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SAFETY AND RELIABILITY PREDICTION METHODS FOR AIRCRAFT PRELIMINARY DESIGN

J.P. Fielding
College of Aeronautics
Cranfield University
Bedford
MK43 OAL
United Kingdom

ABSTRACT

The paper summarises several pieces of work that have been performed to integrate high reliability techniques at the very earliest design stages, where they can have most benefit.

The first tool is a multi-disciplinary design programme which evaluates the effect of reliability improvement on current technology systems. The example chosen shows direct maintenance cost benefits from the use of various mass flows of avionic cooling air. The penalties on air conditioning performance and engine bleed are also evaluated and a total aircraft direct operating cost trade-off is performed. The methodology was then developed to assess reliability and maintainability effects of potentially risky new technology such as, in this case, variable-camber flaps.

A further tool is one to simulate the en-route reliability and safety of transport aircraft with and without common-cause failures. It utilises MONTE-CARLO simulation and MARKOV methods and gives interesting results concerning ETOPS operations.

The final tool is a novel propulsion system safety analysis methodology for commercial transport aircraft and results showed it to be significantly more accurate than current methods. All of the above tools have shown the potential for improving design methods to increase safety and reliability, with consequent social and financial benefits.

1. Introduction

Safety and reliability are essential issues in the design, development and operation of most aircraft. Modern aircraft and systems should meet safety requirements that are stipulated in the principal airworthiness codes, such as FAR. More stringent reliability requirements are included in aircraft specifications, by customers, to reduce unreliability costs as much as possible. These can be achieved only by including safety and reliability analyses early in the design process, to evaluate the proposed design's potential for meeting these requirements, and to compare alternatives in trade-off studies. This led to the need for highly accurate safety and reliability analysis tools that are simple to use in the aircraft design process.

This paper will summarise several pieces of work to meet the above need that have been performed at Cranfield University. Their objectives were to produce methodologies for use during the earliest design stages where they might give the most benefit.

The first pair of tools were designed to

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demonstrate the use of an adapted multi-disciplinary optimisation method to model the effects of system reliability and maintainability (R&M). They were to examine improvements to the design of an existing system and to assess the R and M implications of a new type of technology.

The aim of the third study was to simulate the reliability of redundant systems, subject to common-cause failures. The final study's objective was to develope a new method to better predict the safety of the propulsion systems of turbofan-powered transport aircraft.

2. Reliability Modelling of an Existing System in Conjunction with Multi-variate Optimisation

2.1 Background

Historically, conceptual designs of aircraft were aimed towards fulfilling performance-dominated mission parameters, with fuel and or take off mass the usual objective function, until the cost of maintenance and aircraft market price became so pronounced that the objective function changed to DOC - Sobiesky (Ref 1), further envisaged that conceptual design of aircraft would have to include new modules of thermodynamics, stability and control, reliability, maintainability, supportability, and structures. The College of Aeronautics took the initiative for R&M incorporation in aircraft initial configuration sizing (Ref 2&3). The study in the Ref 4 project was to establish a computer aided conceptual aircraft design (CACAD) for incorporation of R&M enhancement modules for conventional systems and prediction of the R&M implications of future high-risk new technologies (Para. 3, below)

2.2 The Design Synthesis and Optimisation Program (CACAD)

CACAD (Computer Assisted Conceptual Aircraft Design) methodology was developed by the author of ref.4.

It is an explicit optimisation of jet transport aircraft initial sizing, with the facility for extensive maintenance cost break-down, aimed at making it suitable to accept Reliability and Maintainability (R&M) models for further trade-off investigations. Most of the design relation are from Ref 5, and its predecessors, but quite a few are taken from a number of recent aircraft design text books. It solves all the constraints and optimises aircraft configurations for minimum DOC. It assumes constant wing spanwise thickness to chord ratios, along with conventional high lift devices and the engines are either two "installed either under the wing or the rear fuselage" or four installed under the wing only. It also includes updated relationships to include advances in wing design and material selection, with the provision to specify the degree of improvement in the technology of the wing design. The realistic results of the design synthesis are tabulated for comparison with the Airbus A330 in table 1.

2.3 Choice of system to be studied for reliability enhancement

Fig .1. shows delay rates for a typical modern airliner and high-lights the dominant negative effect on reliability of delays caused by the major avionic systems. Ref.6 shows that this is a phenomenon common to most civil and military aircraft. It was therefore decided to search for ways of evaluation of the effects of design improvements for avionic systems.

2.4 Increased avionic system reliability

It was found that the reliability of Avionics is reduced by high vibration, poor thermal management, and faulty component or architectural design. Research showed that there was detailed information available to quantify the reliability benefits that follow increased cooling. Different methods of cooling, and different enclosure designs were investigated to determine penalties, benefits, and other impacts on aircraft mass and performance. The task was extended to determine the optimum cooling for maximum reduction of DOC, for different classes of passenger aircraft at different labour rates and different fuel prices.

2.5 Increased Cooling Benefits and Penalties

Equations were produced which related avionics failure notes to their junction temperatures.

Five modern cooling methods were investigated for equipment in the avionics bay and flight decks of transport aircraft.

Those methods were conduction cooling air rail, conduction cooling air over component, conjunction cooling liquid rail, hollow board LRU, and heat pipe module. The conduction air rail was found to be not only functionally superior but it was cheaper to manufacture, with lower mass, being the least complex. This method used the least amount of equipment, hence had the lowest failure rate, and was highly reliable and maintainable. Three alternative instrument panel cooling methods were investigated and the pressurised panel was chosen as the most suitable.

Relationships were obtained to equate cooling flow rates with equipment bay and instrument panel temperatures. It was therefore possible to model equipment failure notes with respect to cooling flow rates.

Increased flow rates incur mass penalties caused by the requirement to have more capable environmental control systems (ECS). Most ECS systems require considerable amounts of engine bleed air. Increased ECS flows require increased bleed which, in turn, reduces engine thrust and increases fuel consumption. These effects either reduce payload or range or require the aircraft to be larger, with increased direct operating costs. The dilemma is therefore is to see if:-

DOC improvement due to greater avionic reliability $>$ Doc penalty for ECS mass and increased fuel burn or aircraft size

The only way to solve this problem was to model the whole conceptual design process, together with the above benefits and penalties.

2.6 Modelling Stages

2.6.1 Benefit Modelling

There are two areas in direct operating cost of an aeroplane that are positively affected by avionics system reliability enhancement (ASRE). The first obvious one is the maintenance labour, and maintenance material cost both of which are reduced by ASRE. The other is the standing charges of the aircraft DOC. Two sections of this cost are affected by ASRE, the first being the depreciation cost of the avionics in which the life duration element is increased by ASRE, causing the depreciation cost to reduce. The other section is the spare parts holding cost, which is also reduced by ASRE.

In CACAD the base maintenance man-hours allocated to avionics systems correspond to the recommended 5lb/min/kW bleed from engines to cool the avionics bay (ARINC 600), and 8 lb/min/kW bleed from the engines to cool avionics deck (ARINC 408a). Extra values of bleed increment drop the case or junction temperature of the avionics in the flight deck and bay respectively, causing the failure rate of these equipment to fall from the base value.

Para 2.5 above, mentions that equations were derived to show failure rates versus cooling flows. Empirical ECS mass equations were modified to allow for increased flow rates. Models were developed to estimate the reduction in the maintenance material and labour costs, as well spare part reduction.

2.6.2 Penalty Modelling

The TURBOMATCH code developed in the School of Mechanical Engineering at Cranfield University was used to simulate engine performance, subject to bleed at various rates during cruise at 35000 ft, and 0.82 Mach number for four classes of turbofan engines ranging from 15000 lbf TAY class to the 75150 lbf TRENT class. The empirical relationships developed from the data was validated against actual data.

The mass and fuel flow-rate penalties were then incorporated into the CACAD synthesis and optimisation system.

2.7 Modelling results for existing system reliability enhancements

CACAD was run many times to examine four classes of aircraft and to show the DOC sensitivity to various flow rates for different labour rates, fuel prices and different bleed SFC sensitivities. The following results were obtained:-

i) The net effect of penalty functions and benefit modelling in the form of % DOC savings when ASRE are used in jet passenger aircraft is show in Fig 2. A little saving is achieved for long range passenger aircraft and 1.3 % for the short range low capacity aircraft when base values of present cooling flow to avionics systems are increased by 50%. Beyond this value the penalty effects of the bleed on fuel consumption and system mass outweigh the maintenance benefits.

ii) Long rang aircraft DOCs have high percentages of fuel cost and thus the bleed penalty effect on mission fuel mass outweighs the benefits in avionics maintenance cost. The DOC saving is therefore lower for the long range A340 aircraft class. The process is favourable for medium and short-range aircraft.

iii) Sensitivity analysis on labour rate change shows a negligible effect on DOC saving for all classes of aircraft (Fig 3). The reasons lie in the fact that the labour cost is a small part of the total of maintenance material, depreciation, and spare parts holding costs.

iv) Sensitivity analysis on fuel price shows that, when it is lowered, it makes thermal reliability enhancement worthwhile even for long range passenger aircraft, Fig 4.

2.8 Avionic Cooling Conclusions

Any R&M type of improvement on any aircraft system that requires extra bleed as a power source may not be a cost-effective project for long range high capacity aircraft. For short and medium-range aircraft, the modelling of such improvements, integrated into computer-aided conceptual aircraft design is the safest and cheapest way of conducting feasibility studies.

The results might give support to those who propose independent refrigeration cooling systems for aircraft avionics for long-range high-capacity aircraft. This was studied further in ref.4, and was shown to be promising.

3. Design Methodologies to Model Overall DOC of New Technologies

3.1 Variable-Camber Wings on Transport Aircraft (VCW)

3.1.1 VCW Prediction Models

There has been considerable research into variable-camber wings in recent years. Ref 7 summarises some of the work done in Germany, whilst ref. 8 does the same for similar work at Cranfield. The more recent work described in ref.9, produced a multi-disciplinary tool to evaluate a wide range of design factors.

Several computational models were developed and are summarised in fig.5. A brief description of the various models follows:-

i) Synthesis and Optimisation Model (CACAD)

This is a computer-aided conceptual aircraft design (CACAD) synthesis tool described in para 2 above.

ii) Aerodynamic modelling elements:-

- Modelling of the drag saving due to the absence of angle of attack variation effects on rear fuselage unsweep.
- Variable camber wing/fuselage viscous interference drag reduction modelling due to effects of the absence of twist on the fillet size at the wing-fuselage junction.
- Modelling of extra induced drag savings due to the absence of twist in VCW aircraft.
- Modelling of drag-saving in VCW due to the absence of gradual induced drag factor increment as a result of elliptical lift distribution deterioration, through the cruise stages, in fixed camber wing aircraft (FCW).
- Consideration of experimentally-reported drag saving produced by camber variation instead of angle of attack changes. This is reduces lift coefficient to compensate for aircraft mass reduction due to fuel burn during cruise stages.
- Modelling of sweep-angle reduction due to lower critical Mach number of VCW as compared to FCW whose sectional lift coefficients at certain outer-wing sections are higher than the aircraft lift coefficient.
- Conceptual design of a family of aircraft with common wing, having VCW installed on the undersized wing member of the family, to enhance operational flexibility.

iii) Mass modelling elements

- Wing trailing edge, variable camber device mass estimation modelling. (In this study leading edge devices for camber variation have not been considered).
- Hydraulic system mass modelling due to increase of system functions as a result of variable camber deployment.

iv) Maintainability, reliability and development cost modelling

The maintenance cost, as well as the standing charge part of the direct operating costs of the CACAD program are divided into different systems, as well as major structural sections, to facilitate the operation of the following models.
- Modelling of the failure-rate increment of VCW aircraft, and linking it with maintenance man-hours for the hydraulic system. The rise in the mass of the VCW-affected sections automatically influences the maintenance material cost.
- The depreciation and spare-parts holding increase of the VCW-affected section influences on the DOC.
- The extra development cost of VCW technology is modelled, which influences the price of each VCW aircraft relative to FCW aircraft.

3.1.2 Initial Results for VCW Modelling

All the above-mentioned models were incorporated into CACAD for 4-engined long-range transport aircraft resembling the A340-200 class, and the future ultra-high capacity aircraft UHCA. The program first designed and optimised

FCW aircraft and the VCW models were brought into operation, and then VCW aircraft were designed and optimised.

Many comparisons were made in terms of aircraft take-off mass, fuel burn, lift-drag and direct operating costs.

In the interest of brevity, only the DOC savings are shown in fig. 6 for the A340 class aircraft.

The sensitivity factors S1 to S4 are defined as follows:-

S1: FDIM = 1.75, NF = 8, DCL = 0.05
S2: FDIM = 1.25, NF = 8, DCL = 0.05
S3: FDIM = 1.25, NF = 8, DCL = 0.1
S4: FDIM = 1.25, NF = 7, DCL = 0.1

where:-

FDIM is a DOC factor associated with the maintenance complexity of VCW-affected systems such as trailing edge devices, flight control system and hydraulics.

NF is the number of functions that impact the hydraulic system mass, with 7 being for FCW and 8 for VCW.

DCL is a term that indicates how much the overall aircraft C_L is lower than the wing section highest C_L. This difference in FCW aircraft causes the critical drag Mach. number at zero lift to 'fall' and limits the thickness to chord ratios, or gives a higher value of sweep angle. In VCW aircraft, due to the spanwise variation of camber, an elliptical lift distribution, reduces DCL to zero and hence a VCW aircraft for the same flight Mach No. and altitude, and the same aerofoil can utilise a higher thickness/chord ratio, and/or have lower sweep. A DCL value of 0.05 is very conservative and 0.1 is a slightly optimistic value.

FDIF is the Development Intensity Factor in cost estimation. A factor of 1.5 indicates a moderate influence of VCW on all aircraft systems, and included extra requirements for testing, relative to conventional systems. 2.0 indicates very significant development effort, hence higher extra development cost of VCW over FCW.

Reasonably optimistic results for the A340 class of aircraft yield a DOC saving of 2.7% and the comparable figure for the Ultra High Capacity Aircraft is 3.7%. The most pessimistic results give a DOC penalty of about 0.3% for the A340, whilst the UHCA has a DOC improvement of 1%. The truth is probably between those values.

4 Simulation for Reliability Prediction of Aircraft and Systems, Allowing for Common-Cause Failures

4.1 Alternative Safety and Reliability Prediction Methods

These are well-established techniques for predicting safety and reliability of aircraft and systems such as RBD (Reliability Block Diagram) or FTA (Fault Tree Analysis). Traditionally, these methods predict safety and reliability of aircraft and systems with the assumption that failures are mutually independent and missions consist of a single phase. However, real life produces C.C.F.s. (Common-Cause Failures) which leas to simultaneous failures of more than one component or channel. Most aircraft systems are required to perform phased-missions, in which the system configuration is changed during consecutive time periods (phases), such as take-off, climb cruise, etc. These traditionally would be modelled for each phase by means of separate

RBDs, or fault trees incorporating C.C.F. events, but the model becomes quite complex. More fundamental limitations of RBD or FTA methods rise in modelling an operation of systems, which is critical in operational reliability prediction.

In study of Ref 10 a methodology was developed for predicting aircraft safety and reliability incorporating both C.C.F.s and phased missions. Monte Carlo simulation of the Markov process is used for simulating system failure behaviour. Safety and reliability prediction is made through discrete-event simulation of aircraft operations. Since the ETOPS (Extended Range of Twin Engine Aircraft Operations) is an important issue in flight safety, a case study of aircraft propulsion systems has been conducted, to show the effect of diversion time and number of engines, with and without the existence of C.C.F.s, on aircraft safety and reliability.

4.2 Operation Modelling and Simulation

The objective of the operation model is to describe the mission that the aircraft or systems perform. The typical operation of transport aircraft was modelled as follows. The flight route consisted of 5 phases: take-off from the departure and ended with landing at one of three airports: departure, destination or alternate, or being terminated due to system catastrophic failure. The alternatives were assumed to be located randomly over the route, within the allowed diversion time. A top-level logic flow diagram of the aircraft operation is shown in Fig 7, and modelled using the Markov process. The mission consists of the consecutive phases which the system performs. The system is initialised at the beginning of mission and starts with phase 1. In each phase of the mission, alternative sampling are carried out by Monte Carlo Methods for the time of component failure event and for the components involved in the failure event, either independent or common-cause failures.

If the system does not fail, it continues a phase of mission in accordance with the operation logic. The mission ends when either the system catastrophic failure is reached or the last phase of the mission is finished. Statistics are then recorded after termination of the mission, for the system safety and reliability calculations.

4.3 Use of the Methodology for Study of Propulsion Systems Safety and Reliability

With the increased reliability of modern jet engines, coupled with an increased desire to maximise profitability, the diversion time imposed on ETOPS aircraft has been increased up to 180 minutes at one-engined speed. However, the controversy about the flight safety of ETOPS aircraft still continues. A major topic of ETOPS safety is that longer diversion time leads to a corresponding potential increase in single-engined flight time to an alternate airport. This may have significant adverse effects on flight safety, particularly due to the increase in consecutive IFSD (in-flight shutdown) probability. In this study, the investigation of safety and reliability of ETOPS aircraft has been attempted with the developed methodology. The Safety and reliability of two-engined aircraft with 60, 120, and 180 minutes diversion times have been evaluated as functions of mission time. Safety and reliability of three- and four engined aircraft were also evaluated, for comparison with two-engined aircraft.

Operational reliability is the probability of completing the flight without any interruptions, and is shown in Fig 8. In the case of no common-cause in flight Shut-downs (IDSDs), two-engined-aircraft achieved better operational reliability than three- and four-engined aircraft in ranges up to 6 to 10 hours, depending on their ETOPS capability. Among two-engined aircraft, it is seen that longer diversion times are beneficial in operational reliability, over all ranges. In the long range missions, three-engined aircraft achieved higher operational reliability than two-engined aircraft while the operational reliability of four-engined aircraft has the lowest level. The main contribution to these results is the one-engine IFSD event. Since a one-engine IFSD before the mid-point of cruise causes flight interruptions of all types of aircraft, more engines in aircraft result in more interruptions. However, one-engine IFSD events of three- and four-engined aircraft after the mid-cruise point do not cause interruptions, due to their performance capability with one-engine IFSD. This makes the operational reliability of three-engined aircraft exceed the two-engined aircraft operational reliability for long-range missions. For four-engined aircraft, the higher probability of one-engine IFSDs surpasses the advantage of it's relative performance. Due to this, the operational reliability of four-engined aircraft is still lower than that of two-engine aircraft even for long-range missions.

The above simulation assumed that a twin-engined aircraft would fly at a significantly slower cruise speed when subjected to a single engine failure. The simulation could be run at more realistic speeds if accurate data becomes available. The study of ref. 10 covered a wide range of simulations of safety and reliability, with and without the effects of common-cause failures. The method has the capability of use as a design, Certification and Operational planning tool.

5. Propulsion System Safety Analysis Methodology

Airworthiness certification of commercial transport aircraft requires a safety analysis of the propulsion system to establish that the probability of a failure jeopardising the safety of the aeroplane is acceptably low.

The goal of the study shown in Ref. 11 was to identify and remedy shortfalls in the safety analysis of high bypass-ratio jet engines powering large transport category aircraft, and to improve the usefulness and cost-effectiveness of such analysis where possible.

The approach taken was initially to establish a baseline analysis using existing safety analysis techniques in use by the engine manufacturers, to forecast the behaviour of an existing engine. This was compared with actual service date and showed significant discrepancies.

Since different engine families tend to experience different failure patterns, consideration of accidents and incidents pertaining to other manufacturer's engines were adjudged worthwhile. Of study the engines considered in the study were the RB211, Tay, V2500, PW2000, PW4000, JT9D, CF6, CFM56 and ALF502 models, from entry into service of each model until December 1994. Extensive examination of incident and accident reports and prediction methods produced a novel safety prediction method which is described in ref. 11 but will be published later in a technical paper, as space in this paper is extremely limited.

Features of the novel approach include quantified prediction of propulsion-related crew error, engine-level reliability growth modelling to realistically predict engine failure rates, and quantified credit for design features which mitigate the effects of propulsion system failures. The alternate approach was validated by applying it to two existing propulsion systems. It was found to produce forecasts in good agreement with service experience. (Table 2). Use of the alternate approach to propulsion system safety analysis during design and development will enable accurate prediction of the expected propulsion related accident rate and identification of opportunities to reduce the accident rate by incorporating mitigating features into the propulsion system/aeroplane design.

6. Overall Conclusions

- This paper has briefly summarised the work of a number of hard-working, capable doctoral students who are currently applying their knowledge in the

USA, the Middle and Far East

- The studies have shown that it is possible to produced realistic safety, reliability and maintainability prediction methodologies for use during the conceptual and preliminary design phases, when they can be most effective.

- Modern computers and their programs can be used for multi-variate optimisation tools as well as extensive simulation. Careful design of methods provides means to accurately predict in-service behaviour, using the limited information available during the early design stage.

- The particular studies have shown the cost -effectiveness of improved avionics cooling and variable-camber flaps. They have shown that the results might be negative or positive, depending on the type of aircraft.

- Simulation has been shown to be useful in the prediction of the effects of system reliability, with and without common cause failures

- A naval propulsion system safety methodology has been produced, with promising results.

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Table 1 - Study-designed and optimised aircraft comparison with similar-mission Airbus A330

Aircraft Major Parameter	Study Design	A330	% Change
Mass Take-off kg	215238	212000	1.5
Zero Fuel Mass kg	162667	164000	-0.8
Wing Gross Area M^2	351.75	363.1	-3.22
Aspect Ratio	9.37	10.01	-6.83
Wing Span m	57.41	60.3	-5.0
Fuselage Length m	65.47	63.65	2.78
Engine Thrust lbf	63914	67500	-5.61

Table 2 Comparison of Powerplant Prediction Methods with Service Experience

	Prediction (Traditional approach)	Prediction (New approach)	Service experience
IFSD rate	1.4E-2/hr	2 to 6E-5/hr	1.6E-4/hr
Uncontained rate	1E-4/hr	6E-7/hr	1 E-7/hr
Fires	7E-4/hr	4E-7/hr	1.5E-6/hr
Accident rate		5.9E-7/hr	2E-7/hr

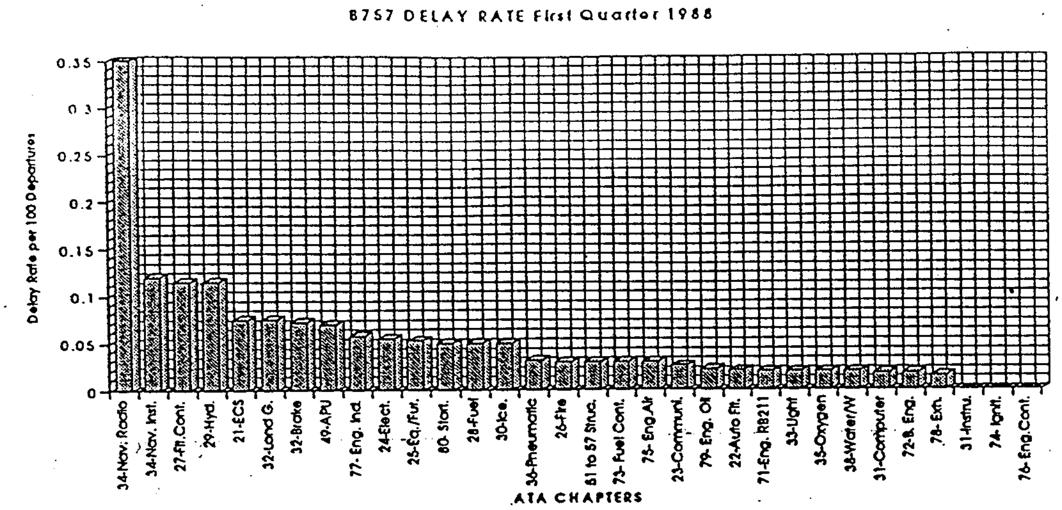

Figure. 1

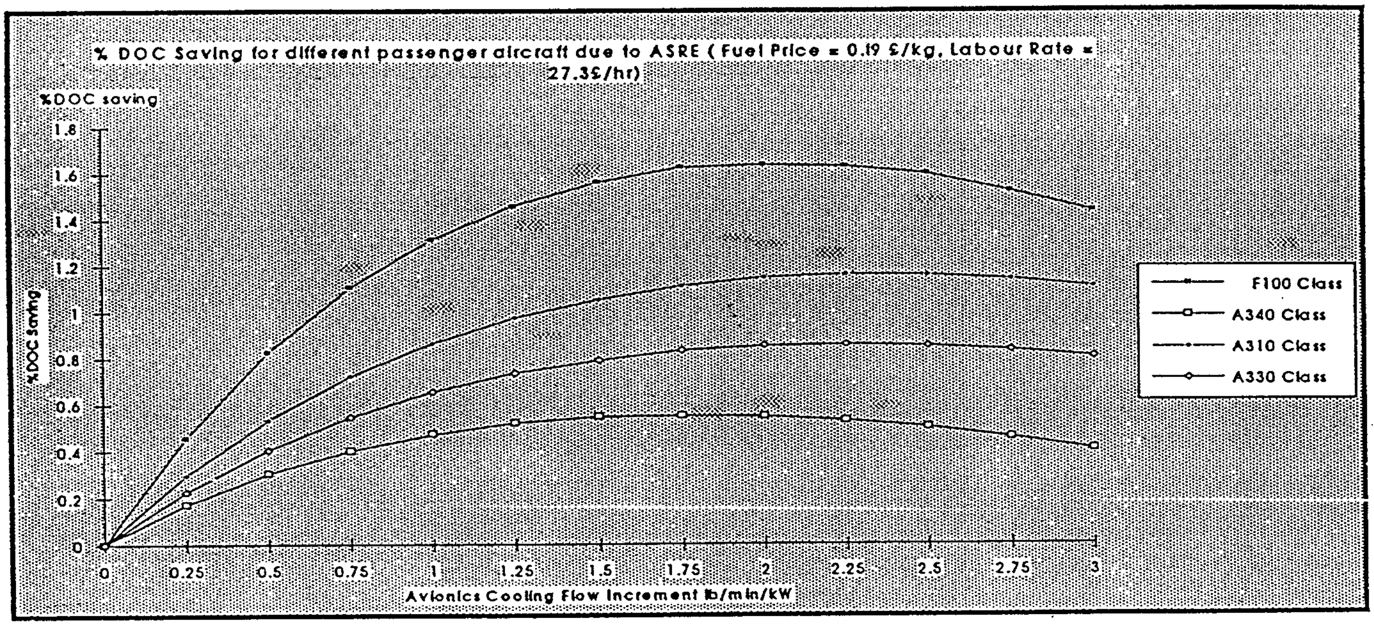

Figure. 2

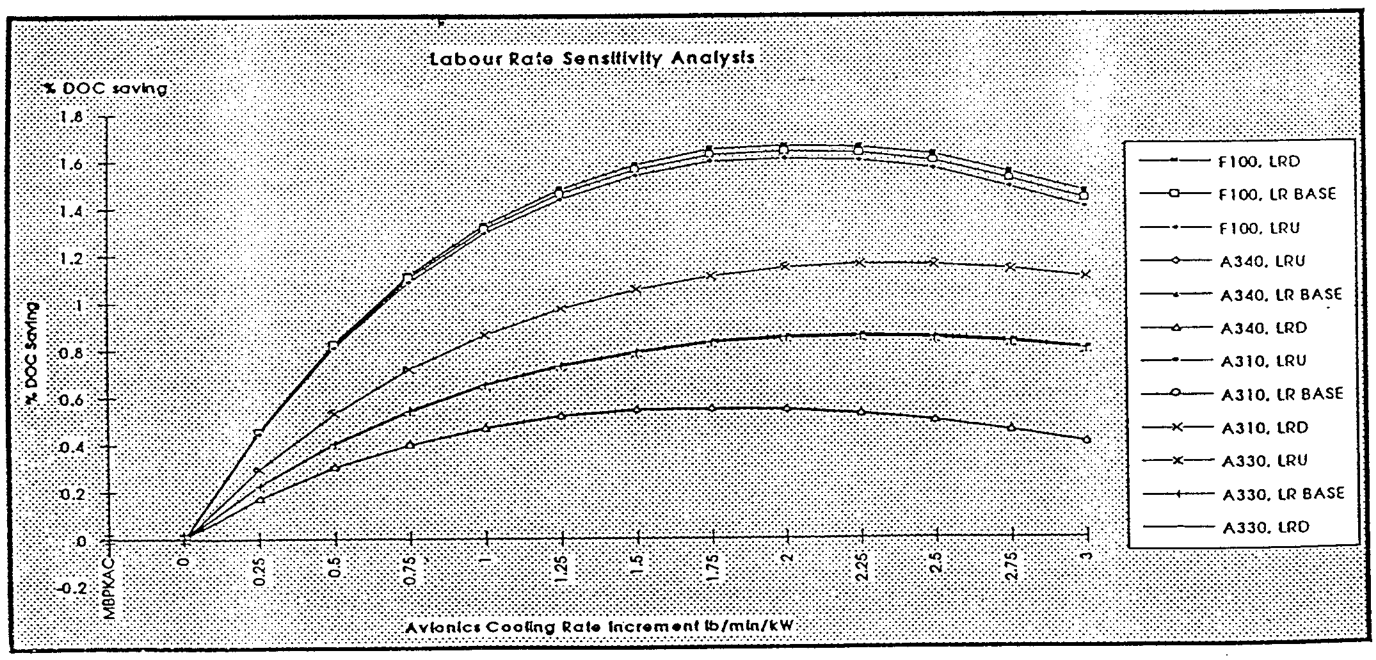

Figure. 3

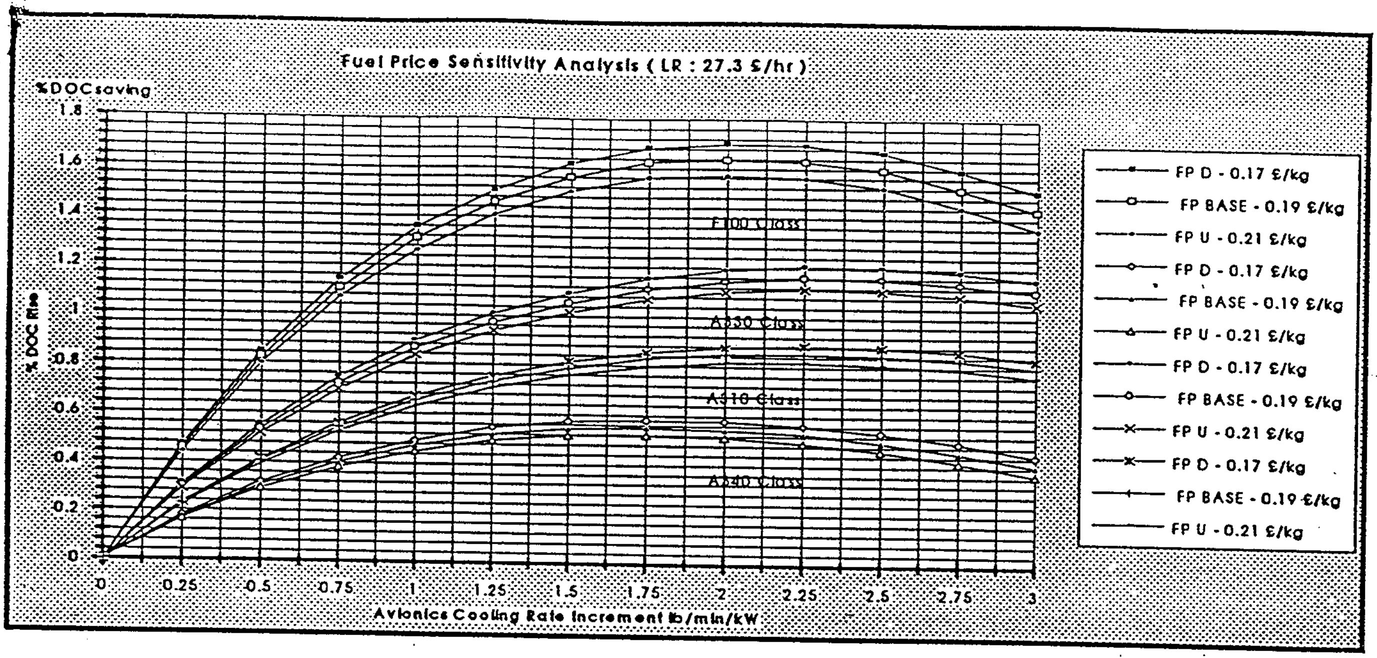

Figure. 4

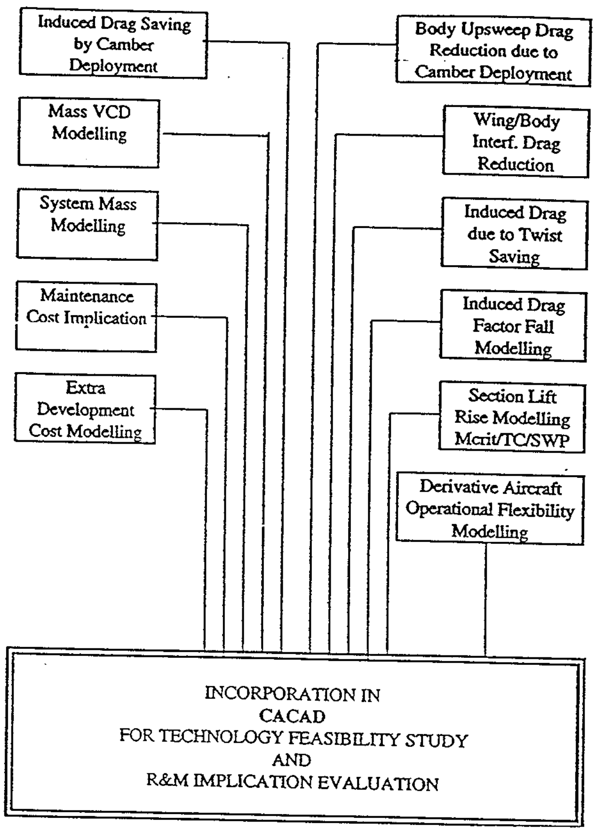

Figure. 5 VCW Technology Modelling

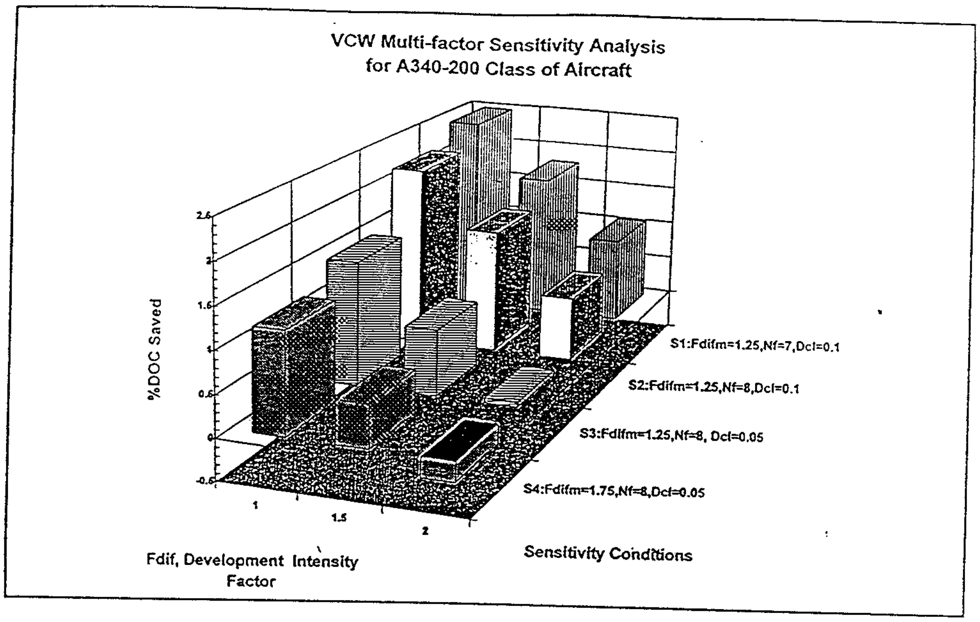

Figure. 6

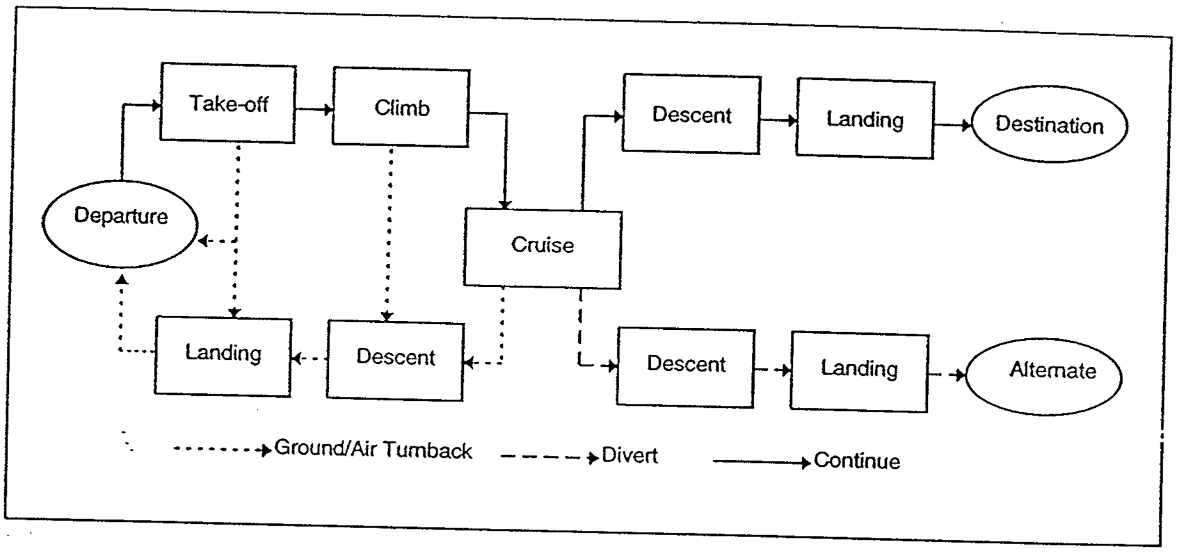

Figure. 7 Operational Phases

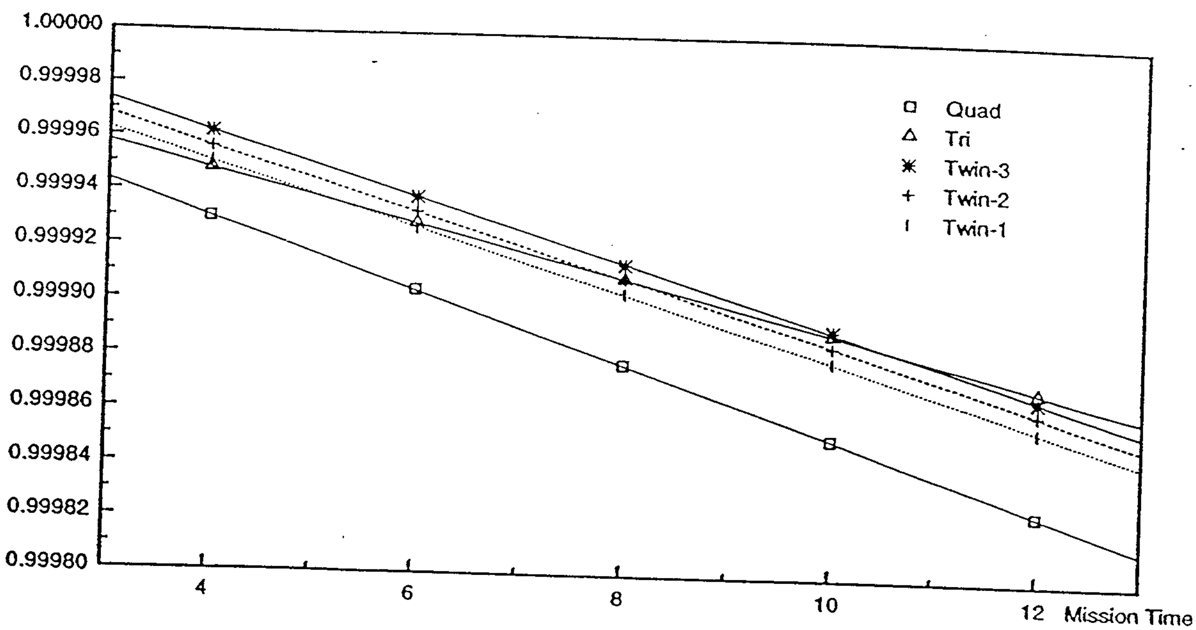

Figure. 8. Mission Simulation Results. Operational Reliability without CCFs