type Research paper

Nomenclature

Symbols

A = max. continuous to take-off engine power ratio
a_i = relative importance coefficient of parameter "i"
A_i = acquisition cost per unit weight for subsystem "i"
B_i = scaling factor of subsystem "i" in equation (19)
CD_0 = zero-lift drag coefficient
$CD_{0\ AEW\&C}$ = CD_0 of AEW&C converted platform
$CD_{0\ Antenna}$ = CD_0 contribution of AEW&C radar antenna
$CD_{0\ Base}$ = CD_0 of basic version
$CD_{0\ Diesel\ Nacelles}$ = CD_0 contribution of diesel engine nacelles
$CD_{0\ Fuselage}$ = CD_0 contribution of fuselage
$CD_{0\ H\ Tail}$ = CD_0 contribution of horizontal empennage
$CD_{0\ Interference}$ = CD_0 contribution of interferences
$CD_{0\ Pylons}$ = CD_0 contribution of pylons to sustain radar antenna
$CD_{0\ Turboprop\ Nacelles}$ = CD_0 contribution of turboprop engine nacelles
$CD_{0\ V\ Tail}$ = CD_0 contribution of vertical empennage
$CD_{0\ Wing}$ = CD_0 contribution of wing
C_f = skin friction coefficient
C_i = average unit acquisition/maintenance cost (USD) for subsystem "i"
CL = lift coefficient
$CL_{min\ pow}$ = CL at minimum power AoA
D_{HOR} = distance of visual horizon (km)
E = aerodynamic efficiency
e = Oswald efficiency coefficient
$E_{min\ pow}$ = E at minimum power AoA
FF_c = shape factor
h = flight altitude (km)
k = induced drag coefficient
K = scaling factor in equation (18)
K_i = learning curve effect coefficient for subsystem "i"
MTOW = maximum take-off weight (kg)
n = power decrease coefficient
N_p = number of produced subsystems "i"
OEW = operating empty weight (kg)

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P_a	=	maximum engine available power (kW)
P_{max}	=	maximum engine available power at sea level (kW)
P_n	=	required power for flight (kW)
P_s	=	maximum shaft power (kW)
P_{TO}	=	take-off engine power (kW)
Q_c	=	interference factor
Q_i	=	main characteristic of subsystem "i" (e.g. weight)
R_E	=	mean earth radius (km)
S	=	wing area (m^2)
SFC_{diesel}	=	specific fuel consumption diesel engine (gr/kWh)
SFC_{global}	=	specific fuel consumption for combined solution with both diesel and turboprop engines operating (gr/kWh)
$SFC_{turboprop}$	=	specific fuel consumption turboprop engine (gr/kWh)
S_{ref}	=	reference surface area (m^2)
S_{wet}	=	wetted surface area (m^2)
t_i	=	duration of the flight phase "i" (h)
U(x)	=	global effectiveness of a platform
$U_i(x)$	=	effectiveness of parameter "i"
V_z	=	vertical speed (m/s)
W	=	in-flight aircraft weight (kg)
W^i_{Fuel}	=	fuel weight necessary for flight phase "i" (gr)
$W_{Max\ Fuel}$	=	maximum fuel weight (kg)
W_{Pay}	=	payload weight (kg)
ΔCD_0	=	CD_0 variation due to AEW&C conversion
λ	=	wing aspect ratio
ρ	=	air density (kg/m^3)
σ	=	density ratio (air density/SL air density)

Definitions, acronyms and abbreviations

AEW&C	=	airborne early warning & control
CERs	=	cost estimation relationships
DOC	=	direct operating cost
IFF	=	identificator friend or foe
ISA	=	international standard atmosphere
LOS	=	line-of-sight
MAW	=	Missile approach warner
MDO	=	multidisciplinary design optimization
MIDS	=	multifunctional information distribution system
MMH/FH	=	maintenance man hour/flight hour
POL	=	petrol, oil and lubricant
RAMS	=	reliability, availability, maintainability and safety
RWR	=	radar warning receiver
SATCOM	=	satellite communication
TACAN	=	tactical navigation
SFC	=	specific fuel consumption
SL	=	take-off
UAS	=	unmanned aircraft system

Introduction

Airborne Early Warning and Control (AEW&C) identifies a mission profile which consists of the surveillance of an assigned airspace in order to detect possible hostile flying objects as aircraft or missiles. Nowadays in a global environment where terroristic attack eventuality has not to be underestimated, it is quite mandatory for a nation the possibility to assure a complete surveillance on its airspace. Systems able to comply with AEW&C functionality typically are converted civil or cargo aircrafts. Conversion usually implies the installation of an airborne radar system above the fuselage. The use of an airborne radar system, instead of a land-based one, allows having a higher visual horizon due to the higher height. This permits to have an early warning of a hostile presence into the assigned airspace so that it is possible to adopt countermeasures against it. Therefore, a good AEW&C platform typically assures a service ceiling at least of 30,000 ft. For this reason AEW&C platforms are:

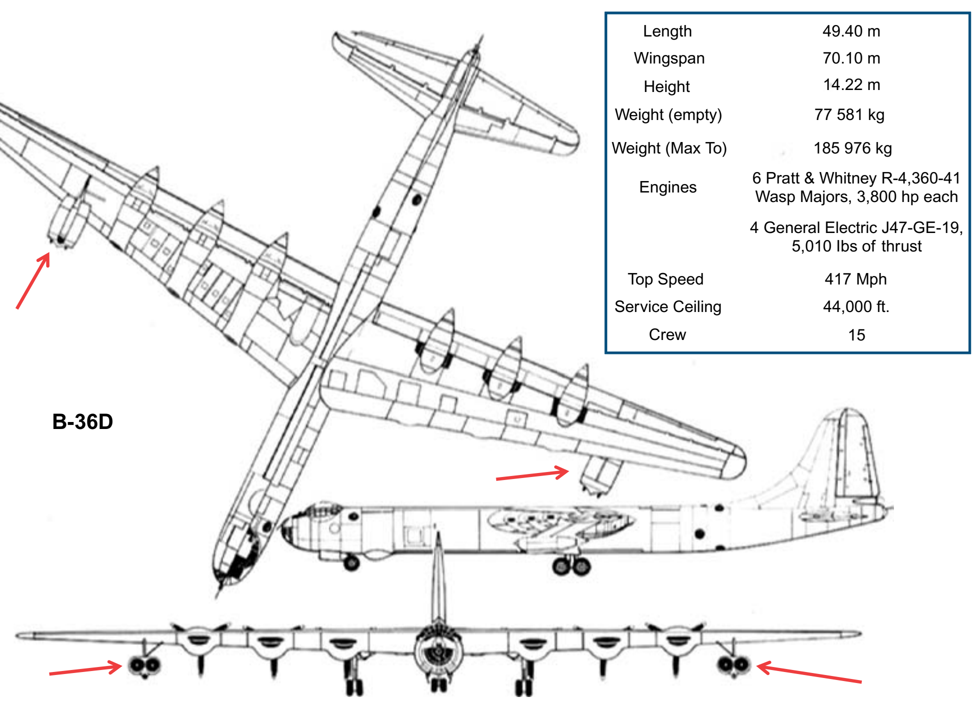
- jet liners (e.g. Boeing 737 or Embraer 145) which typically has no compliance problem with altitude requirement; and
- regional turboprops with a power to weight ratio above 0.20 kW/kg (e.g. Saab 2000 or Saab 340B). It is to notice that in regional turboprop category typical values for power to weight ratio are 0.16-0.17 kW/kg (e.g. ATR 72-500).

AEW&C jet liners concern high operating costs, AEW&C turboprop platforms offer lower operating costs than jet ones. It is possible to obtain a further reduction of operating costs by supposing the employment of a typical regional turboprop platform with typical values of power to weight ratio. The main problem to solve is the low service ceiling of this category, which is about 25,000 ft. It is possible to solve this problem by installing two auxiliary turbocharged diesel engines in separate wing-nacelles. Considered diesel engines will be analyzed in detail in the article, they assure a constant power with the altitude until 32,808 ft in order to contrast the rapid decrease of turboprop engine power with altitude; in addition, diesel engines has a lower SFC than turboprop engines that are installed on the considered platform. This last assertion is the reason for which it reasonable to think that proposed solution has less operating costs than a typical AEW&C turboprop platform with high power to weight ratio engines and so with higher SFC. The addition of supplementary auxiliary engines is unusual in aeronautic field but it is possible to find an example of such a solution in the strategic bomber Convair B-36D. Four jet engines were installed in addition to six piston engine in order to assure a better maximum speed performance. The solution was not so efficient because piston engines and jet engines needed two different fuel types; this led to separate fuel system installation. Our solution is more efficient in this point of view because the same fuel type supplies both turboprop engines and considered diesel engines so minimal modifications to fuel system of the platform are necessary. Figure 1 shows specifications of Convair B-36D where additional jet engines are putted in evidence.

Conversion to AEW&C platform: technical analysis and effectiveness-cost assessment

The present work can be divided in three sections. At first the problem of conversion of a regional turboprop aircraft to an AEW&C system is analyzed by considering all related issues. Conversion process leads to the definition of the AEW&C system;

Figure 1 Convair B-36D specifications



it is possible to conduct a performance analysis focusing on two relevant parameters for AEW&C patrolling: service ceiling and endurance. In the end, by defining a common mission profile, it is possible to perform the evaluation of direct operative costs of several AEW&C platforms and to assess an effectiveness-cost analysis in order to demonstrate validity of proposed solution. Figure 2 shows a three dimensional concept view of proposed solution.

Conversion issues

As already said, the chosen platform is a typical turboprop for regional transport belonging to 70-seats category. Radar supposed to be installed on the platform is Saab PS-890 Erieye AEW&C radar (Table I).

Figure 2 AEW&C diesel turboprop

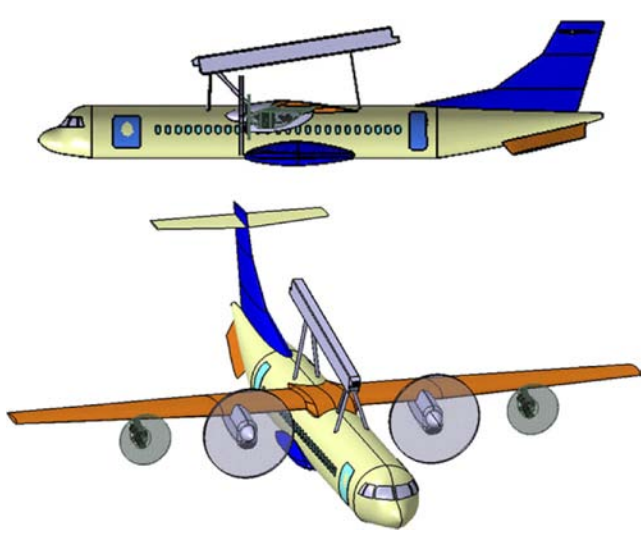


Table I Typical 70-seats class regional turboprop specifications

Typical regional turboprop platform data	
MTOW (kg)	22,000
OEW (kg)	12,950
Max fuel weight (kg)	5,000
Service ceiling (ft)	26,700
Engine power at TO	2 × 2,000 kW turboprop
Wing span (m)	27
Overall length (m)	27

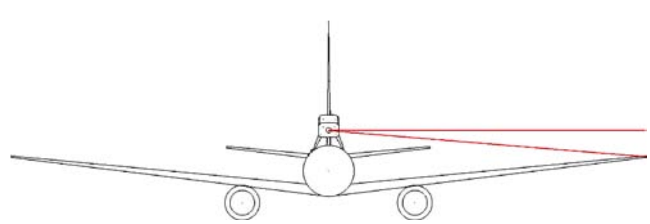
AEW radar antenna installation

Radar antenna has parallelepiped shape whose dimension are $0.44 \times 0.86 \times 9.7$ m and it is supposed to be installed on the fuselage. Requirements for the installation are:

- Distance between antenna and fuselage have to assure a sight angle of 7° in unloaded wing condition.
- Inclination of antenna toward fuselage has to assure antenna to be parallel to horizon during patrol flight phase.

Figure 3 shows clarifications about sight angle definition. Simple geometrical considerations lead to a mean distance between fuselage and antenna of 1.36 m and an inclination angle of 9.6°.

Figure 3 Sight angle of radar antenna



Diesel engine installation

A typical turboprop platform has a service ceiling too low to assure a competitive surveillance performance. It is to underline that surveillance performance of an AEW&C aircraft-system is linked to its service ceiling because higher is patrolling altitude higher is the distance where a hostile menace can be detected and earlier is the warning that is possible to assure due to the increased distance of visual horizon. Two auxiliary power engines can be installed in under-wing nacelle in order to increase service ceiling as it is possible to see in Figure 1. They are turbocharged diesel engine developed for UAS application and able to assure 183 kW power to be constant with altitude until 32,808 ft. They have been chosen for low SFC and for fuel commonality with turboprop so that minimal modifications to aircraft fuel system are required. Installation of the engines concerns:

- Installation of engine nacelles and support pylon under the wing.
- Installation of electrical lines and fuel pipes for alimentation of engines.

Table II contains specifications of the turbocharged diesel engine. Figure 4 shows power variation with altitude of the engine:

$$P_s = P_{\max} \cdot \sigma^n \quad (1)$$

It is to notice that power supplied by the engine is equal to 183 kW until an altitude of 32,808 ft. Above this altitude it decreases by following equation (1) where P_s is the maximum engine shaft power (kW), P_{max} is the maximum shaft power at sea level (kW), σ is the density ratio and n is a power reduction coefficient which is equal to 1.117 for piston engines.

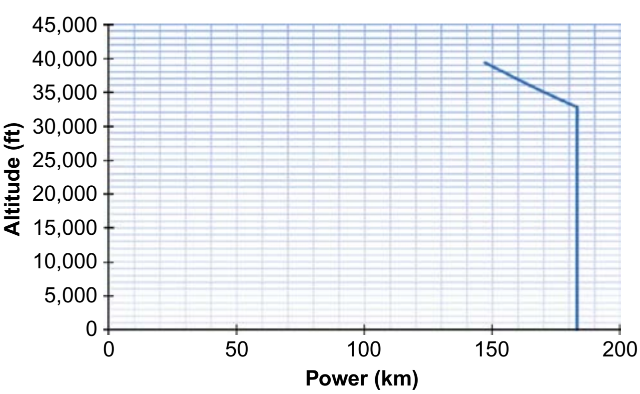
Electrical power supply

Power absorption of Erieye radar system is a restricted data but considering other AEW&C radar whose power is known it is possible to estimate power absorption to be about 60 KVA. Considered regional turboprop platform is equipped with two 20 KVA AC class generators. In addition, we have a further electrical power supplied by diesel engine 10 kW DC class starter generators. Available electrical power is however not sufficient to assure alimentation to Erieye mission system. Substitution of 20 KVA turboprop generators with 40 KVA generators will assure electrical alimentation for Erieye mission system. It is to notice that all platforms converted for AEW&C purposes are equipped with supplementary power generation unit on board. On some of them more powerful engine generators are installed, on other ones electrical power from APU is extracted during flight.

Table II Diesel engine installation specifications

Diesel engine installation specification	
Capacity (cm^3)	2,400
Max power (kW)	183
Engine weight (kg)	330
Nacelle weight (kg)	42
Pylon weight (kg)	18
Starter/generator (kg)	20
Pipes and electrical lines (kg)	40

Figure 4 Diesel engine power curve



Systems and crew accommodation

Conversion to AEW&C concerns the elimination of all civil interiors and installation of mission system interiors. Figure 5 shows an hypothesis of systems and crew accommodation by considering a cabin floor of 41 m^2.

Zero-lift drag coefficient increase

Installation of radar antenna, pylons for antenna support and new engine nacelles causes an increase in zero-lift drag coefficient. It is necessary to estimate this coefficient in order to correctly evaluate aircraft performances. Equations (2)-(4) explain how zero-lift drag coefficient has been broken-down:

$$CD_{0_{AEW\&C}} = CD_{0_{base}} + \Delta CD_0 \quad (2)$$

$$CD_{0_{BASE}} = CD_{0_{WING}} + CD_{0_{FUSELAGE}} + CD_{0_{V.TAIL}} + CD_{0_{H.TAIL}} + CD_{0_{TURBOPROP-NACELLES}} \quad (3)$$

$$\Delta CD_0 = CD_{0_{ANTENNA}} + CD_{0_{PYLONS}} + CD_{0_{DIESEL-NACELLES}} + CD_{0_{INTEFERENCES}} \quad (4)$$

CD_0 represents the zero-lift drag and it depends on the surface and the quality of the surface moving through the air, on the shape and on the air viscosity. Summing up, these effects give the equation (5) for CD_0 contributions (Roskam, 1985c *Part VI: Preliminary Calculation of Aerodynamic, Thrust, and Power Characteristics*):

$$CD_0 = \sum C_f \cdot FF_c \cdot Q_c \cdot \frac{S_{wet}}{S_{ref}} \quad (5)$$

C_f represents skin friction coefficient, FF_c represents shape factor, Q_c represent interference factor, S_{wet} is the wetted area (m^2) of the considered component and S_{ref} is the reference area (m^2) used to normalize CD_0 contributions. We used wing area as reference area.

For drag calculations, radar antenna has been considered as a fuselage with an angle of attack of 9.6°, pylons have been considered as vertical fins. It is to notice that in the calculation of zero-lift drag of basic version, interference contribution is concerned in each component calculation, for additional zero-lift drag coefficient ΔCD_0 calculation, contribution of interference have been separately considered. Table III contains result of coefficient calculations.

Weight break-down

Conversion to AEW&C aircraft-system causes a variation in operating empty weight (OEW) of the basic platform. Indeed, interiors and flight attendant weights have not to be considered

Figure 5 Systems and crew accommodation

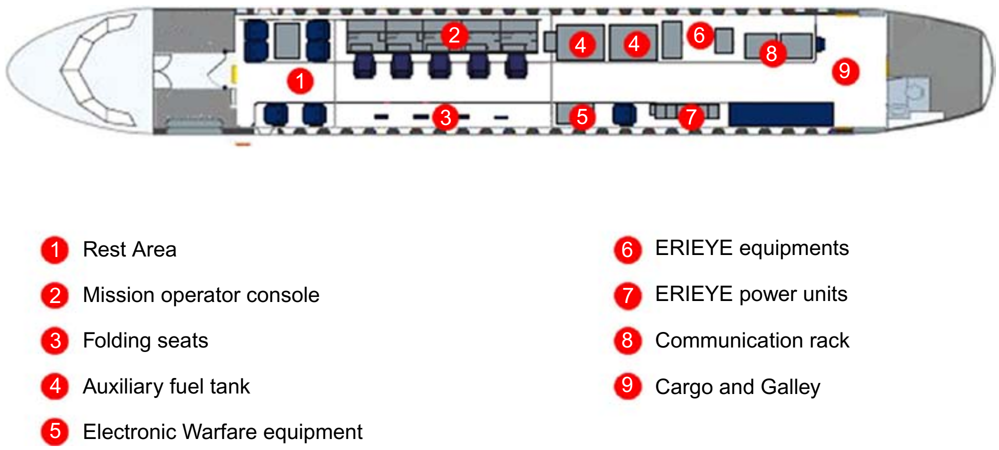


Table III Zero-lift drag coefficient break-down

Component	$CD_{0\ base} = 0.02740$
Wing	0.014
Fuselage	0.008053
Horizontal tail	0.0008347
Vertical tail	0.001315
Turboprop engine nacelles	0.0032
Component	$\Delta CD_0 = 0.0084$
Radar antenna	0.002980
Pylons	0.002389
Diesel engine nacelles	0.001853
Interferences	0.001178
$(CD_0)_{AEW\&C}$	*0.03580*

any more, on the other hand installation of Erieye radar system and of diesel engine nacelle concerns new items to be considered in OEW calculation. Starting from OEW of the civil version of the aircraft it is possible to obtain the one of AEW&C version, Table IV contains OEW break-down. It is to notice that Erieye radar system has been considered as payload and so it is not included in OEW.

Table V shows mission payload estimation.

Considering that no changes of the MTOW are supposed it is possible to evaluate maximum fuel weight of the platform by using equation (6):

$$MTOW = OEW + W_{PAY} + W_{MAX\_FUEL} \qquad (6)$$

MTOW represents maximum take-off weight (kg), OEW represents operating empty weight (kg), W_{PAY} represents mission payload (kg) and W_{MAX_FUEL} represents maximum fuel weight (kg).

Supposing a mission performed at the maximum take-off weight, the maximum weight of fuel on board can be 6,886 kg. By considering that considered platform has a fuel tank of 5,000 kg, it is possible to suppose installation of a supplementary fuel tank of 1,886 kg into the fuselage. Supplementary fuel tanks are usually installed on AEW&C platforms and they allow endurance increasing in order to have a higher time on station during patrolling mission phase.

Table IV OEW variation break-down

$(OEW)_{basic\ version}$ = 12,950 kg	
OEW eliminations	
2 × flight attendants (kg)	140
72 seats (kg)	1,080
OEW additions	
2 × diesel engines (kg)	660
2 × diesel engine nacelles (kg)	84
2 × starter/generators (kg)	40
Fuel and electrical lines (kg)	80
Nacelle pylons (kg)	36
Strakes surface (kg)	50
Pneumatic de-icing system for radar pylons (kg)	40
8 × mission specialists (kg)	744
$(OEW)_{AEW\&C\ (kg)}$	*13,464*

Table V Mission payload estimation

Communication	
IFF (kg)	5
TACAN (kg)	5
SATCOM datalink (kg)	25
MIDS/link 16 (kg)	20
Defence	
Chaff and flare (kg)	40
RWR (kg)	16
MAW (kg)	14
Computing	
5 × mission control stations (kg)	120
Data storage system (kg)	5
Table + chairs (kg)	100
Sensor	
Erieye mission radar (kg)	900
Erieye power and control unit (kg)	400
Mission payload (kg)	1,650

Performance analysis

A performance analysis has been conducted in order to evaluate service ceiling and endurance of several configurations of considered platform. In particular, we analysed four configurations:

1 *Basic version.* It is intended turboprop platform in civil version without any AEW&C modification.
2 *AEW&C version without diesel engine installation.* It is intended the platform equipped with AEW&C radar and mission systems but not considering diesel engines and additional fuel tank installation.
3 *AEW&C version with diesel engine installation.* It is intended the platform equipped with AEW&C radar, mission systems and diesel engines but not considering additional fuel tank installation.
4 *AEW&C version with diesel engine and additional fuel tank installation.* It is intended the platform equipped with AEW&C radar, mission systems, diesel engines and additional fuel tank.

Service ceiling

It is to remember that service ceiling is defined as the altitude where the aircraft has a residual climb rate of 100 ft/min. Equation (7) provide a simple formulation for rate of climb calculation:

$$V_z = \frac{P_a - P_n}{W} \quad (7)$$

V_z represents climb rate (m/s), P_a represents maximum available engine power (kW), P_n represents required power for flight (kW) and W represents weight of the aircraft (KN).

Service ceiling can be also defined as the altitude where the difference between maximum available engine power and required power for flight is equal to supposed aircraft weight multiplied by residual rate of climb of 100 ft/min. Equations (8) and (9) provide formulations for available engine power calculation:

$$P_a = P_s \cdot \eta_p \quad (8)$$

$$P_s = P_{TO} \cdot A \cdot \sigma^n \quad (9)$$

P_a and P_s have been already defined, η_p is propeller efficiency, A is the ratio between TO power and maximum continuous power, *n* is the power reduction coefficient. Suitable values for constants are: $A = 0.9$ and $n = 0.728$ (Nità, 2008) and $\eta_p = 0.8$ (Roskam, 1985a, b, c).

Supplementary power provided by diesel engines is calculated by using equation (1) and it is summed to turboprop engine power. For evaluation of required power for flight equation (10) can be used:

$$P_n = \frac{W}{E}\sqrt{\frac{2 \cdot W/S}{\rho \cdot CL}} \quad (10)$$

E represents aerodynamic efficiency, S represents wing area (m^2), CL represents lift coefficient, ρ represents air density (kg/m^3). Flight efficiency E and lift coefficient CL have been estimated at the angle of attack where required power is minimum due to the will to maximize endurance performance in patrol flight phase. Equations (11)-(13) explain how terms in equation (10) have been calculated:

$$CL_{\min pow} = \sqrt{\frac{3 \cdot CD_0}{k}} \quad (11)$$

$$E_{\min pow} = \frac{1}{4}\sqrt{\frac{3}{k \cdot CD_0}} \quad (12)$$

$$k = \frac{1}{\pi \cdot e \cdot \lambda} \quad (13)$$

CL_{min_pow} is the lift coefficient at minimum power angle of attack, E_{min_pow} is the aerodynamic efficiency at the minimum power angle of attack. k is the induced drag coefficient and it is calculated by using equation (13) where e is the Oswald efficiency coefficient and λ is the wing aspect ratio.

Figure 6 is obtained by conducting calculations for basic version and for AEW&C version with diesel engine installation.

Intersection between maximum engine available power and required power curves represent absolute ceiling. For basic version this intersection is at 28,200 ft which corresponds to a service ceiling of 26,700 ft (i.e. typical value for regional turboprop platforms). The conversion to AEW&C version and installation of diesel engines causes an increase in required power due to aerodynamic drag increase and an increase of available engine power due to diesel engine additional power supply. As a result, the intersection is at 32,680 ft, which corresponds to a service ceiling of 31,100 ft (i.e. typical value for turboprop platforms with high power to weight ratio). The addition of a small but constant amount of power (i.e. 366 kW overall) causes an increase of service ceiling of about 4,400 ft and a percentage increase of 16 percent. Visual horizon distance can be evaluated by using equation (14):

$$D_{HOR} = \sqrt{2 \cdot R_E \cdot h} \quad (14)$$

D_{HOR} represents visual horizon distance (m), h represents altitude (m) and R_E represents earth radius (m).

Percentage increase of visual horizon is about 11 percent by comparing basic version with AEW&C version with diesel engines. Percentage increase of surveyed area increase is about 24 percent. This allows a better employment of AEW&C radar-system and higher patrol effectiveness. It is to notice that Saab 2000 AEW&C, which can be identified as main competitor of our aircraft, has similar patrol performances but it can assure them by having about 6,000 kW available power supplied by two turboprop engines versus our overall power of 4,366 kW supplied by both turboprop and diesel engines. Fuel consumption issues related to this aspect will be investigated in the next sub-paragraph.

Endurance

It is possible to conduct an endurance analysis by supposing an hypothetic mission profile and by evaluating time on station of each version identified. We supposed distance to patrol station to be equal to 250 km and fuel reserve to be able to assure a 45 min autonomy at 5,000 ft (Figure 7).

We considered the value of 275 gr/kWh as SFC for our turboprop engine (Obe and Gunston, 2002), diesel engine has a SFC equal to 231 gr/kWh. When the power is supplied by both turboprop and diesel engines we supposed diesel engines to generate maximum available power. SFC can evaluated by using equation (15):

$$SFC_{global} = SFC_{turboprop} \cdot \frac{(P_n - P_a)}{P_n} + SFC_{diesel} \cdot \frac{P_a}{P_n} \quad (15)$$

SFC_{global} represents the overall SFC (gr/kWh), $SFC_{turboprop}$ represents the SFC just of turboprop engine (gr/kWh), SFC_{diesel} represents SFC just of diesel engines (gr/kWh).

Figure 6 Service ceiling performances curves

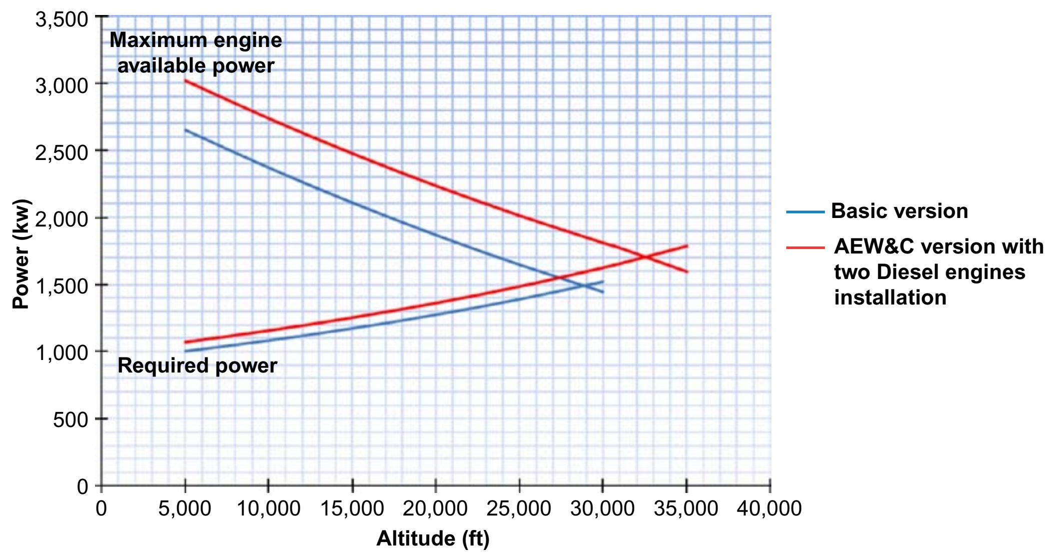
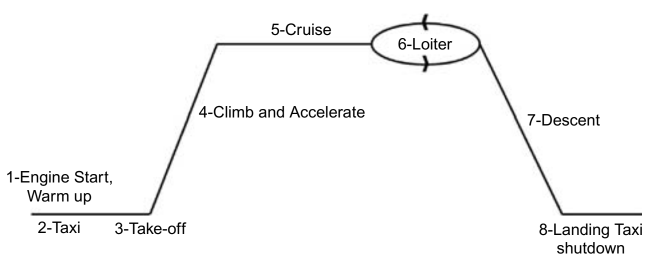


Figure 7 Mission profile



By using equation (15) and by knowing required power for flight by equation (10) it is possible to calculate SFC_{global} in every flight phase. In particular, equation (16) can be used in order to calculate necessary fuel and so time on station during loiter and cruise phases:

$$W^{i}_{FUEL} = SFC_{global} \cdot P_n \cdot t_i \tag{16}$$

W^{i}_{FUEL} represents necessary fuel weight in the phase "i" (gr), t_i represents duration of phase "i" (h).
Necessary fuel during warm-up, taxi, take-off, climb, descend, landing and shutdown phases has been evaluated by using fuel fraction methodology suggested by Roskam (1985a) *Airplane Design Part I: Preliminary Sizing of Airplanes*. Table VI shows results of endurance and fuel calculations.

Figure 8 shows time on station results for the four considered aircraft versions.

The installation of AEW&C radar causes the reduction of time on station due to the required power for flight increase. The installation of diesel engines balances time on station reduction thanks to their lower SFC than turboprop engines. Endurance performance of our aircraft is better than other turboprop AEW&C aircraft and comparable with heavier turbojet AEW&C aircraft; this aspect will be investigated in the following section.

Effectiveness-cost analysis

Effectiveness-cost analysis is a useful tool able to show validity of proposed solution in an economical point of view. Effectiveness analysis assesses an overall performance of our AEW&C diesel turboprop solution compared to similar AEW&C platforms on the market. By evaluating direct operating costs, it will be possible to assess which are advantages/disadvantages of considered AEW&C aircraft-systems in a tight economical point of view. In the end, it is possible to assess "performance price" by combining these two analyses.

Effectiveness analysis

Effectiveness of an aircraft is a unique number, which expresses an overall performance assessment. The used method derives from multidisciplinary design optimization (MDO) techniques. MDO concerns the issue of finding the best solution among a set of solutions by defining a set of objective functions. Scoring techniques are developed to assign a merit value to each solution in order to make it comparable with other solutions. Weight coefficients can be used for quantify relative importance of defined objective functions. Examples of described MDO techniques can be found in Mastroddi and Gemma (2011) and Locascio and Thurston (1998).

The first phase of effectiveness method concerns to select among all aircraft performances/parameters the most significant parameters in a AEW&C-mission point of view. In order to select the most significant parameters AEW&C mission profile has to be analyzed for each mission phase.

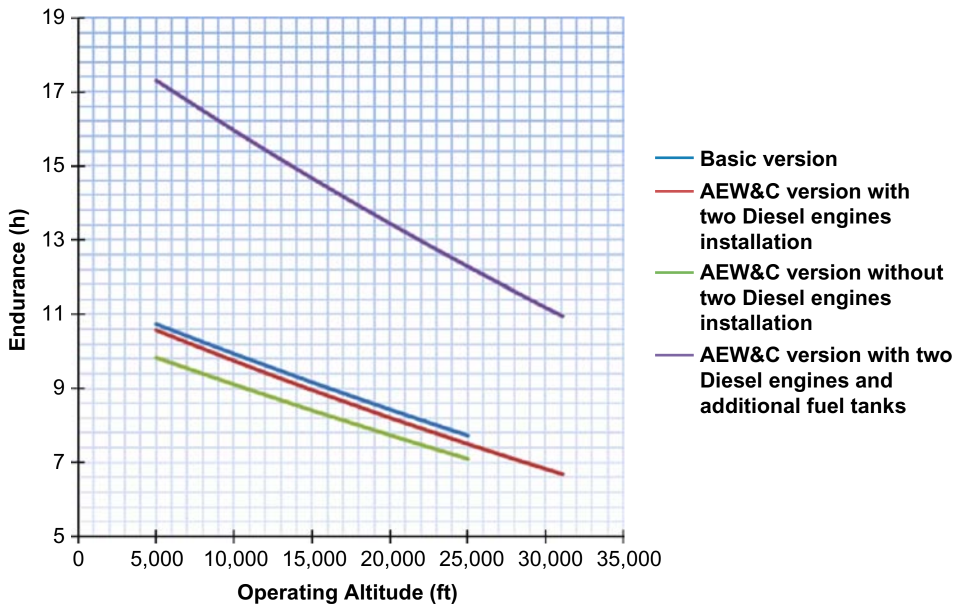
Take-off

During take-off phase the main parameter to be considered is the take-off field length. This parameter is a measure of the flexibility of employment of the aircraft. Furthermore, an aircraft with an low value of take-off field length can be employed in a higher number of airport by the customer, so after the definition of the loiter station to be patrolled the probability to find an airport as near as possible to this loiter station is higher. This allow saving fuel due to the reduced cruise phase until loiter station. Take-off field length will be considered at the MTOW and in ISA and SL condition.

Table VI Necessary fuel for flight phases and times on station

	Basic version	AEW&C version without diesel engine	AEW&C version with diesel engine	AEW&C version with diesel engine and auxiliary fuel tank
Max. fuel weight (kg)	5,000	5,000	5,000	6,886
Necessary fuel weights for flight phases				
Warm-up, taxi, take-off, climb, descend, landing, shut down (kg)	1,188	1,188	1,188	1,188
Cruise (kg)	627	670	642	642
45 minutes at 5,000 ft reserves (kg)	208	222	210	210
Loiter phase				
Available fuel (kg)	2,977	2,919	2,959	4,845
Time on station (25,000 ft) (h)	7.7	7	7.5	12.3
Time on station (30,000 ft) (h)	N/A	N/A	6.8	11.2

Figure 8 Time on station graph



Cruise

During cruise phase for reaching loiter station, the main parameter to be considered is maximum cruise speed. This parameter gives an indication of the time of arrival of the aircraft at the loiter station. A platform with high value of maximum cruise speed is able to assure a quick response in case of emergency.

Loiter

The loiter is the main flight phase of a surveillance flight. Parameters that allow an effective loiter are: service ceiling, maximum endurance, maximum range, performance radar system and number of crew members. Service ceiling, as already said, is a good measure of the warning time that the aircraft is able to assure because higher is the service ceiling, higher is the altitude where the patrol mission will be performed and earlier is the warning time when a threat is detected. Maximum endurance is a good measure of the time on station that the aircraft is able to assure. Maximum range is a measure of the maximum area that the aircraft is able to survey during a patrol flight. Among the performances that an AEW&C radar system concerns, it is difficult to choose a representative parameter. In a first approximation maximum range for missile detection has been chosen as representative of AEW&C radar system performances. It is possible to conclude that an AEW&C aircraft system which concerns a high value for service ceiling, maximum endurance, maximum range and a performing radar system is highly desirable in the loiter phase. In the end, also crew member number has been chosen as a parameter for effectiveness evaluation. Crew member can be considered a measure of the efficacy of a radar system because considering other parameters being equal it is desirable that radar system could be operated by a reduced number of specialists.

Table VII shows selected parameters for considered aircraft.

A second step in effectiveness analysis is to establish relative importance coefficients a_i associated to each parameter in an increasing linear scale between the value of 0, for a not significant parameter, to 0.5, for a crucial parameter which heavily condition overall aircraft performance. The rationale which applies to the assignation of relative importance coefficients is explained in the Table VIII, the value chosen for these coefficients is showed in Table IX.

Table VII Selected parameters for effectiveness analysis

	AEW&C diesel turboprop	Saab 340 AEW&C	Saab 2000 AEW&C	EMB 145 AEW&C	E3 sentry
Max. endurance (h)	12.5	7	9	8	11.4h
Max. range (nm)	2,261	937	2,000	2,000	5,000
Service ceiling (ft)	3,1100	3,1000	3,1000	3,6991	3,8894
Radar system	Erieye	Erieye	Erieye	Erieye	AN/APY-2
Crew members	10	7	10	10	17
To field length (ISA, SL, MTOW) (m)	1,223	1,285	1,220	1,970	3,054
Max cruise speed (km/h)	511	522	660	833	973

Table VIII Rationale of relative importance coefficients

Relative importance coefficient	Rationale
0.5	This is the maximum value for relative importance coefficient and it is assigned to a crucial parameter for the mission profile. If a platform concerns a scarce value of a parameter belonging to this category there is no sense in choosing this platform for AEW&C application
0.4	This value is assigned to a parameter which heavily affects the whole performance of the AEW&C mission. If a platform concerns a scarce value of a parameter belonging to this category there is sense in choosing this platform for AEW&C application but the whole mission will be conducted with heavy limitations
0.3	This value is assigned to a parameter which moderately affects the whole performance of the AEW&C mission. If a platform concerns a scarce value of a parameter belonging to this category the whole mission will be conducted with moderate limitations
0.2	This value is assigned to a parameter which scarcely affects the whole performance of the AEW&C mission. If a platform concerns a scarce value of a parameter belonging to this category the whole mission will be conducted with small limitations
0.1	This value is assigned if a parameter marginally influences the whole performance of the AEW&C mission but the mission will be conducted with no limitations
0	This value is assigned if a parameter does not influence the whole mission performance

By normalizing each parameter, it is possible to evaluate merit of a single parameter in a linear scale where 0 is a parameter with minimum merit and 1 is a parameter with maximum merit. It is possible to evaluate global effectiveness of a platform by using equation (17) (Locascio and Thurston, 1998), where U(x) represents global effectiveness of the aircraft, $U_i(x)$ represents effectiveness related to the parameter "i", a_i is the relative importance coefficient related to parameter "i", K is a scaling constant calculated by using equation (18) (Locascio and Thurston, 1998):

$$U(x) = \frac{1}{K}\left\{\prod_{i=1}^{n}[Ka_iU_i(x)+1]-1\right\} \tag{17}$$

$$1+K = \prod_{i=1}^{n}(1+Ka_i) \tag{18}$$

Table IX Relative importance coefficients a_i

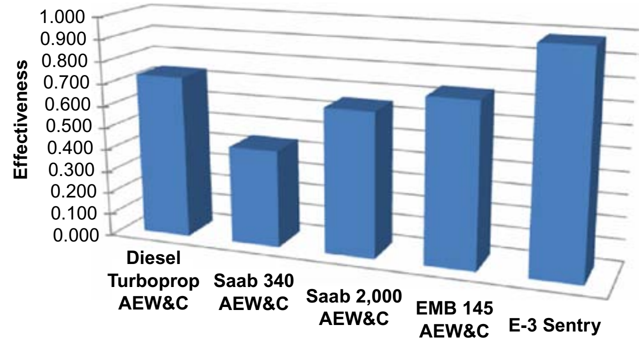
	Relative importance coefficients
Max. endurance	0.4
Max. range	0.3
Service ceiling	0.5
Radar system	0.3
Crew members	0.3
To field length (ISA, SL, MTOW)	0.1
Max. cruise speed	0.2

Figure 9 shows results of performed effectiveness analysis. It is to notice that E-3 Sentry has the highest effectiveness and in general jet platforms (i.e. E-3 Sentry, EMB 145 AEW&C) has higher effectiveness than turboprop platform (i.e Saab 340 AEW&C and Saab 2000 AEW&C) due to their higher service ceiling. Our diesel turboprop AEW&C solution has effectiveness higher than turboprop platforms and equal to EMB 145 AEW&C thanks to the increased service ceiling and the good endurance performances which are the most relevant parameters for AEW&C missions.

Cost analysis

The cost estimation tool has been developed by Politecnico di Torino during a PhD thesis (Fioriti and Chiesa, 2011) with

Figure 9 Effectiveness analysis results



the support of the preliminary design office of Alenia Aeronautica. The tool is based on parametric and statistical approach and it uses a large number of statistical points for turboprop, very light business jet, regional jet and liner. This technique employs a consistent database composed of all physical dimensions, characteristics and performances used as cost drivers. Defined formulas are implemented in order to evaluate cost variation with cost drivers. The maximum hydraulic flow, the electrical energy provided by generators and the fuel tanks volume are examples of cost drivers for, respectively, hydraulic, electric and fuel systems. Effects on costs of changes in aircraft design can be evaluated by using this technique, which finds application in the preliminary design phase. As a final result the technique estimates, by linear regression, the cost-estimating relationships (CERs). equation (19) shows general form of CERs:

$$C_i = A_i \cdot Q_i^B \cdot N_p^{-K_i} \tag{19}$$

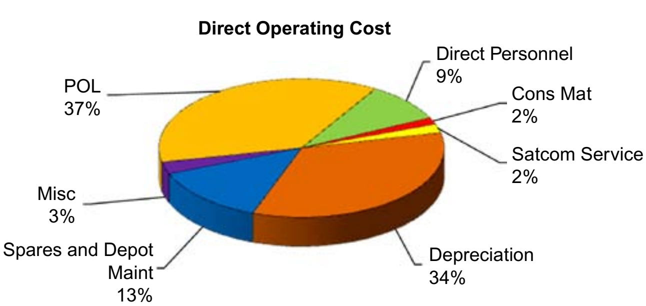
C_i represents the average unit acquisition cost or maintenance cost of the subsystem "i" (USD), Q_i is the main characteristic parameter (e.g. weight) of the subsystem "i", N_p is the production quantity, K_i is a coefficient that takes into account the learning curve effect. B_i represents a "scale factor" whose values vary from zero to one and it considers the currency saving due to the increase of dimensions, indeed, costs increase with weight augmentation. This factor is only applicable for airframe structure acquisition CERs. A_i is the subsystem acquisition cost per unit weight (USD/kg). By considering the maintenance cost CERs, A_i represents the specific maintenance cost related to a design parameter of the subsystem "i". In particular, A_i is relevant for the airframe acquisition CER, feeble for CERs regarding general systems and it assumes intermediate values for avionic systems. The N^{-Ki} coefficient is not considered in the maintenance cost CERs.

Moreover, the DOC model has been normalized to mission hours, in this way the model is enough flexible to be applied to every mission type (military or commercial). Many other DOC estimating models, such as Roskam (1990) or ATA (Maddalon, 1967), have been normalized by using block hours, block speed and block distance, where the block is a specific commercial flight. These models are not able to appropriately asses costs of AEW&C mission because this concerns a long loiter phase.

By applying described cost evaluation methodology, it is possible to evaluate direct operating cost (DOC) of our diesel turboprop AEW&C platform.

Figure 10 shows that the most relevant parameters which affect DOC are petrol, oil and lubricant (POL) cost and depreciation cost. As a consequence, a platform with low fuel consumption and low unit acquisition cost will have a low DOC.

Figure 10 DOC breakdown for diesel turboprop AEW&C



By performing cost analysis for every considered AEW&C platform, it is possible to have a comparison in terms of cost. Tables X and XI describe, respectively, the cost assumption and main cost data, and Figure 11 shows the results. The MMH/FH values, introduced in Table XI, have been calculated using a specific RAMS model (Chiesa, 2008), the other data have been estimated using the above mentioned cost estimating tool (Fioriti and Chiesa, 2011).

Diesel turboprop AEW&C has the lowest DOC because it has the lowest fuel consumption and an affordable unit acquisition cost. Jet platforms (i.e. EMB 145 AEW&C and E-3 Sentry) reveal to have a high DOC respect to turboprop platforms and in particular, E-3 Sentry reveals to have huge DOC. Turboprop platforms (i.e. Saab 2000 AEW&C and Saab 340 AEW&C) have slightly higher DOC than Diesel turboprop AEW&C due to their higher SFC caused by their high power to weight ratio.

Effectiveness-cost results

By dividing effectiveness results to cost results, it is possible to obtain an estimation of the effectiveness-cost ratio of considered AEW&C platforms. Figure 12 shows the results.

Our solution has the best effectiveness-cost because it represents a good compromise between good effectiveness and low cost. E-3 Sentry has great effectiveness but it concerns also huge DOC. Turboprop platform Saab 2000 AEW&C is the real competitor of our solution but the choice of high power to weight ratio to reach high altitude causes an higher fuel consumption than diesel turboprop AEW&C and consequently a lower endurance performance.

Conclusion

In the present work an innovative approach has been supposed for conversion of turboprop platform for AEW&C purposes. By installing turbocharged diesel engines instead of using powerful turboprop, it is possible to reach an acceptable value of service ceiling and better endurance performances due to the lower SFC of turbocharged Diesel engines than turboprop engines. In addition, low SFC of diesel engines allows to balance the typical loss of endurance performances due to additional aerodynamic drag generated by AEW&C radar antenna installation. In an economical point of view this solutions concerns lower DOC and better effectiveness than other AEW&C turboprop aircraft-systems. This is confirmed by the optimum effectiveness-cost performance in comparison with other existing AEW&C platforms.

Further work

Effectiveness-cost analysis is a powerful toll which allows comparing in tight economical point of view different solutions by assessing the "performance price" of each solution. Confidence of results of this tool is based on the correct assignation of relative importance coefficient that is conditioned

Table X Cost assumptions

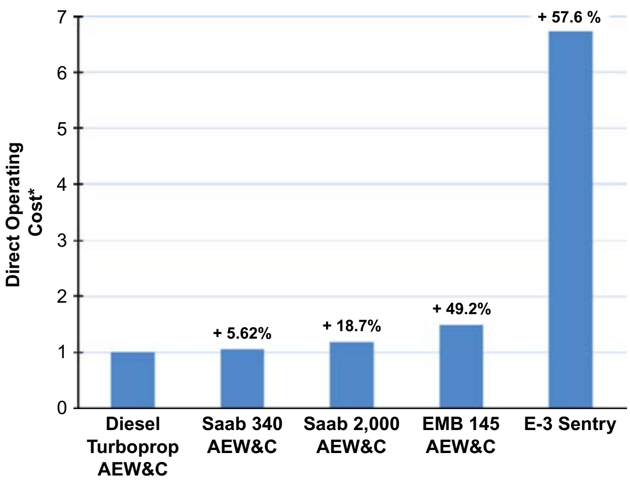
Fuel price	3 $/gal
Maintainers labour cost	50 $/MMH
Wide band sat comm cost	200 $/H
Aircraft depreciation years	20 years
Aircraft residual value	15 percent of acquisition cost

Table XI Cost estimation main data

	AEW&C diesel turboprop	Saab 340 AEW&C (%)	Saab 2000 AEW&C (%)	EMB 145 AEW&C (%)	E3 sentry (%)
Acquisition cost[a]	1	−5.06	+3.80	+6.33	+241.78
MMH[a]	1	+13.08	+26.05	+91.43	+266.76
Spare replenishment[a]	1	+13.20	+37.87	+71.22	+189.05

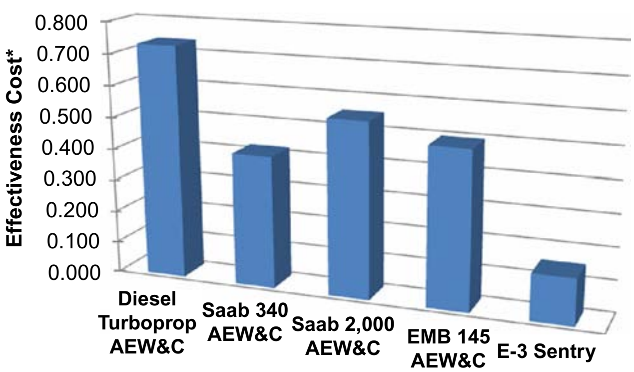
Note: [a]Normalized values

Figure 11 Cost analysis results



Note: *Normalized Values

Figure 12 Effectiveness-cost results



Note: *Normalized Values

by a qualitative metric. Further research can be conducted in order to create a criterion allowing a quantitative approach to relative importance coefficient calculation.

References

Chiesa, S. (2008), *Affidabilità, sicurezza e manutenzione nel progetto dei sistemi, nuova edizione*, CLUT Editrice, Turin.

Fioriti, M. and Chiesa, S. (2011), *Innovative Solutions for Light, Very Light and Unmanned Aircraft: Preliminary Design and Life Cycle Cost Estimation*, LAP LAMBERT Academic Publishing, Saarbrücken.

Locascio, A. and Thurston, D.L. (1998), "Trasforming the house of quality to a multiobjective optimization formulation", *Structural Optimization*, Vol. 16, pp. 136-46.

Maddalon, D.V. (1967), *Standard Method of Estimating Comparative Direct Operating Cost of Turbine Powered Transport Airplanes*, Air Transport Association of America, Washington, DC.

Mastroddi, F. and Gemma, S. (2011), "Analysis of Pareto Frontier for multidisciplinary design optimization of aircraft", *3rd CEAS Air and Space Conference 21st AIDAA Congress Venice Proceedings of the International Conference in Venice, Italy*, pp. 1418-27.

Nità, M.F. (2008), "Aircraft design studies based on the ATR 72", Master thesis, Hamburg University of Applied Sciences, Hamburg.

Obe, B. and Gunston, F. (2002), *Jane's Aero Engines*, Janes's Information Group, Coulsdon, Surrey CR5 2YH.

Roskam, J. (1985a), *Airplane Design Part I: Preliminary Sizing of Airplanes*, 1st ed., Roskam Aviation and Engineering Corporation, Ottawa, KS.

Roskam, J. (1985b), *Airplane Design Part II: Preliminary Configuration Design and Integration of the Propulsion System*, 1st ed., Roskam Aviation and Engineering Corporation, Ottawa, KS.

Roskam, J. (1985c), *Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust, and Power Characteristics*, 1st ed., Roskam Aviation and Engineering Corporation, Ottawa, KS.

Roskam, J. (1990), *Airplane Design Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing and Operating*, 1st ed., Roskam Aviation and Engineering Corporation, Ottawa, KS.

Further reading

Bernard, B. (2002), *Jane's Radar and Electronic Warfare Systems*, Jane's Information Group, Coulsdon, Surrey CR5 2YH.

Fielding, J.P. (2000), *Introduction to Aircraft Design*, Cambridge University Press, Cambridge.

Jackson, P. and MRAeS (2004), *Jane's All the World's Aircraft 2004-2005*, Jane's Information Group, Coulsdon, Surrey CR5 2YH.

Wilson, M. (2003), *Jane's Avionics*, Jane's Information Group, Couldson, Surrey CR5 2YH.

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