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RTO-MP-37

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 37

Design for Low Cost Operation and Support

(la Conception en vue d'une exploitation et d'un soutien à coût réduit)

Papers presented at the RTO Applied Vehicle Technology Panel (AVT) Specialists' Meeting, held in Ottawa, Canada, 21-22 October 1999.

Published September 2000

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

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- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine
- MSG Modelling and Simulation

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Design for Low Cost Operation and Support

(RTO MP-37)

Executive Summary

Affordability and reliability are essential requirements of all military equipment and many NATO nations now consider life cycle costs (LCC) to be of equal importance to the performance of the weapon system. The military customer needs to establish methodologies that allow investment at the design stage to produce weapon systems with lower operational support costs. LCC must be tackled early in the design and acquisition of military systems, since 90% of LCC may be fixed by the early decisions made before production commences. This Specialist Meeting offered a forum for the NATO nations to discuss where the major LCC are incurred and the applicability of LCC models developed for existing and future systems.

About 50 delegates attended the formal presentations. Discussions confirmed that NATO forces are under great financial pressure. The life cycle cost of defence systems is under close scrutiny and the service life of equipment is being extended. This emphasises the importance of logistic support and the selection of the most cost-effective approach. Cost-modelling tools are available to aid this selection, although full model validation may not be available until equipment has been in service for many years.

Close co-operation between the manufacturer and the end-user is vital to achieve the most cost-effective solutions. The civil aircraft industry has exploited this partnership by including airline customers at all stages of the design process. This needs to be extended to military equipment and the support systems. Cost benefits can accrue from the shift towards a 2-level maintenance system where industry co-operation ensures a rapid turn around of parts in peacetime. However, there must be sufficient flexibility in the system to ensure full support during conflicts and remote deployment. It may be necessary for military personnel to work alongside industry in peacetime, so that they have the required skills to support active deployments.

The greatest problem for fleet managers and cost-effective logistics is unplanned maintenance. This hits system availability and jeopardises mission success. Reliability and predictability are key goals of current projects. Manufacturers and end-users need to co-operate to achieve the long-term goal of no unplanned maintenance. Greater use of prognostic and health monitoring systems will play a major role in achieving this objective. Much of the basic technology is already available, so the new challenge is to apply the techniques in selective, cost effective application. This requires a deeper understanding of the system and the failure processes, which are inherent in the design.

Finally, there is a cost associated with equipment disposal at the end of its life. This cost is both financial and environmental and at the moment does not play a major part in the design process. Equipment in the design phase now is not due for disposal until the middle of the 21st century. Following current trends, it is expected that future disposal and re-cycling requirements will be very stringent. More thought should be given to the effects that this will have on life cycle cost.

la Conception en vue d'une exploitation et d'un soutien à coût réduit

(RTO MP-37)

Synthèse

Le caractère acceptable du coût d'acquisition et la fiabilité sont des critères essentiels pour tout matériel militaire et aujourd'hui, bon nombre de pays membres de l'OTAN considèrent que les coûts globaux de possession (LCC) d'un systèmes d'armes sont tout aussi importants que ses performances. Le client militaire doit établir des méthodologies permettant d'investir au stade de la conception dans le but de réaliser des systèmes d'armes dont les coûts de soutien opérationnel soient réduits. Les LCC doivent être évalués très tôt lors de la conception et l'acquisition des systèmes militaires, puisque 90% des LCC peut être figé si les décisions appropriées sont prises avant le lancement de la production. Cette réunion de spécialistes a servi de forum aux pays membres de l'OTAN pour discuter de la manière dont les principaux coûts LCC sont encourus et de l'applicabilité des modèles LCC développés pour systèmes existants et futurs.

Environ 50 délégués ont assisté aux présentations officielles. Les discussions qui ont eu lieu ont confirmé l'importance de la pression financière subie par les forces de l'OTAN à l'heure actuelle. Les coûts globaux de possession des systèmes de défense sont surveillés de très près et des efforts sont faits pour prolonger la durée de vie des équipements. Ces efforts ne font que souligner l'importance du soutien logistique et du choix de l'approche la plus rentable. Des outils de modélisation des coûts sont disponibles pour faciliter ce choix, même si la modélisation complète du modèle n'est souvent pas réalisable avant que les équipements n'aient été en service pendant plusieurs années.

Une coopération étroite doit impérativement être établie entre le fabricant et l'utilisateur afin de parvenir aux solutions les plus rentables. L'industrie aéronautique civile a su exploiter ce partenariat en consultant les clients des compagnies aériennes à chaque étape du processus de conception. Cette approche doit être étendue au matériel militaire et aux systèmes de soutien. Pourvu que le partenaire industriel fasse preuve de coopération en assurant des délais d'exécution courts en temps de paix, l'adoption d'un système de maintenance à deux niveaux peut générer des gains en matière de coûts. Cependant, le système doit être suffisamment souple pour assurer le soutien nécessaire en cas d'éventuels conflits nécessitant le déploiement de troupes et de matériels à distance. Le personnel militaire pourrait être appelé à travailler aux côtés du personnel civil dans l'industrie au temps de paix, afin de lui permettre d'acquérir les compétences nécessaires au soutien des déploiements actifs.

La maintenance non-prévue représente le plus grand problème qui se pose pour les gestionnaires de flottes aériennes, ainsi que pour le maintien d'une logistique rentable. En outre, elle met en cause la disponibilité des systèmes et la réussite des missions. Les projets en cours à l'heure actuelle privilégient la fiabilité et la prévisibilité. Une coopération étroite entre fabricants et utilisateurs est essentielle pour espérer atteindre l'objectif à long terme d'une disparition de la maintenance non-planifiée. L'utilisation généralisée de systèmes de pronostic et de contrôle de l'état des matériels sera l'un des facteurs majeurs dans la réalisation de cet objectif. Bon nombre des éléments technologiques de base sont déjà disponibles. Par conséquent, le nouveau défi à relever consiste à mettre en oeuvre ces techniques de façon sélective et rentable. Cette mise en oeuvre passe par une meilleure compréhension du système ainsi que de l'origine des pannes, qui sont liées à la conception.

Enfin, la liquidation du matériel en fin de vie entraîne un coût supplémentaire. Ce coût, qui est à la fois financier et environnemental, ne joue pas un rôle majeur dans le processus de conception. Le matériel en cours de conception aujourd'hui ne sera liquidé qu'au milieu du 21ème siècle. Si la tendance actuelle se maintient, les modalités régissant la liquidation et le recyclage à l'avenir seront très strictes. Il y a lieu de réfléchir dès à présent aux conséquences de ces procédures pour les coûts globaux de possession.

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† Paper not available at time of printing.

Theme

Affordability and reliability are essential requirements of all military equipment and many NATO nations now consider life cycle costs (LCC) to be of equal importance to the performance of the weapon system. The military customer needs to establish methodologies that allow investment at the design stage to produce weapon systems with lower operational support costs. LCC must be tackled early in the design and acquisition of military systems, since 90% of LCC may be fixed by the early decisions made before production commences.

This meeting offered a forum for the NATO nations to discuss where the major LCC are incurred and the applicability of LCC models developed for existing and future systems. Most examples were taken from the air environment but the principles apply equally to other systems. Critical parameters include reliability targets, mission specifications and the logistics system adopted by the operator. These will be dependent on existing facilities, fleet sizes and the mode of operation. Modelling techniques can quantify how simplified designs with fewer parts and improved maintainability reduce overhaul time and cost. This permits the design engineer to make informed trade-off decisions between the ultimate system performance and the cost. The concept of fault free operating periods offers the possibility of more effective fleet management with associated cost benefits. The new concept of prognostics and intelligent monitoring systems was discussed to show how they allow more flexible management of the fleet and increased system availability, while simultaneously reducing the in-service support costs. The sharing of experiences and difficulties encountered in LCC estimation during the design process will contribute to the acquisition of more cost effective systems in the future.

Thème

Pour tout matériel militaire, coût d'acquisition et fiabilité sont des critères essentiels et aujourd'hui, nombreux sont les pays de l'OTAN qui considèrent que pour un système d'armes les coûts globaux de possession (LCC) d'un système d'armes sont aussi importants que les performances. Le client militaire doit établir des méthodologies dès le stade de la conception afin de pouvoir réaliser des systèmes d'armes dont les coûts de soutien opérationnel sont réduits. Les LCC doivent être abordés très tôt dans la conception et l'acquisition des systèmes militaires, puisque 90% de ces coûts peuvent être maîtrisés grâce à la prise rapide de décisions avant le lancement de la production.

La réunion a servi de forum aux pays membres de l'OTAN pour discuter de l'origine des coûts LCC et de l'applicabilité des modèles LCC développés pour les systèmes existants et futurs. La plupart des exemples proviennent du milieu aéronautique mais les principes en jeu s'appliquent également à d'autres systèmes. Les paramètres critiques comprennent les objectifs en matière de fiabilité, les spécifications de mission et le système logistique adopté par l'opérateur. Ces paramètres dépendront de la nature des installations existantes, de l'importance des flottes aériennes et du mode d'exploitation choisi. Les techniques de modélisation peuvent être utilisées pour quantifier la diminution des coûts et des délais de révision en fonction d'une simplification de la conception, avec moins de pièces et plus de facilité d'entretien. Ceci permet à l'ingénieur concepteur de prendre des décisions en connaissance de cause lorsqu'il s'agit de choisir entre les performances définitives d'un système et ses coûts. Le concept d'exploitation sans pannes offre la possibilité d'une gestion de flotte aérienne plus efficace associée à des avantages en matière de coûts. Le nouveau concept de pronostics et de systèmes de contrôle intelligents était discuté afin de démontrer sa capacité de créer une gestion plus souple de la flotte aérienne, avec une disponibilité accrue du système, et une diminution des coûts de soutien en service. L'échange d'expériences et la discussion des difficultés rencontrées dans l'estimation des LCC lors de la phase de conception contribuera à l'acquisition de systèmes plus rentables à l'avenir.

Publications of the RTO Applied Vehicle Technology Panel

MEETING PROCEEDINGS (MP)

Design for Low Cost Operation and Support
MP-37, September 2000

Gas Turbine Operation and Technology for Land, Sea and Air Propulsion and Power Systems (Unclassified)
MP-34, September 2000

Aerodynamic Design and Optimization of Flight Vehicles in a Concurrent Multi-Disciplinary Environment
MP-35, June 2000

Structural Aspects of Flexible Aircraft Control
MP-36, May 2000

New Metallic Materials for the Structure of Aging Aircraft
MP-25, April 2000

Small Rocket Motors and Gas Generators for Land, Sea and Air Launched Weapons Systems
MP-23, April 2000

Application of Damage Tolerance Principles for Improved Airworthiness of Rotorcraft
MP-24, January 2000

Gas Turbine Engine Combustion, Emissions and Alternative Fuels
MP-14, June 1999

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Qualification of Life Extension Schemes for Engine Components
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Fluid Dynamics Problems of Vehicles Operation Near or in the Air-Sea Interface
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Design Principles and Methods for Aircraft Gas Turbine Engines
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Airframe Inspection Reliability under Field/Depot Conditions
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Development and Operation of UAVs for Military and Civil Applications
EN-9, April 2000

Planar Optical Measurements Methods for Gas Turbine Engine Life
EN-6, September 1999

High Order Methods for Computational Physics, Published jointly with Springer-Verlag, Germany
EN-5, March 1999

Fluid Dynamics Research on Supersonic Aircraft
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Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems
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TR-28, April 2000

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TR-27, December 1999

Programme Committee

Chairman
Dr. M. Winstone
Technical Manager, SM2, Structural Materials Center
Room 2008, Griffith Building (A7), DERA, Ively Road
Farnborough, Hampshire, GU14 0XL, UK

BELGIUM
Prof. Dr. J. Vantomme
Royal Military Academy (RMA)
Department of Civil Engineering
avenue de la Renaissance, 30
B-1040 Brussels

CANADA
Mr. D. Simpson
Structure, Materials & Propulsion Lab.
IAR, NRC, Montreal Road,
Ottawa, Ontario K1A 0R6

FRANCE
ICA P. Armando
DGA/DSA/SPAe
Adjoint Cellule Mobilité, Systèmes
et Techniques Aéronautiques
00460 Armées

Mr. D. Chaumette
Dassault Aviation
78, quai Marcel Dassault-Cedex 300
92552 St. Cloud Cedex

GERMANY
Prof. Dr. O. Sensburg
DaimlerChrysler Aerospace AG
Militaerflugzeuge LME2
Postfach 80 11 60, 81663 Munich

ITALY
Prof. M. Marchetti
University La Sapienza, Aerospace Department, via Eudossiana
11-16, 00189 Roma

Lt. Col. G. Zennaro
c/o D.G.C.A.A.A.S.
13 Div., viale dell' Universita 4
00185 Roma

NETHERLANDS
Ir. W. Van der Hoeven
National Aerospace Laboratory NLR
P.O. Box 153, 8300 AD Emmerloord

UNITED KINGDOM
WG CDR S.Chamberlain
SM17 (RAF), B Block Room B009
RAF Wyton, P.O.Box 70, Huntington
Cambridgeshire PE17 2EA

Prof. R.T. Potter
Room G030 A1 Building, DERA,
Farnborough, Hants GU14 0LX

UNITED STATES
Mr. J. Coyle
The Boeing Company, P.O. Box 516
Saint Louis, Missouri 63166-0515

Dr. D. Paul
Air Vehicles, Air Force Research Lab.
2130 8th Street, Suite 1, WPAFB,
OH 45433-7524

Dr. S.G.Sampath
Aeronautics & Mechanics Branch, US Army - ERO
Edison House, 223-231 Old Marylebone Road,
London NW15, UK

Technical Evaluation Report

M R Winstone
Mechanical Sciences Sector
Room 2008, A7, DERA
Ively Road, Farnborough
Hampshire, GU14 0LX, United Kingdom

Introduction

The idea for a Specialists' Meeting on design for low cost operation and support was first advanced by Wg Cdr Steve Welburn (RAF). At the time Wg Cdr Welburn was a UK member of the AGARD Structures and Materials Panel and had responsibility within the RAF for technical support of in-service airframe maintenance. Over the past 20 years the maintenance costs of combat aircraft had increased significantly and much of this cost could be attributed to design decisions made early in the project life cycle. Performance was the dominant goal of aircraft design and this led to poor maintainability and low system availability. Both of these parameters have a major effect on the through-life cost of the aircraft system. Discussions amongst the AGARD SMP members revealed that this was a common NATO problem. Systems designed during the 1970's took insufficient account of maintainability/availability issues and the operators are now paying the cost.

With the recognition of the link between design and maintainability, there was a change in the priorities when specifying new systems. System designers are now required to include life cycle cost studies as part of the procurement cycle and a new 'science' of life cycle cost modelling has emerged. Each country has faced the same problem and developed its own methodology to achieve an optimum cost/performance/availability balance. This presented an opportunity for AGARD to bring together the specialists from various NATO countries, discuss current life cycle cost modelling as practised in the various countries, and highlight future trends in logistic support. Initially this topic was developed by AGARD SMP Sub-Committee 82 and the activity transferred to AVT Technical Team 031 with the creation of the RTO in 1998.

The Specialist Meeting was attended by about 50 delegates and offered a forum for the NATO nations to discuss operation and support costs, the applications of LCC models developed for existing and future systems, and new equipment concepts designed to reduce LCC. Most examples were taken from the air environment but the principles apply equally to other systems.

Summary of Presentation

Session I - Introduction to operation and support costs

An excellent introduction to life cycle cost issues was provided the Belgium Air Force. Affordability is the key issue to NATO military planners and there is a clear compromise to be made between capability and cost – enhanced lethality, survivability and supportability usually have costs attached to them. A range of LCC models incorporate R&D, production, operation, support, retirement and disposal costs. Each cost needs to be calculated within the range of missions and the force structures appropriate to a particular operator. Modelling allows many alternative options to be evaluated before procurement decisions are made. Furthermore, the models are used to decide on the viability of new maintenance and quality processes, which must be funded out of the resultant savings in the routine maintenance costs.

The second paper in this session concentrated on the modelling of logistic support mechanisms. Modelling is used to make decisions on the quantity and phasing of spares procurement and the most appropriate repair chain. Should components be repaired by the operator or returned to the manufacturer? It may be cheaper to use the manufacturer but the increased turn around time and the loss of independence can impair operational capability during active deployments. Models also need to identify the appropriate levels of provisioning for rapid deployments. Simulations calculate the availability as a function of support, allowing the RAF to provision for a specified mission success rate.

Cost modelling should be a continuing process throughout the life cycle of a system. Re-analysis of costs as more data become available and operational roles change allows the reassessment of the optimum level of support. An often overlooked capability of cost models is to predict the effect of in-service modification. Modelling saves the operator significant sums by demonstrating that costly improvements will never recover the investment required for their implementation.

Session II - Life Cycle Cost Modelling

The USAF is developing PC-based LCC tools, which present meaningful data on the cost impact of new technologies to scientists and engineers. Virtual Expert Cost-Estimator for Air Vehicle Science and Technology Science and Technology (VECAST) uses existing commercial databases and analytical relationships with extrapolations to quantify the effects of new technologies. It is then possible to make trade-offs between cost and capability at the component level, which can be summed, into sub-systems. Probabilistics are included to reflect the uncertainties inherent in new technologies.

A different approach to life cycle management has been developed for the French Navy. Here the focus is on the availability of all the systems required to launch a successful mission. In a complex system such as a warship, each given physical system will participate in several functions. Often it does so concurrently with other physical systems. The interactions and the variety in contribution levels among the systems cannot be ignored when making long term decisions about systems architecture and logistic support. The advocated methodology provides a commonly understandable representation of how physical systems contribute in fulfilling operational functions and shows which are the performance drivers. It can be done in real time and lets decision-makers make the decisions.

Dedicated modelling of the operational functions of the whole ship is co-operatively developed by users and systems architects. A tree-structure representation is developed for each top-level ship operational function. It provides a simple way of showing the contributions and the interactions of physical systems. The model allows representation of partial functional redundancy. A software programme provides sensitivity analysis of all the parameters versus the overall availability level of each top-level ship function. The methodology is being used with several major naval programmes. It is also instrumental in re-engineering the logistic elements of in-service ships, based upon actual feedback and failure reports.

Another application of cost modelling is within preliminary design studies. A UK MoD study has developed a tool which optimises the design of a conceptual combat aircraft for minimum life cycle costs, where life cycle cost is the total of RDT&E, production, ground support equipment and spares, operation and support, and disposal. A surprising conclusion was that a twin engine aircraft would be lighter but more expensive. However the study did indicate that designs are now possible which would reduce operation and support cost to only 50% of the life cycle cost. This compares with a typical 60-70% for current combat aircraft systems. One solution offered as a means of further reducing this operation and support cost is the Low Support Vehicle. This aircraft is a flying wing design containing many features to reduce its direct support requirement. Large combat radius, stealthy design, and self-defence capability would allow this aircraft to operate autonomously, reducing the costs by removing much of the support requirement for conventional strike aircraft.

Session III - Application of Cost Models

A paper from Dassault Aviation confirmed the current situation by stating that the operating costs of the Mirage 2000 account for 60% of the LCC. However it is important to tailor the support infrastructure to match the needs of individual customers. The concept of 'safe and simple' leads to reliability and reduced costs. The Mirage 2000 is considered to be a reliable and cost effective system, with mean flying hours between failures of 6.8 hours, requiring 8-10 direct maintenance man-hours per flight hour. This equates to 5 missions with the French Air Force. For the future, an integrated logistic support system is advocated. This was applied to Rafale, where affordability was an important design parameter from the start of the project. It was necessary to demonstrate affordability in the virtual environment before approval for the projects. Potential customers for the aircraft require this information as part of the primary selection process.

Priorities within the commercial aviation world are different but cost is still a prime driver in making procurement decisions. Other commercial factors such as interest rates and insurance costs are also important due to their influence on cash flow. Life cycle costing is a highly systematic process drawing on past experience and parametric studies. A successful trade off between aircraft price and operating costs must be achieved to ensure commercial success. Analytical models are used to measure the effect of design options on the investment costs and the operating costs to derive a commercially attractive solution. Numerical modelling allows many thousands of options to be explored and sophisticated sensitivity analyses aid in the assessment of risk. The civil aircraft designer gains from close collaboration with the customer.

Teaming with customers provides valuable operating data and experience. From an airline perspective, about 20% of their direct operating costs are attributable to maintenance, which is highly influenced by the design.

Military aircraft design now gives equal priority to performance, reliability, maintainability and flight safety. Performance was only one design requirement, which needed to be met for the Eurofighter Typhoon. Maintainability requirements affected the general structural layout for even simple requirements. Equipment bays were positioned at chest height and space is provided for the use of standard hand tool with easy access. This design process has been aided by the introduction of virtual engineering tools that allow the simulation of components, their spatial relationships and digital product assembly. Degradation of the airframe in service is predicted by corrosion modelling and structural fatigue monitoring. A real time structural health monitoring system performs fatigue calculations, based on flight parameters and strain gauge readings. These allow maintenance plans to be developed on the basis of real data rather than fleet predictions.

Propulsion systems are also being subjected to close scrutiny of LCC. The affordability focus is driving fundamental changes in the design and support processes. Improved supportability will result in increased reliability, improved safety and reduced maintenance. Simpler but more efficient designs are preferred, which incorporate prognostic and health monitoring capabilities. Cost control is enforced by defining a target cost for every component and using cost modelling to ensure that the design meets that goal. 3D solid modelling techniques are used to assess maintainability and the entire multidisciplinary design team uses a common master model. Some 30% of mission aborts are due to maintenance induced failures. Typically, the repair of one system induces a fault elsewhere, often due to human error. This is an inherent feature of certain designs and can be drastically reduced if the assembly can be visualised at an early stage and due account taken of human factors. Prognostic health management will allow engine condition to be assessed automatically prior to aircraft arrival, enhance failure detection/isolation and minimise no-fault-found events.

An attractive engine logistic support system for both engine manufacturer and the operator is power-by-the-hour. This allows the operator to reduce the support tail. No spare engines or components are purchased but the manufacturer undertakes to supply all that is required. The rate paid by the customer is charged per flying hour. The advantage to the customer is prior knowledge of the costs and the manufacturer has a strong incentive to improve reliability and availability. The successful implementation of this strategy needs a strong partnership between industry and the operator to achieve an equitable split of costs and risks. Prognostic tools used in design need to give accurate life predictions for the setting up of the initial power-by-the-hour agreement and on-board monitoring systems provide accurate measurements of service damage accumulation. This is used to optimise the benefits to both manufacturer and customer through service life extensions without jeopardising safety.

Session IV - Techniques for Reduced Logistic Support Costs

Experience over the past 20 years has shown that the increasing complexity of weapon systems has led to a decline in reliability and the establishment of a complex 4 level maintenance system. New systems use integrated logistic support systems, which consider reliability and maintainability as important features of design. Next generation systems will achieve much higher reliability targets and so the logistic support structure needs to be reassessed. There is scope for significant savings if industry and military customers co-operate through the life cycle and rationalise the provision of facilities and trained personnel. Long, low rate procurement cycles mean that the original manufacturing equipment and manpower is available for support functions. For minimum cost, this leads to a 2-level support system with 70% of maintenance tasks conducted by the single source industry supplier. Calculations for Eurofighter Typhoon indicate that the 2-level system will reduce total costs of operation and support by 15%. Close collaboration between the manufacturer and service user is essential if these benefits are to be realised without detriment to mission availability. A fast, responsive service from industry must be assured and the military user may require service personnel to receive the training and experience required to support equipment through critical deployments.

The UK is exploring a radical new approach to availability and reliability. Equipment specifications typically set a mean time between failures (MTBF). However, this is an average figure and provides no useful data for the prediction of failure of individual components in particular systems. The random nature of failures has been accepted by the user and individual components may last 1 hour or a 1000 hours. Both fall within the definition of MTBF. A new concept of maintenance free operating periods (M-FOP) is proposed to re-define reliability. This requires a deeper understanding of the reasons for failure at the design stage. Once the causes of unreliability are identified and understood it is intended to anticipate failures and design them out, rather than react to developmental failures. 'Maintenance free' does not imply zero faults but such faults that do occur should not hazard the mission and would be repaired during a maintenance recovery period. An essential factor within the M-FOP concept is application of fault detection using built in test equipment and health/usage monitoring equipment, which can anticipate failure. The successful application of this new definition of reliability would lead to systems being available when they are required and a reduction in mission failures. Furthermore, maintenance downtime would be programmed around the operational commitments with a simplified supply chain. The reduction in unscheduled maintenance would minimise logistic support and cost.

From the manufacturers point of view the issue of M-FOP warranties places great emphasis on understanding the origins of failure and accurate forecasting of reliability. This requires co-operation of companies at all levels within the supply chain. The objective is to eliminate unscheduled maintenance. Reliability data need re-analysis now that MTBF is not the key parameter. The minimum failure life, with appropriate statistical confidence, is more important. The goal is to achieve a 50% reduction in defect arisings.

Safety is an over-riding requirement of logistic support for all air systems. The increasing age of fielded systems and the need to extend operational life have an impact on safety and operational capabilities. Within the USAF this has resulted in an increase in the mishap rate. Mishaps occur for a wide variety of reasons. The most common is human error but that may be exacerbated by design features, inadequate manuals or training. An integrated systems engineering approach to safety has been adopted to develop a new policy consistent with the downsizing and reducing DoD budget. Partnership with industry is exploited to maximise use of scarce resources and establish best practice. System Safety Groups oversee programmes throughout the life cycle of the system and document the risk review process. They also define the level of Government authority for acceptance of residual mishap risk. An orderly and incremental sequence of activities is required to lead to aircraft flight clearance and this must be adhered to every time a configuration change is proposed.

Traditional aircraft support systems have concentrated on fault identification and reacting to these faults. Prognostics and health monitoring focus on the health and safety of the system while it is in operation but must provide the precision and accuracy required to allow maintenance during planned periods compatible with the operational need. The move to lower cost 2 level maintenance systems and greater collaboration with industry shifts the location of prognostic and diagnostic systems onto the aircraft itself. However the output of these systems must be available to both the end-user for trend analysis and the identification of potential problems and the maintenance facility when items are returned for repair. This emphasises the need for an effective information management system.

The increasing service life of systems is imposing a very high inspection burden to ensure structural integrity. This portion of LCC could be reduced by increased use of automation but this is not practical with conventional inspection techniques. An alternative approach is structural health monitoring. It should be possible to incorporate self-diagnostic systems into the structure, which would detect flaws and cracks in metallic, and CFRP structures. Such self-diagnostic systems should have an impact on LCC, which needs to be validated. A detailed analysis of Tornado metallic structures shows that inspection cost is approximately equal to repair costs. This data was used to validate a cost estimation tool for structural health monitoring. Calculations show that structural health monitoring offers little benefit for simple metallic covers. However the benefits for highly stressed parts are considerable. Inspection of main landing gear fittings could be eliminated. Read across to composite structures in new aircraft suggests similar trends. Monitoring devices need to be targeted to the most highly loaded parts where the cost benefits are highest.

Conclusions

The formal presentations and the discussions all demonstrated that NATO forces are under great financial pressure. The life cycle cost of defence systems is under close scrutiny and the service life of equipment is being extended. This emphasises the importance of logistic support and the selection of the most cost-effective approach. Effective cost modelling tools are available to aid this selection but there is little hard data to validate models. Full validation will not be available until equipment has been in service for many years. In the meantime efforts are being made to quantify the uncertainties and risks.

Close co-operation between the manufacturer and the end-user is vital to achieve the most cost-effective solutions. The civil aircraft industry has exploited this partnership by including airline customers at all stages of the design process. This needs to be extended to military equipment and the support systems. Cost benefits can accrue from the shift towards a 2 level maintenance system where industry co-operation ensures a rapid turn around of parts in peacetime. However, there must be sufficient flexibility in the system to provide full support during conflicts and remote deployment. It may be necessary for military personnel to work alongside industry in peacetime so that they have the required skills to support active deployments.

The greatest problem to fleet managers and the cost-effective logistics is unplanned maintenance. This hits system availability and jeopardises mission success. Reliability and predictability are key goals of current projects. Manufacturers and end-users need to co-operate to achieve the long-term goal of no unplanned maintenance. Greater use of prognostic and health monitoring systems will play a major role in achieving this objective. Much of the basic technology is already available, so the new challenge is to apply the techniques in selective, cost effective application. This requires a deep understanding of the system and the failure processes, which are inherent in the design.

Logistic support costs can be reduced if the peacetime usage of equipment reduced. Advanced simulation techniques can be used to reduce actual flying time of military aircraft but flight crews will always need live training. A longer-term possibility is more extensive use of uninhabited combat air vehicles. This issue will be discussed more fully during an RTO-AVT symposium on uninhabited vehicles, due to be held in 2000.

In the course of discussion, it became clear that there are 2 other problems, which confront the service customer when assessing system support costs. Politically, it is easier to justify spending money to maintain an existing system than it is to purchase a new, more capable and less costly system. This political reality will continue to frustrate efforts to buy new equipment and put more pressure on life extension programmes that require extensive logistic support. Finally, there is a cost associated with equipment disposal at the end of its life. This cost is both financial and environmental and at the moment does not play a major part in the design process. Equipment in the design phase now is not due for disposal until the middle of the 21st century. Following current trends, we can expect future disposal and re-cycling requirements to be very stringent and more thought should be given to the effects that this will have on life cycle cost.

Acknowledgement

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Life Cycle Cost – An Introduction

A. HUSNIAUX, Logistic Support Manager Transport Aircraft and Helicopters
Belgian Air Force Staff (VDV/Tpt)
Rue D'Evere 1
B 1140 BRUSSELS
Belgium

Summary

"Life Cycle Cost" (LCC) calculations, which give the global cost for the complete life cycle of a system, are becoming most common in the aeronautical field.

Due to the actual budgetary context, characterised by stringent budget reductions, LCC is becoming a design parameter, having the same importance as the operational performance of the considered systems.

Cost-effectiveness analyses, combined analyses of total cost and operational effectiveness, are now often an integral part of the decision cycle, starting with the expression of an operational need and ending with a procurement order of the production aircraft.
Recent examples are the American Joint Strike Fighter (JSF) and the European Future Transport Aircraft (FTA).

LCC models are very well suited to make cost-effectiveness analyses. They generate the necessary data for the planning cycle, give a clear insight in the expense flows and guarantee a transparent cost structure.

There are a lot of different LCC models available. Some of them are predictive models, allowing weighing different design alternatives against each other. Others are models, allowing calculating the LCC of existing systems based on statistical exploitation data.

The experience of the Belgian Air Force using life cycle cost models is illustrated with two examples. These examples demonstrate that life cycle costing is a strong instrument assisting the logistic support manager, both on existing weapon systems and on weapon systems still to develop.

Introduction

The need for *"design for low cost operation and support"* will be demonstrated, based on an example. This example is the acquisition of a future fighter aircraft.

A future fighter aircraft has to meet several stringent requirements in the fields of survivability, agility and manoeuvrability, capacity, performance, systems, avionics and sensors, weapons load and logistics.

It has to be survivable. Therefore it needs integrated self-defence systems and automated countermeasures, should have low observability, be fitted with NBC protection and be hardened against EMP.

It should possess agility and manoeuvrability. Vectored thrust is desired, giving the pilot the ability to look, to identify targets and to shoot in almost any direction. From the point of view of the aerodynamics, the airframe should be statically unstable, and the aircraft should have a high thrust-to-weight ratio.

The weapon system should be multirole: the aircraft should have fighter and air-to-ground capabilities.

In the performance domain, range and endurance should be high. Prolonged supersonic flights must be possible, the aircraft should have an excellent range and endurance, and be fitted with an air refueling capacity. Supersonic cruise should be possible.

The systems, avionics and sensors should be tremendously powerful. This is valid for the identification system, the electronic counter measures, the fire control system, the communication systems and the sensors. Moreover, all the systems and sensors should be integrated as much as possible.

Keywords for these systems are: security, reliability, interference-free, all-weather, ECCM, look-down and shoot-down, fire and forget, multiple engagements, detect and engage without radiating, ECM resistant communications, real-time distribution of voice and data, electro-optical and thermal imaging, sensor fusion, accessibility to GPS data, systems harmonisation and integration, beyond visual range, precision guided weaponry, internal weapon bays, ...

In the logistics field, robust, reliable, easily maintainable and easily deployable systems are desired. The logistic "footprint" should be small, and the systems, components and consumables should be standardised.

During the last decades, these requirements were met by systems with more and more complexity, and therefore a higher cost, especially in the field of the avionics.
Further escalation of this cost, with the same growth rate, is not acceptable, especially when taking into account the today's budgetary context.

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

Most of the countries want to decrease the cost of defence. "Defence at any cost" is a thing of the past: the amount of money spent on defence is carefully weighed against the amount of money needed to tackle the other challenges of today's society.

Affordability is therefore becoming a critical issue. Looking at the United States, where the Joint Strike Fighter (JSF) is under development, the situation is straightforward: either the JSF will be "affordable", or the JSF will not come to full production.
The "capability/cost" balance is a real issue: all systems have to meet the operational requirements, but the operational requirements must not drive the systems' cost up to the point that the JSF becomes unaffordable.

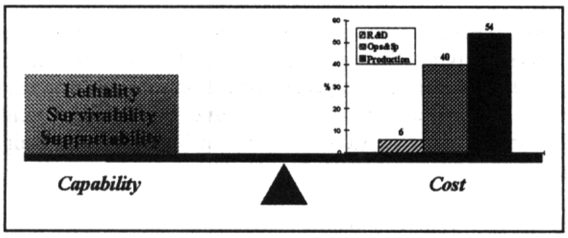

Figure 1: Cost-capability balance

Evident cost reduction solutions are to limit the quantity and the complexity of the next generation fighter aircraft. The real challenge however is to come to innovative designs, driven by cost and by operational effectiveness.

The *"operations and support cost"* will have to be tackled early in the *design*. *Reliability*, *supportability*, *maintainability*, and fleet management using *prognostics* and *intelligent monitoring* systems are to be considered.
To do so, *modelling* techniques are needed, allowing assessing the *cost* and *operational effectiveness* of the considered systems.

Life cycle cost models

The notion of "life cycle cost" will be introduced and analysed. Its use in the different phases of the life of a weapon system will be shown. Through generic LCC-models, the link with Integrated Logistic Support (ILS) will be established.

Life cycle cost

Affordability is a key issue for the acquisition of weapon systems, which are typically very complex systems, expensive both in acquisition and in operation and support.
For those systems a trade off exists between the acquisition cost and the operation and support cost, as indicated in the figure below.

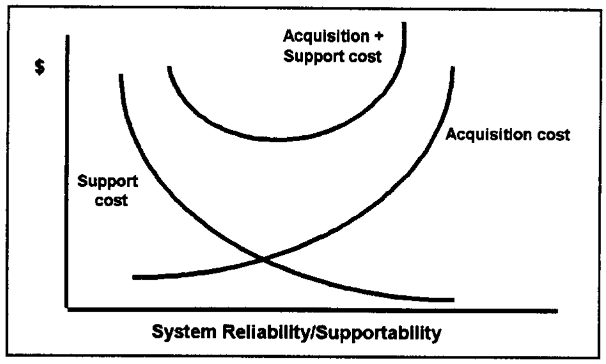

Figure 2: Trade-off between acquisition and support cost

The optimum solution has to be determined, based on the life cycle cost, the sum of all costs, estimated to be incurred in the anticipated life cycle of a weapon system.
Research and development costs, production and construction costs, operation and support costs and retirement and disposal costs constitute the LCC.

The nominal cost distribution of a typical Department of Defence program is indicated in the figure below.

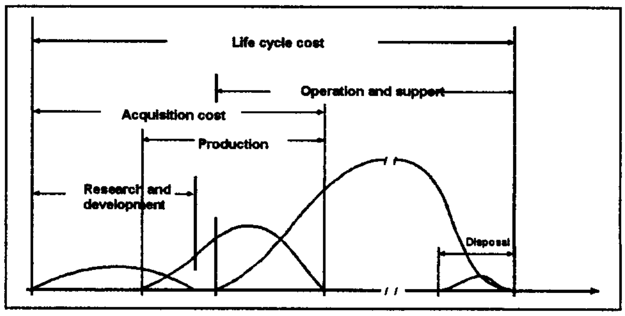

Figure 3: Nominal cost distribution of a typical DoD program

The life cycle cost commitment has a completely different profile. Early in the program, in the design phases, actual expenditures are low, but the decision-induced LCC are very high. It is in this phase that the design has to focus on low cost operation and support.

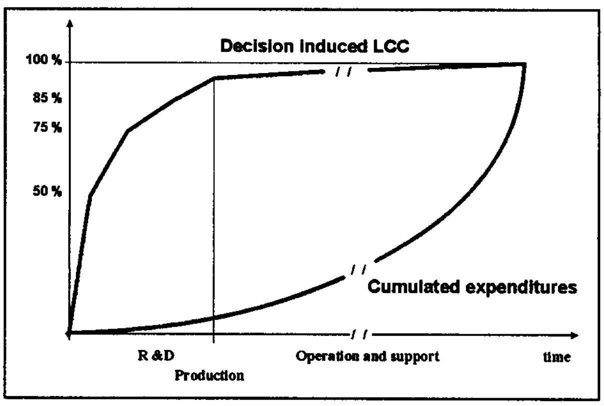

Figure 4: Life cycle cost commitment

Role of LCC in the different program phases

To describe the role of LCC in different program phases, the research and development phase has to be split in three distinct phases: a conceptual design phase, a preliminary design phase and a detailed design phase.

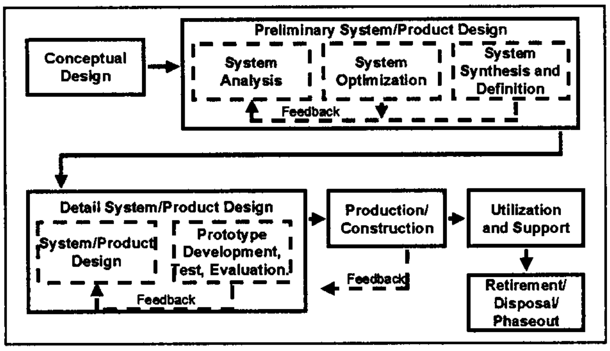

Figure 5: Role of LCC in the different program phases

During the conceptual design phase, a feasibility study will be made, system operational requirements will be written and the preliminary support concept will be outlined. The LCC model will have to generate budgeting figures and define key (cost driving) parameters.

During the preliminary design phase, a system analysis, a system optimisation and a system definition will be performed. This phase ends with a preliminary design, the analysis of a chosen configuration and the system definition (specifications and plans). The LCC model will have to predict and evaluate the LCC, based first on generic system characteristics and later on vendor data.

During the detailed design phase, a detailed design of the system, of the logistic support and the documentation will be performed. The design will also be reviewed. The LCC model will have to predict and evaluate the LCC based on vendor data.
During the detailed design phase, an engineering model, a prototype and the logistic support capability will also be developed, tested and evaluated. The LCC model will have to assess the LCC, based on test data.

During the production phase, the system will be produced and the initial logistic support fielded. The LCC model will collect cost data, analyse and report them. It will be used to assess the LCC based on production data.

During the system operation and support phase and the disposal phase, the LCC model will collect, analyse and report the cost data. It will be used to assess the LCC, based on field data and on disposal data.

Different LCC models thus are to be used. These models should have a structure, tailored to the program phase in which they are employed.

The input of the models, their output and cost resolution will vary throughout the program life, allowing the decision-makers to take the appropriate decisions in each program stage.

Generic LCC models

Before paying attention to LCC models, it has to be stressed that LCC models have to be integrated in a global cost-effectiveness analysis, based on design attributes and logistic support elements, as indicated in the figure below.

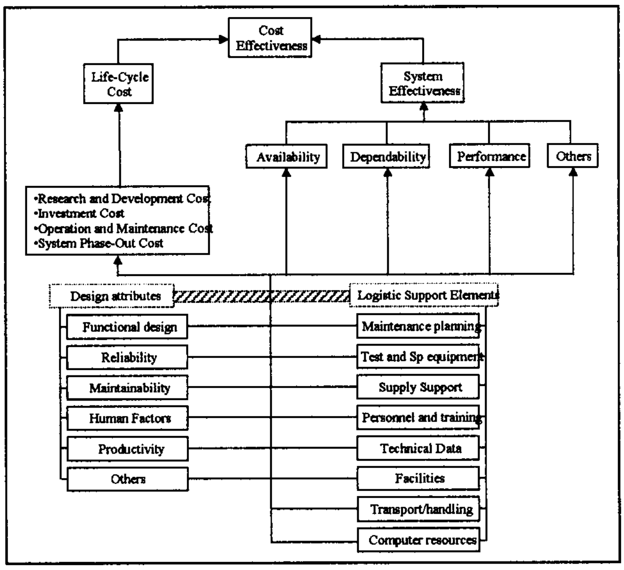

Figure 6: Cost-effectiveness analysis

In the United States, the United Kingdom (combined effectiveness and investment appraisal, COEIA) and the Netherlands, such a combined appraisal is mandatory for acquisition costs above a certain magnitude.

To be able to generate the LCC, a cost breakdown structure (CBS) has to be defined. To produce this CBS the events occurring during the life span of the system have to be identified.

Aggregating the cost estimates of these events (per year) will produce a "cost tree", modulated in time.

The aggregation of the costs, and the structure of the tree, depend on the purpose of the analysis and the program phase during which the LCC calculations are made.

A generic LCC model can be considered as a network of specialised models, generating all the costs mentioned in the cost breakdown structure and a calculator, producing the life cycle cost.

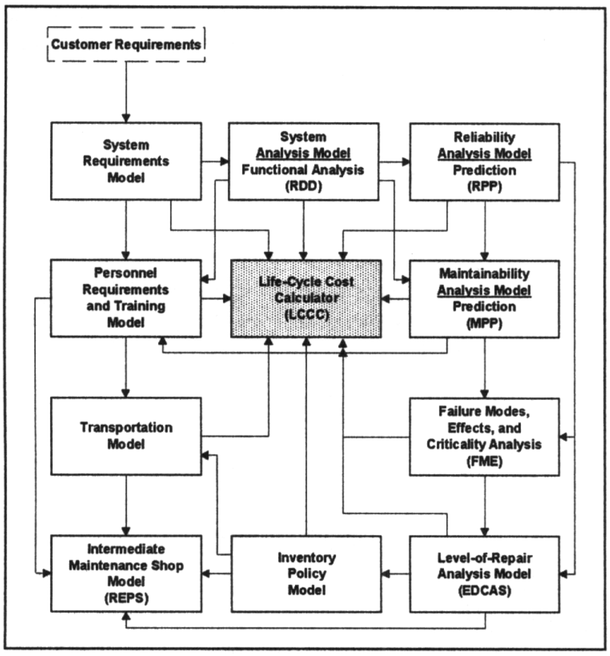

Figure 7: Generic life cycle cost model

There are a lot of specialised models, such as models calculating spare parts inventories, models determining the levels of repair, models predicting the reliability of the system components, ...

Cost estimation methods

To populate the cost breakdown structure, cost estimating methods have to be used.

There are two cost estimation methods: a predictive method, used before historical data are available, and a method based on statistical data, available for existing systems.

Predictive methods are based on different approaches.

The "parametric" method uses "cost estimating relationships", mathematical relations between the costs and physical or technical characteristics of the systems, to estimate the costs.

The method "by analogy" estimates the costs by using data, available for existing similar systems.

The method based on "the opinion of experts" generates costs by consulting experts, having experience with similar systems.

The "engineering" of "analytical" method generates costs using the cost of every component or activity. It uses a lot of design information and cannot be used early in the design.

Predictive methods will mainly be used in the design stages, while statistical methods primarily will be adopted during the operation and support phase.

LCC and Integrated Logistic Support (ILS)

ILS is a logistic function, with the following objectives: the integration of the logistic support in the design of weapon systems, the development of the specifications for the logistical support, the acquisition of the logistic support and the delivery of logistical support in the most cost-effective way.

ILS brings into the design, features such as reliability, maintainability and testability, which will be determining parameters for the operation and support cost.

The use of ILS allows the designers to search for the best compromise between performance, availability and life cycle cost of a weapon system.

Belgian Air Force experience with LCC

The BAF experience with LCC will be documented through two examples. In the first example, existing aircraft will be considered. In the second example, an aircraft in his early conception stage, the Future Transport Aircraft, will be discussed.

Belgian Air Force LCC experience with existing aircraft

The mission of the logistic support of the Belgian Air Force is clear: assuring the best technical condition and the flight safety of the aircraft, and guaranteeing the best technical condition of the other operational means.

To fulfil that mission, a global approach was defined and implemented. It was focused on the production of the best support of the operational units by the optimal use of the available resources.

The logistic management structures and the support structures were trimmed down and reorganised and an economic approach of the logistic support management was introduced.

Key to the reorganisation was the creation of business units at Airstaff level, responsible for all logistic aspects of a particular weapon system (combat aircraft, training aircraft, transport aircraft, ground radars,...).
These business units, managed by "material managers" define and implement the support policies, necessary to realise the best technical content and the flight safety of the aircraft.

The support policies induce four categories of actions: routine maintenance, long term (structural) maintenance, "quality efforts" and the procurement of equipment through investment.

Routine maintenance is the basic maintenance, as defined by Belgian Airstaff, based on the recommendations of the aircraft constructor.

This maintenance constitutes the minimum level of activities to be performed on the aircraft. Its cost is the minimum budgetary level necessary to operate and support the weapon system. Belgian Air Force policy is to trim the routine maintenance expenses to the lowest level possible, without impairing the quality of routine maintenance.

Long term (structural) maintenance is the preventive maintenance needed to guarantee a good technical condition of the aircraft in the long term. It mostly consists of preventive replacements of structural parts of the aircraft. It is performed to alleviate the inspection workloads of the operational units and to boost the availability of the aircraft.

"Quality efforts" are maintenance actions performed to guarantee the best level of technical performance of the aircraft in the long term. They consist of (partial) system upgrades, beefing up the technical content of the considered systems to a state of the art level. They are performed to continuously operate, throughout the whole life cycle, supportable weapon systems, experiencing all the benefits of the best available technology.

Procurement actions are investment actions with the aim of adding more operational capacities to the aircraft or to replace them. They are funded by dedicated investment budgets.

Long term maintenance and quality efforts are, with the agreement of the Ministry of Finance, funded with "operations and support" money. They can only be performed with the results of the savings achieved in routine maintenance.

This stresses the importance of the "material managers" level. Their creativity to diminish the routine maintenance cost is stimulated by allowing them to explore ways to trim it even more, by creating and implementing long term maintenance and "quality efforts".

These dynamics work: a very substantial reduction of the routine maintenance expenses has been realised and our aircraft are continuously improved. On the C130 for example, the gas turbine compressor (GTC) was replaced by a modern auxiliary power unit (APU), the avionics are up-to-date and an On Board Oxygen Generating System (OBOGS) will be aboard from 2000 on.

To allow the material managers to obtain these results, it is obvious that financial analyses have to be performed. These analyses constitute the first BAF experience with life cycle cost models.

Because of the dedicated LCC structure, the analysis of the routine maintenance cost with LCC models allows the material manager to identify the major cost drivers and the most promising areas to explore in order to realise savings on routine maintenance costs.

LCC models are used to analyse the economic implication of long term maintenance or "quality efforts".

The material manager will calculate and compare the future costs of the logistic support of the system with and without the alterations considered. He will use statistical data, and will be able to perform a very straightforward economical analysis.

Based on this economical analysis, and taking into account supportability factors, a decision whether to proceed or not with the long-term maintenance plan or to the quality effort will be taken.

The BAF experience with a COEIA for the modification of existing aircraft is rather reduced, though a methodology to perform a COEIA was developed.

This methodology is aimed to provide the decision makers with a cost-effectiveness study, trading off all the possible options: no modification, change the utilisation or support policy, refurbish, upgrade, procure off the shelf, or develop and procure in different numbers.

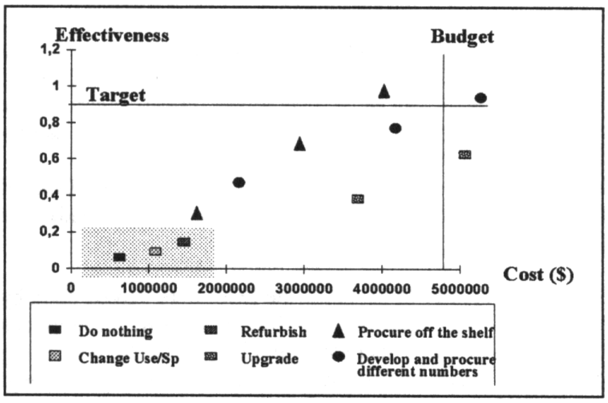

Figure 8: Cost-effectiveness for existing systems

BAF LCC experience with the Future Transport Aircraft

Four European Nations, Belgium, France, Spain and the United Kingdom launched a competition to procure a "Future Transport Aircraft". The specifications for it were written down in a "European Staff Requirement" (ESR).

This ESR not only contains the typical specifications, such as the general and specific characteristics for the aircraft and the design standards, but also the Integrated Logistic Support requirements. The aircraft has obviously to be designed with "low cost operation and support" in mind.

The ILS part contains the general specifications for the ILS, specifications for the maintainability, servicing and testability and time limits. It specifies reliability, maintainability and testability demonstrations as well.

To appraise the different competitors, a joint concept of assessment was adopted by the nations.

The "Joint Concept of Assessment document" details the principles for the competition and describes how the participating nations intend to judge jointly the proposals for the FTA procurement:

"The assessment will compare the cost-effectiveness, in whole life cycle cost terms, of defined fleets of candidate aircraft needed to deliver a prescribed level of transport capability in particular operational scenarios".

Three candidate aircraft were in the running: the A400M proposed by Airbus, the C17 proposed by Boeing and the C130J-30 proposed by Lockheed Martin Aeronautical Systems (LMAS).

The criteria used for the comparison of the tenders are: the fleet cost estimates derived from the COEIA, the compliance with the ESR, the ability to meet the time constraints, a risk assessment, commercial aspects (terms, conditions and pricing) and industrial/economic aspects (offsets, share of work).

The COEIA was performed in a particular way: the LCC of a single A400M fleet was compared to (equivalent) fleets of C17/C130J with the same operational effectiveness. The equivalence between fleets was determined with nation-dependent operational scenarios.
Because of this construction, the comparison of the LCC of these operationally equivalent fleets immediately provides the COEIA.

The data necessary to calculate the LCC were agreed upon by the nations. They constitute a "Master Data & Assumptions List" (MDAL), and include: the LCC methodology (along with the cost breakdown structure), the government questionnaire, which comprises " harmonised data " and assumptions generated by the nations, and data from bidders, extracted from proposals. They are complemented by a support scenario/LCC analysis.

Several cost analyses were performed.

In a first stage, the support cost per aircraft was calculated to select preferred support scenarios in function of the fleet sizes considered.

In a second stage, the total cost per aircraft type was calculated to identify the main cost drivers for LCC and to identify the parameters subject to a sensitivity analysis.

In a third stage the LCC for equivalent fleets was calculated, for the different nation-particular operational scenarios.

In a fourth stage sensitivity analyses were performed, adding bands of uncertainty to the previous results. Retained parameters were the exchange rate, the unit-cost of the different aircraft and the maintenance cost.

Final result of all these calculations is a LCC comparison of the equivalent fleets, for each of the retained operational scenarios.

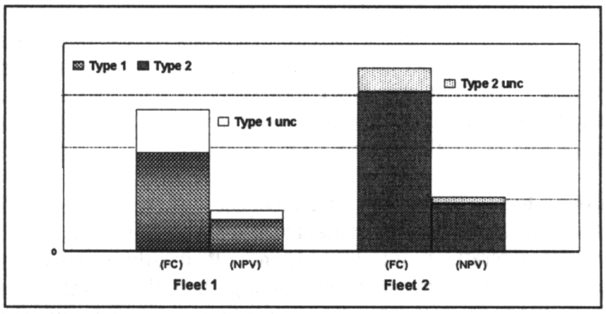

Figure 9: FTA cost-effectiveness

Conclusion

To address the affordability of weapons systems, life cycle costing can be used.

Using this methodology has a lot of benefits: it forces long-range considerations instead of short-term thinking, it provides a total cost visibility, establishes clear relationships between the system elements and the elements of cost and causes a reduction in risk by identifying high risk areas.

Life cycle costing is applicable, both to new systems, by influencing design for lower life cycle cost and operation and support cost in particular, and to existing systems, where it can drive the search for continuous improvement leading to lower life cycle cost.

The adoption of integrated logistic support allows the designers to search for the best compromise between performance, availability and life cycle cost of a weapon system.

Life cycle costing proves to be a very powerful tool, allowing every logistic support manager to optimize his resources management.

Acknowledgements

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MINIMISING LOGISTIC SUPPORT COSTS
MODELLING TECHNIQUES IN THE ROYAL AIR FORCE

Presented by: Mr F Boydell Head of Logistic Support Costing Block A Royal Air Force Wyton Huntingdon Cambs PE17 2EA England	Any views expressed are those of the author and do not necessarily represent those of the Agency.

INTRODUCTION

In all MOD procurement programmes, LCC is a prime metric in the selection process. The single biggest portion of a weapons system's LCC is the Logistic Support Cost (LSC). This paper will address the major considerations, models and analytical methods currently employed by the RAF to achieve maximum aircraft operational capability for the minimum LSC and analytical effort. The paper is broken into 2 distinct areas: introduction to service and through life support.

INTRODUCTION TO SERVICE

TEAMING FOR LSA

The RAF recognises those aircraft manufacturers and operators have, by necessity, very different skill sets and experience. Manufactures' expertise lies in the design, development and manufacture of aircraft, but they have little or no experience of operating and supporting them. The RAF, by comparison, have precisely the opposite skill sets. The advantages of manufacturer/operator teaming are obvious; the manufacturer gets an extra team working alongside for free and the RAF get a better product. Consequently, the RAF has Project Teams based at the manufacturer's site for all major programmes. However, despite the clear win/win advantages of teaming, some manufacturers still resist any form of integration.

THE ANALYSIS PROCESS

The development of a joint manufacturer/customer LSA process is complex and needs to address: areas of responsibility, provision of data, data interchange, data and modelling review processes, as well as the models and methods for conducting LORA, Initial Provisioning (IP) and sustainability modelling.

LORA

LORA Screening. The first area of analysis that the RAF gets involved in, is how and where a system should be maintained and repaired. This is the objective of Level Of Repair Analysis (LORA). LORA is a manpower intensive and very costly process requiring the generation of large amount of data. A typical aircraft will contain around 3000 – 4000 repairable items to module level and each data set requires around 40 data elements. To carry out analysis on all repairable systems regardless, would be financially irresponsible and very time consuming. Consequently, the first step is to screen out items with obvious Maintenance Policies (MPol). Typical criterion for screening would be:

System Already In-Service On Other Aircraft. Providing we are not effecting a major change in the total fleet size for the system, we will usually adopt the existing MPol. This will still need an internal review of the existing stock of spares and available repair capacity. The use of an existing repair infrastructure and a common spares pool will have large potential savings.

Highly Reliable and Cheap Items. If the cost of establishing a repair infrastructure can clearly not be justified, the item will be scrapped on failure.

Strategic MPol. There may be operational reasons for imposing a particular MPol regardless of cost.

Specialist Facilities Required. If the item support requirements are beyond your capabilities, or require an unjustifiably large investment in new facilities, organic support will not be an option.

IPR Restrictions. Particularly when buying from the USA, IPR or transfer of technology restrictions will negate any organic support options.

This screening process can, depending on the aircraft type, reduce the items requiring LORA modelling to as few as 500 LRIs, greatly reducing the cost and time required and making huge savings on duplicate repair infrastructure and spares costs.

LORA MODELLING

Introduction. Simplistically, LORA compares the cost of pipeline spares against repair infrastructure. Figure-1 shows typical Repair Turn Round Times (RTRT) for RAF lines of maintenance.

Option 1: 1A-Scrap. The cheapest option might be to scrap the item on failure, for the reasons already discussed.

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

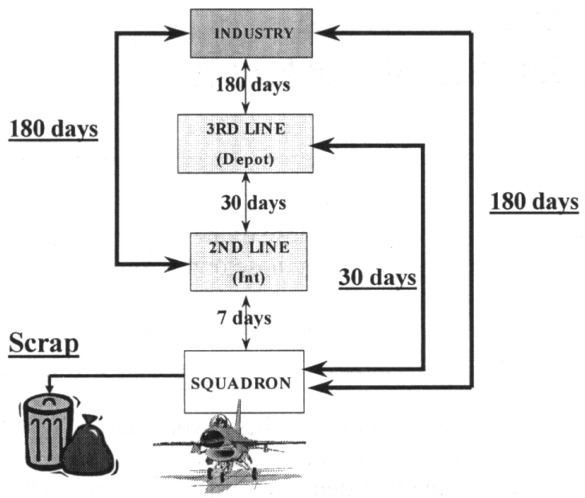

Figure-1: Repair Turnaround Times

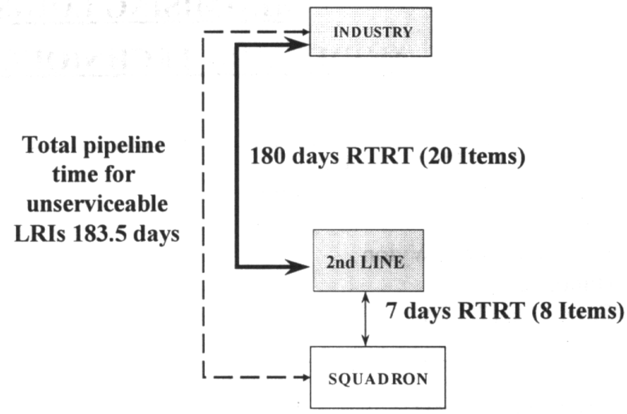

Figure-2: Modified RTRT For 1A-2FB-4 MPol

Option 2: 1A-4. An alternative option might be to send items back to the manufacturer for repair. In this case we would require a large number of LRIs to fill the long pipeline, but no repair infrastructure. However, spares cost will be very high. Example 1 shows some theoretical costs that we can use for comparison with other MPol.

FFR: 5760 Hrs per year	RTRT: 180 days
Unit Cost: £10,000	Spares: 9.46 = 10
MTBF: 300	Repair Costs: £1,000
Arisings: 19.2 = 20	

COST	1A-4
Spares	£100,000
Test Equipment	
Manpower	
Publications	
Training	
4th Line repairs	£20,000
Total	£120.000

Example 1: Costs of 1A-4 Mpol

Option 3: 1A-2FB-4. We need to consider other factors such as the No Fault Found (NFF) rate. If, as is not uncommon, an LRI has a NFF of 40%, the arisings in the above example rise to 28, our spares cost increase to £140,000 and our repair costs to £28,000. It may now be more cost effective to establish a Filter Bench at 2nd Line to prevent NFFs being sent back to the manufacturer. This would increase the pipeline times slightly for unserviceable items as shown below but - based on the figures used in Example 2 - reduce the annual support costs.

AFFR:	5760 Hrs/year	4th Line RTRT:	183.5 days
LRI Unit Cost:	£10,000	4th line Spares :	9.46 = 10
MTBF:	300 Hrs	2nd Line RTRT:	7 days
Indicated Arisings:	28	2nd Line Spares:	0.82 = 1
Time to Test:	1Hr	4th line Repair Costs:	£1,000
Manpower cost: £35 per hr		FB Test Set Cost	£10,000

	1A-4 (NFF)	1A-2FB-4
LRI Spares Costs	£ 140,000	£ 110,000
Module Spares Costs		
2nd Line Manpower		*£ 980*
FB Test Set Cost		*£ 10,000*
Depth B Test Set Cost:		
AP Costs:		
Training Costs:		*£ 1,000*
LRI 4th Line Repair Cost:	£ 28,000	£ 20,000
TOTAL	£ 168,000	£ 141,980

Example-2: Costs For Filter Bench Option

Option 4: 1A-2B-4. The final example considers establishing a Depth B repair facility at 2nd Line. Now we need Depth B support equipment and spare modules, but fewer LRIs. The additional infrastructure costs are shown below.

AFFR:	5760 Hrs/year	Manpower cost:	£35 per hr
Indicated Arisings:	28	4th Line RTRT:	183.5 days
LRI Unit Cost:	10,000	Modules Spares:	9.6 = 10
LRI MTBF:	300 Hrs	2nd Line RTRT:	7 days
Time to FB LRI:	1Hr	LRI Spares:	0.82 = 1
LRI Repair Time	3 Hrs	Depth B Test Set Cost:	£50,000
Module Unit Cost:	£2,250	Publications Costs:	£5,000
Module Repair Cost	£300	Training Costs:	£10,000

	1A-4 (NFF)	1A-2FB-4	1A-2B-4
LRI Spares Costs	£ 140,000	£ 100,000	£ 10,000
Module Spares Costs			*22500*
2nd Line Manpower		£ 980	*2380*
FB Test Set Cost		£ 10,000	
Depth B Test Set Cost:			*50000*
AP Costs:			*5000*
Training Costs:		£ 1,000	*10000*
Module 4th Line Repair Cost			*6000*
LRI 4th Line Repair Cost:	£ 28,000	£ 20,000	
TOTAL	£ 168,000	£ 131,980	£ 105,880

Example-3: Costs For 1A-2B-4 Mpol

The table summarises the cost for all the examples. **N.B.** These are first year figures only. In subsequent years we do not need to buy spares and support equipment and hence the savings increase. Figure-3 shows the costs for all examples over a 10-year period.

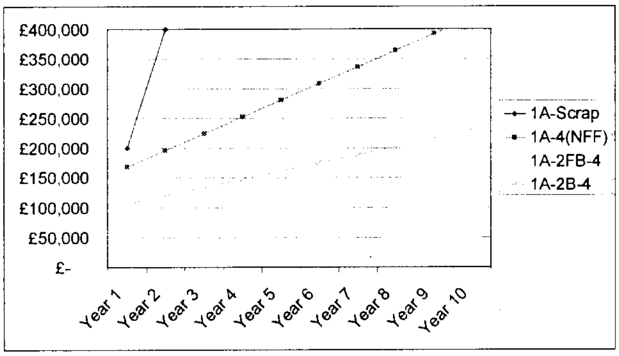

Figure-3: Cumulative Costs For 10 Years

These are of course only simplified examples. The true algorithms for LORA (defined in Mil Std 1390D) are far more complex, scaling spares against a chosen availability. Some models use single item scaling, whilst others optimise across the system. However, the scaling calculations in the LORA model are only used to determine the optimum MPol. Initial Provisioning of spares is carried out across the whole aircraft using specialist models as outlined below.

SPARES SCALING

Single Item Modelling. As we have seen in the LORA examples, the MPol drives the type of spares required. For scrapped or items returned directly to the manufacturer, only LRIs are required; whereas, any Depth B repairs will require modules. Spares are one of the largest cost elements within the LSC and consequently, the RAF has invested much of its development effort in a bid to minimise spares cost. For many years the RAF used Single Item Modelling (SIM) for both IP and Re-Provisioning (RP) of spares and indeed many manufacturers still use this method. SIM scales spares using a cumulative Poisson distribution for a given fill rate. What SIM does not do is take account of the cost of an item; hence, an item costing £10,000 with the same reliability as another costing £1, would be scaled exactly the same, regardless of what improvement in system availability is achieved for each Pound spent. Further, simple Poisson distribution assumes demand rate equals arising rate which may not be so due to batching of demands.

Cost Optimised Scaling. Cost optimised scaling scales a whole range of items – even an entire aircraft – in a single analysis, The use of a Compound Poisson distribution caters for the probability of batched demands. To achieve a cost-effective scale for a range of components, effectiveness must be maximised with respect to cost. To achieve this, the RAF use a scaling model which uses the technique of Marginal Analysis (MA), also called a heuristic optimisation algorithm. To determine the value of incrementing a scale a Component Improvement Factor (CIF) must be calculated. This CIF can then be compared with CIFs for other components and hence, the best component to increment can be identified. The scaling model used by the RAF is OPUS 10. The output from OPUS is a series of scales (for all repairable components on the aircraft) that make up the OPUS curve. The curve allows us to select ap scale that will provide a chosen availability and will cost that scale. Alternatively, it will indicate what availability can be achieved for a given cost. When compared with SIM, MA will achieve the same availability for 10%-15% less as shown in the diagram below. Benefits of OPUS are that it:

Models the whole weapon system.

Optimizes on cost and reliability or weight and reliability or volume and reliability.

Provides a range of equipment scale options

Recommends the optimum location for spares.

Takes into account spares pipelines from forward operating bases to the manufacturer.

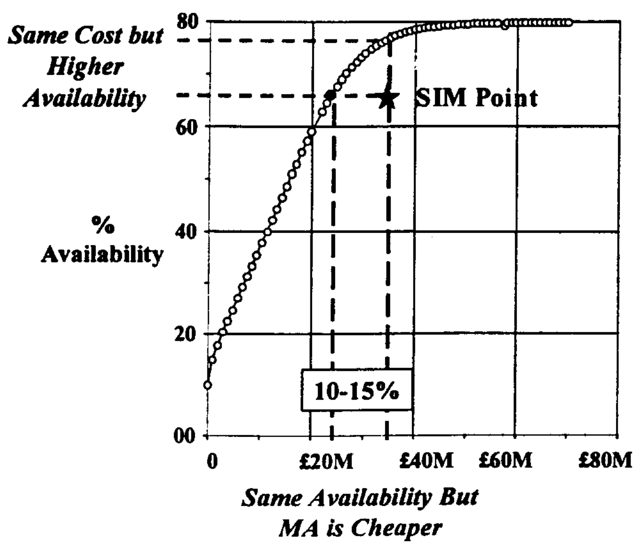

Figure-4: OPUS v SIM Comparison

OPERATIONAL AVAILABILITY

The availability predicted by the OPUS model is that due to spares. However, aircraft availability will always be lower due to the need to re-arm, replenish and repair, as well as carrying out scheduled maintenance. Additionally, generating aircraft depends on availability of other resources such as Support Equipment (SE), maintenance technicians etc. All these will effect the Operational Availability (Ao). One limitation of the OPUS model is that it assumes that flying hours – and hence arisings - are accumulate linearly over the flying period rather than batched into irregularly spaced multi-aircraft sorties. To take account of all the above points and evaluate the effectiveness of the spares scale, the RAF use a bespoke simulation model – Operational Support Simulation (OpSSim). The model is particularly useful for validating scales for Priming Equipment Packs (PEPs) to support deployed operations. The scenario describing the support environment and how modelled resources interact with each other also needs to be defined.

A full day's, week's, month's or even year's flying scenario is entered as individual sorties with take off times, number of aircraft and sortie duration. Every sortie within the flying period can be different and we can choose how many days flying we wish to simulate. We can state which systems are mission critical and how many none-critical systems can fail before a sortie is aborted. Lastly we need to state the number of days between re-supply of spares.

Throughout the simulation OpSSim tracks how many aircraft are:

On missions.

Available for operations.

In maintenance.

This allows us to check that we can achieve our mission targets, with the number of aircraft deployed and the PEP spares recommended by OPUS until the next re-supply date. Conversely, OpSSim ensures we do not procure or take more spares than are absolutely necessary. This reduces spares, transport and storage costs.

Outputs from OpSSim include:

Mission success rate.

Aircraft availability.

Problem spares.

Where a spares pack is found to be inadequate, we can choose another scale of spares from higher up the OPUS curve and repeat the simulation process. This process allows the RAF to procure for a missions success rate rather than a meaningless spares availability figure.

THROUGH LIFE SUPPORT

Support analysis is never a once only exercise. The uncertainty of initial predicted equipment data, and changing operational, scenarios require regular re-analysis throughout the life of an aircraft. The addition of new aircraft to our modelling databases during procurement (updated throughout the aircraft's life) and the availability of an integrated modelling suite, simplifies iterative analyses and ensures that logistic support remains optimised throughout the life of the system. Our modelling suite, which uses a common source database to feed an integrated suite of models, allows rapid operational and cost analysis of proposed scenarios. A simplified representation of the suite is shown at Figure-5 below.

LORA Reviews. MPol reviews of in-service systems are carried out due to:

Changing reliability.

Changes in operational scenario.

Changing fleet size.

However, in reality, it is rarely cost effective to change an MPol as the majority of the support infrastructure costs are already sunk.

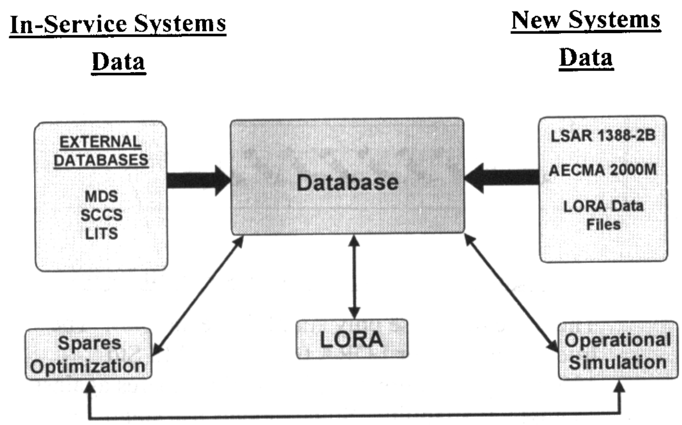

Figure-5: The R AF's Integrated Modelling Suite

LORA Harmonisation. The demands for ever-greater savings are breaking down the logistics autonomy of the British Armed Services. LORA harmonisation is the process of defining a single MPol for common items used by several platforms; often across all three Armed Services. This can be applied to both legacy and new systems. Invariably we find common legacy systems – such as avionics and aero-engines - with discrete support infrastructures. Defining and establishing a single repair infrastructure using a common spares pool can generate very significant savings in manpower, facilities and spares. Because we aim to make maximum use of sunken cost, the solution may well be sub-optimal when compared to a green field analysis.

Cost Benefits Analysis. The RAF receives many unsolicited bids from manufacturers for reliability or operational improvement modifications. Claims of massive costs savings invariably accompany these bids, but it is important that we investigate them independently before making any commitment. The initial phase of any Cost Benefits Analysis (CBA) is to determine the support cost for the remaining life of the current system, i.e. the 'do nothing' option. LORA tools and spreadsheets are a useful way of extrapolating these cost. The second phase is to carry out a full LCC of the proposed system. This will entail the use of our entire modelling suite to assess all initial and recurring costs. Occasionally, a relatively inexpensive modification will realise huge lifetime savings; a simple hydraulic coupling on the Tornado aircraft was just such an example. However, in the majority of cases, the modifications will never repay the capital investment within the remaining life of the aircraft.

It is ironic that we save the MOD enormous amounts of money, by persuading them not to invest in cost saving measures.

Scaling Reviews. As for LORA reviews; changing physical and operational factors, plus condemnation of items that become beyond repair, requires periodic scaling reviews to determine any deltas between current stock holdings and requirements. Because of poor procurement decisions made in the past, it is sometimes found that the actual spares holding for an aircraft may run to tens of millions of pounds, but give only a very poor Ao. This is because we have lots of the wrong spares. A recent study identified an aircraft with holdings of £80M that could achieve a better availability with a green field scale of only £25M. With the punitive fines imposed under resource accounting and budgeting rules, we found we could save circa £56M over the life of the aircraft by selling unwanted spares and buying (at a cost of £1.5M) the correct spares to align holdings to the green field scale.

Operational Sustainability. Much of the in-service analysis is for PEPs to support deployed operations. The OPUS/OpSSim combination allows for rapid assessment of spares packs to support a variety of known and hypothetical operational scenarios. The modelled scenario will depend on whether the PEPs are independently funded or abated from main stock holding at the Main Operating Base (MOB). For the latter, both MOB and deployed operations must be modelled together to take account of the spares requirements of both sites, plus the pipelines between. This is currently being expanded to investigate the combined spares requirements of all aircraft involved in major operations and by evaluating against weight and volume, the total number of transport aircraft required for both initial deployment and continuing re-supply. Further studies are planned to investigate the long-term effects on home base flying and training.

SUMMARY

The methods and working practices outlined above ensure that for introduction to service:

The combined skills and experience of both manufacturer and operator are used to carry out the development and LSA of new aircraft.

The use of common models and methods simplifies joint analysis and verification.

The maximum use is made of existing spares and support infrastructure, thus minimising the amount of analysis required and both initial and recurring costs.

Where there is no existing support for a system, LORA ensures the optimum MPol is established.

Cost optimised scaling and operational simulation ensure the cost of IP spares is minimised to those necessary to achieve our designated operational requirements.

During the in-service phase:

LORA and spares analysis continues throughout the life of a system to maintain optimum capability at minimum cost.

Harmonisation of support for common items throughout the 3 Armed services achieves substantial cost savings.

CBA of proposed modifications and mid-life updates, highlights all financial implications and areas of risk of proposed modifications and prevents the wasting of money on non-viable cost saving schemes.

Sustainability modelling evaluates the minimum spares and transport requirements required to sustain known and hypothetical operations.

The use of a common user database with an integrated suite of models means that analysis can be carried out in very short time scales with a minimum of staff.

APPROACHES TO S&T COST MODELING AT THE U.S. AIR FORCE RESEARCH LABORATORY / VEHICLE AERONAUTICS DIRECTORATE

Robert Quaglieri and Max Blair
AFRL/VAAI Building 45
2130 Eighth St. Ste 01
Wright Patterson AFB
Ohio 45433-7542
United States

Introduction

The mission of the Air Force Research Laboratory (AFRL) is to lead the discovery, development, and transition of affordable, integrated technologies for our air and space forces -- to keep our Air Force "the best in the world." The Air Vehicles Directorate (AFRL/VA) is one of nine directorates within AFRL. VA develops and integrates fixed wing air vehicle technologies for the warfighter, and focuses resources to: (1) Demonstrate affordable and supportable options to improve capabilities in current fixed wing air vehicles and (2) Deliver revolutionary fixed wing air vehicle technologies for new warfighting capabilities.

The paradigm of "performance at any price" must change under the relentless pressure to lower military costs, and that pressure is exacerbated by the lack of a competing super power to justify present expenses. While the US is successfully performing worldwide geopolitical missions, today's national objective is to accomplish them as affordably as possible (Figure 1). Weapon affordability can be seen as a function of the parameters of weapon effectiveness and weapon system Life Cycle Cost, LCC, and is a major player in the Air Force Modernization Plan. Today there is a strong focus on properly modeling these parameters and a great deal of effort is being expended to improve the accuracy of the analyses. In the acquisition world, cost modeling is normally associated with accounting and finance, and there is a strong emphasis on achieving credible absolute values. In the Science and Technology, S&T, world, the scientist and engineer require insight into the war fighter's mission to varying levels of detail to develop affordable technology while providing an effective technology. However, analyses of the war fighting effectiveness/LCC of a potential weapon system is a new area for AFRL and that requirement means the S&T world has to take a fresh look at how it develops affordability metrics. We can not do it in the same old traditional way of independent system design followed by cost analysis. Figure 2 is 25 years old.

Generally, with respect to the weapon system price, the scientists and engineers do not require knowledge of all the contractual aspects such as fee, overhead, G&A, etc.. These serve to cloud the issue of selecting an S&T program to pursue based on benefits, both in capability and cost. But to better plan the Science & Technology program, Principal Investigators, PIs, do require a sense of the impact of their research programs on weapon system cost (Figure 3). While accounting and finance may have access to a wealth of engineering, production, operations and support cost data, it may only be available at fairly abstract levels. There are at least three reasons technology brokers in the S&T world lack useful cost data. One, because the effects of their technology are not discernable within traditional accounting and finance data or pricing approaches. Two, the technology has not reached sufficient maturity. Three, a technology can be so pervasive that it alters the design of the aircraft, introducing enormous complications in the cost analysis of a system.

Section 1
Present Cost Work at VA

The AFRL/VA, has explored two cost estimating approaches. (1) a Virtual Expert Cost-Estimator for Air Vehicle S&T (VECAST), and (2) a Cost Activity Process design Tool in a Unified Rapid modeling Environment (CAPTURE). VECAST is being built to cover the breadth of the VA technology set, effectively using existing commercially available databases and analytical relationships with appropriate extrapolations. CAPTURE is an activity-based cost approach based on the Adaptive Modeling Language, AML, which engineers can use to rapidly synthesize an integrated geometry and cost model at the early stages of design. CAPTURE presently emphasizes structural and manufacturing aspects. Currently, these are two separate activities that will mutually benefit in the far term.

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

VECAST Tool Development

VECAST utilizes a surrogate LCC approach, one that focuses on determining the impact or shift in weapon system cost that an advanced technology makes. It is not dependant on modeling absolute cost, although the answers generated by VECAST could be scaled and combined with financial/price information. To this end, VECAST is a formulation for cost modeling that utilizes a constellation of existing tools to determine *increments* in the surrogate life cycle cost caused by the introduction of a new technology. As an early attempt to bring cost modeling into the routine technology development process of the Vehicle Aeronautics Directorate, VECAST attempts to mitigate the effects of inadequate tools, model inaccuracy/ lack of functional relationships and existing database lack of granularity/detail. Previous options for the S&T personnel included (a) know all the cost models, (b) get a resource that does or (c) do not do cost analysis.

The objectives of this program are to develop a tool, useable by non-experts in costing, to determine the cost impact of new technologies that is credible, traceable, timely and broadly accepted (Figure 4). The genesis of the current program came from the melding together of three Phase I Small Business Innovative Research, SBIR, contracts. Each company held a piece of an overall workable solution and the government combined them under two Phase II SBIR contracts. One company Frontier Technology Inc, FTI, has a unique, easy-to-use questionnaire within their Graphic User Interface, GUI, that utilizes Commercial Off The Shelf, COTS cost tools (i.e. those ubiquitous black boxes). Another, TECOLOTE Research Inc, TRI, accomplishes cost calculations based on specific airframe databases; while the third, Cognition Corporation, utilized a form of Artificial Intelligence, AI, to help generate cost numbers (Figure 5). AI is also to be used to guide the user to the appropriate cost model set to calculate the elements of LCC; EMD, Production, and O&S.

Integrating these three approaches into a single tool can simplify the job of the S&T engineer, while he or she is directly imputing the technical characteristics they are assisted by a virtual cost expert. The tool provides meaningful insights into the affordability issues for new or improved weapon systems. This increase in capability coupled with the change in LCC becomes a measurand of the viability of a new technology vis-à-vis the needs (increased combat effectiveness and cost reduction) of the war fighter.

The original questionnaire will be re-formulated through interviews with program PIs to cover generic airframe technologies. It will allow the user to deselect LRUs that belong to the old technology and define new LRUs to be inserted that represent the new technology. Lastly; rules, fuzzy logic, etc. techniques will be developed, based on interviewing government and industry personnel, to determine the proper application to use and in some cases guide the modification of cost models and their inherent Cost Estimating Relationships, CERs, for the specific technology being analyzed.

To implement this program requires that an airframe baseline be established at a level of detail sufficient to discern the differences brought about by the application of the new technology. Airframe specific databases will be established by Boeing, Lockheed-Martin and Northrop-Grumman based on their proprietary JAST designs of '95. This maintains continuity and consistency within each company's analysis based on previous work.

As new technologies mature, defined as achieving a Technology Readiness Level, TRL, up to 6 in a research environment, (Figure 6), they may be analyzed as to their impact on system LCC. The government will require a configuration definition of the baseline aircraft and decomposition of the data base to enable more detailed drill downs to achieve the proper depth of modeling required to do a realistic representation and analysis of a new technology's impact on costs.

The companies will build a tool that meets the difficult task of justifying future cost benefits by using numerous cost estimating tools already available and make it a simple task to describe the known, salient features of an advanced technology. The contractors will:

- Develop and implement a GUI to allow representation of VA technologies
- Decompose costs to WBS level required to isolate technology impacts
- Develop calibrated baseline LCC model based on airframe prime data
- Develop cost methodology library of selected generic CERs
- Determine appropriate COTS tools for inclusion
- Provide generic predictor of O&S for new technologies
- Develop and implement AI engine using generic shell for rules, etc.
- Provide for inclusion of airframe industry tools

VECAST can be seen as an overarching tool integrating a variety of present approaches in a way that increases the power of hitherto isolated tools only useful in reality to an expert cost modeler. It is also an augmentation of presently available tools for Air Vehicle technologies (Figure 7). And lastly, it will allow the technical expert a way to determine the major cost drivers, their impact and the output changes due to various implementations. A limited prototype, Build 2, was developed in September. The most recent event has been to supplement FTI and TRI expertise in AI with the hiring of two professors, plus Galorath and Associates, and lastly SHAI (Stottler & Hinke Associates Inc).

CAPTURE Tool Development

The second cost-related effort in the Air Vehicles Directorate is based on the Adaptive Modeling Language, AML. It has evolved from an in-house (Materials Directorate of the Air Force Research Laboratory) feature-based design project to a commercial product in use by industries ranging from automotive, e.g., Ford Motor and Volvo; to aerospace, e.g., Lockheed-Martin, and McDonnell-Douglas; and power generation, e.g., Zurn Balke-Durr and Siemens. AML supports a multi-disciplinary environment emphasizing the structural and manufacturing aspects of interactive product-process design.

While AML has been used to capture a number of proprietary and published design products and processes, the emphasis in this effort is to develop and integrate cost modeling aspects with geometric modeling. Here, the term *integrate* emphasizes the tight relationship between the geometric model and the cost model.

As a technology broker, the Air Vehicles Directorate has a mission to develop new technology, including technology where there is more intuition than hard data. Where untested technology is planned and developments are prioritized, it is important that planners and developers have the capability to rapidly synthesize a new cost model. This can be accomplished by decomposing the model into discrete activities and materials where we can intelligently extrapolate from past experiences. Data for this model will be available from the VECAST tool development, or may come from other sources. Details of this approach follow a description of the enabling design environment.

AML is an object-oriented environment with built-in dependency-tracking and demand-driven calculations, which facilitate the integration and control of all aspects of the design process. With dependency tracking, AML facilitates the control of a large number of design alternatives with a single set of driving requirements. Dependency tracking can also be used to facilitate design parameterization. With demand-driven calculations, the designer can readily control when and how design information flows.

Native objects cover a variety of geometric constructs, non-geometric features and forms. These objects also come with an extensive suite of methods. This environment is used by a software developer to create a process which an application designer may use. In our case, AML is used to create a process for rendering geometry and assigning manufacturing and cost intent. AML provides the single open-access environment which makes it practical to model a very complex process (i.e. air vehicle design integration) with a single suite of objects and methods. References 7 – 9 are provided here for additional information.

An example where the CAPTURE cost model will be useful in the Air Vehicles Directorate arises from the current push for the development of new technology for affordable hypersonic vehicle concepts. Clearly, production data is lacking. Yet the Air Vehicles Directorate has a requirement to identify, prioritize and develop these technologies. One of the primary metrics for prioritization is cost. Consider active cooling concepts which involve the use of ceramics, hot structures and cooling channels for which we have little or no data. However, it is reasonable to expect we can develop affordability metrics at an early stage if we look at only materials and activities. We can gather this data from samples and extrapolate to a manufacturing scenario. By decomposing the data – we can target the cost and can generate a prioritized technology development strategy to reduce the cost.

With both cost and geometry objects written in AML, there is no software barrier to impede the flow of data. In fact, both the cost and geometry could not be more integrated since they are merged into the same object and object structure with automated dependency tracking. From the end-user's perspective, this means that both cost and geometry changes can be made with the same system (not separate CAD and cost programs). Furthermore, changes in the geometry are immediately reflected in the cost and if CAIV is programmed in, changes in cost are immediately reflected in the geometry.

A design process is measured by how long it takes to develop a design, how many designers are being paid (include overhead), the fidelity of the design proposal, and a probabilistic measure of risk. Automated dependency tracking will prove to reduce design time and a single system, which runs both geometry and cost, tends to reduce the number of designers. These savings can be transformed into increased data fidelity for a few designs or into increasing the number of designs at a lower fidelity.

Section 2
The Near Term Evolution

Cost is becoming a 1st order design variable – Affordability is rapidly becoming *the* metric of choice. - It is a function of system cost and combat effectiveness. However, the war fighting effectiveness/ LCC of a potential weapon system is difficult to assess. The capability change enabled by a new technology can run the gamut from simply doing the present job better or cheaper to enabling a totally new capability. The increase in capability coupled with the corresponding change in LCC becomes a measurand of the viability of a new technology vis-à-vis the needs (increased combat effectiveness and cost reduction) of the war fighter.

VECAST Improvements & Extensions

Work will need to be done in the following areas:

- Costs will need to be represented along with pertinent technologies in a real-time Collaborative Engineering Environment, CEE.
- As new systems are envisioned, the costs associated with new technologies that enable the new concepts will need to be calculated in near real time.
- Life Cycle Costs/Total Cost of Ownership of the advanced concept will become as important to the final solution as the technologies that enabled the advanced concept
- A disciplined costing approach – A widely held, well ordered approach would allow for the cost increments calculated in VECAST by different PIs for different technology programs to be accurate enough for comparison between technology programs.
- Lastly, as the present work establishes the viability of this costing approach, the construction of a commercially viable tool will need to be funded through additional SBIRs, including Phase IIIs and potentially the use of Dual-Use contractual efforts.

AML Improvements & Extensions:

In Figures 8 and 9 we begin the process to generate an engineering assessment of cost for undeveloped technology. Here, a wing structure is depicted. This was developed independently of the cost tool. The cost estimation begins by the interactive selecting parts (mouse picks) of the structure, materials, structures type and a manufacturing process. Existing processes can be edited and appended to form new object source code for future processes. Parts are stored in a "parts bin". Pointers are attached to the part design. Current work focuses on assembling the parts to form the product. The example shown highlights the work to capture the process for carbon/carbon structures manufacturing.

Geometry is the only prerequisite for implementing activity-based cost (ABC) in CAPTURE. There are currently two options in generating the geometry needed for the ABC model.

The first option is to utilize the provided geometry sketcher, thus simultaneously create both geometry and cost. This sketcher creates a conceptual wing and substructure, which can be applied to the cost model. This sketcher was reported in Reference 7. An example of a wing model is depicted here in Figure 8.

A second option involves two distinct processes. A geometric modeling expert completes the job of synthesizing a configuration and subsequently takes the geometric model to a cost expert. This cost expert uses the ABC model process in CAPTURE to develop the cost model. The practicality of this second option will become apparent in the ongoing development reported in the last section of this paper.

As indicated earlier, while the combined geometry and cost models are developed interactively, they automatically maintain dependency. Changes in the geometry can be immediately reflected in the cost model.

COMPONENTS: Once the geometry is created, the costing module can be implemented. The first task is to designate unique components. This requires the assignment of a structural type, a material type, and a manufacturing process to the displayed geometry. Assignments can be made to individual geometry objects or to a group of geometry objects that will be identical in structure, material and manufacturing process. This process is accomplished using the geometry in Figure 8, and the form depicted in Figure 9.

For each geometry selected for assignment, a component object is created and stored in a "component bin". This component object has four significant features: a pointer to the selected geometry object, a pointer to the assigned material storing physical (mechanical) and cost data, structure information such as dimensional data and area, and a sequence of operation pointers used to manufacture the component.

The assignment of a manufacturing process to any given component requires a priori knowledge of the procedure. In general terms, the manufacture of a component occurs by a single operation or by an ordered sequence of operations. Several manufacturing processes are available through the given Operation Catalog. The user can browse through the catalog and select a given process or create a new operation that will then be added to the Catalog. When the user decides on an operation, he must transfer it to the Operation Sequence list. For a multi-step manufacturing procedure the user continues to select and transfer operations to the Operation Sequence list in a user-prescribed order. The form, which drives a carbon-carbon x-core process, is depicted in Figure 10. The cost associated with a Operation Sequence is subsequently displayed. Figure 11 portrays a detailed cost breakout for a composite laminate lay-up.

All the operations in the Operations Sequence list are stored in an "Operations Bin". The Operations Bin manages the processes for any copying, editing, or deleting prescribed by the user. When the user finalizes the Operations Sequence list, it is assigned to the active component(s) within the Components Bin.

The joining of components into sub-assemblies requires the checking out of the necessary components from the Component Bin as well as the assignment of a manufacturing process or sequence.

ASSEMBLY: The assembly functionality is the capability to select any number of components and/or sub-assemblies and apply manufacturing assembly techniques, in order to instantiate a new object known as a sub-assembly. This functionality requires a method to roll-up component and/or subassembly cost metrics for the component level (i.e. material and operation costs). In addition, it requires a method to calculate the assembly-specific operation costs, and prompt the user to apply new manufacturing assembly techniques.

The assembly mechanism is the interactive operations performed by the user to define sub-assemblies using GUIs. First the user identifies the objects which will define a sub-assembly. This occurs by accessing objects from the Component Bin through a menu list or by graphically selecting components from the screen. Second, the user assigns the manufacturing assembly techniques, such as bonding, mechanical fastening, or welding from the Operation Catalog to the sub-assembly. Lastly, the assigned sub-assembly is accessible to the user through the Assembly Bin.

Cost modeling efforts at the conceptual level must be viewed probabilistically. In order to reflect this in CAPTURE, it is planned to develop a probability-object which can be inherited along with any property-object to create a new probabilistic-property-object. In this way, probabilistic effects can be considered and rapidly calculated along with the set of deterministic quantities.

Section 3
The Future

Currently the separate activities of VECAST and CAPTURE are just beginning to come together for mutual benefit. Clearly, AFRL/VA has a goal to use VECAST to generate cost data for a wide variety of individual technologies across VA, technology integration of these into technology sets and accomplish affordability studies. These studies may be conducted with other software tools and address requirements at the mission and system levels. In the structures area for instance, CAPTURE will use baseline cost data generated by VECAST. A further melding of VECAST and CAPTURE will occur as VECAST builds depth across its breadth and capture expands its repetoire across its technology set.

AML's capabilities will also be extended under a Dual Use Science & Technology (DUS&T) agreement between the Air Force Research Laboratory (AFRL) and Lockheed Martin Electronics & Missiles (LME&M). These enhancements will be developed and integrated in two phases to provide: a multiple, simultaneous, networked user capability and a network-distributed modeling capability. This has strong implications for the next steps in our future.

Cost & Performance can be interrelated through the design and use of aircraft volume. In most current cases, "Performance still rules." However LCC, especially O&S costs, increase dramatically as the fleet ages, and as new systems become increasingly sophisticated the future burden to the defense budget is obvious - Get the cost per system down or buy fewer systems. Fighter aircraft are routinely driven to the minimum volume necessary in order to achieve maximum performance.

JSF is a recent example of the counter trend, where performance is to be held roughly constant and the benefits of newly developed technologies are used to lower LCC. A new approach should be considered for reducing cost, the interaction of LCC and performance as it pertains to vehicle volume. The way of balancing cost and performance may be by judicious use of vehicle downsizing. All other considerations held constant, i.e., if performance is held constant, then some of the volumetric decrease enabled by the application of new technologies might be better held in reserve and used to make the maintenance job of the ground crew easier (Figure 12). The internal volume thus retained would allow better placement of Line Replaceable Units, LRUs, Shop Replaceable Units, SRUs, etc. and facilitate maintenance "remove and replace" actions. Performance would not achieve an absolute best, but LCC and especially O&S costs could be significantly lowered.

Studies and analyses of maintenance actions, like the time to remove and replace items could be done in a virtual world using virtual prototype models, virtual aircraft models (a la the Boeing 777), and virtual production line representations to optimize box locations for service. In fact, use of virtual reality techniques could be employed to put the ground crew "in the picture" and with tactile sensations. Maintenance personnel would have "a hands on experience" with the equipment and could put their hands into the access spaces. Much further out is the possibility of altering structural elements, their positions, numbers, etc. in a cognizant, organized fashion to provide the required volume to place LRUs conveniently inside the removable panels in the outer skin/moldline. A reduction in the number of such panels may also be achievable.

A single model accessed by multiple users has the potential to integrate cost and geometric/volumetric considerations (i.e. configuration synthesis) which incorporates the simultaneous input of multiple designers and does not require the traditional pass-off of data. A fully engaged integrated product team (IPT) can conduct an electronic design meeting in which real-time, what-if vehicle design scenarios are played out.

Following today's trend, future IPT's will involve both customers and designers. For the AFRL, the network-distributed modeling capability opens the possibility to involve the end-users and the technologists in real-time design scenarios. Exactly how this would play out remains to be seen, however, it is clear that this shared modeling capability will help to shorten design decision processes and improve integrated team understanding of the design issues. Probably the most important hurdle is establishing the right cost for the right performance. The cost modeling developments in VA are certainly a healthy step in this direction.

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FIGURES

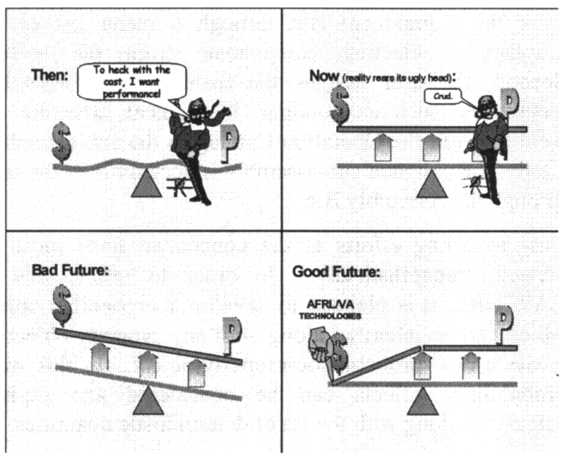

Figure 1 - Breaking the Paradigm

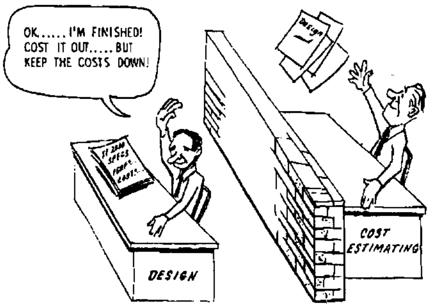

Figure 2 - Design to Cost ???

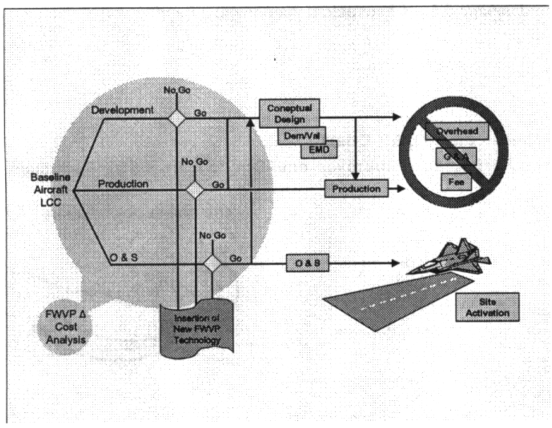

Figure 3 - Cost Increments for New FWVP Technologies

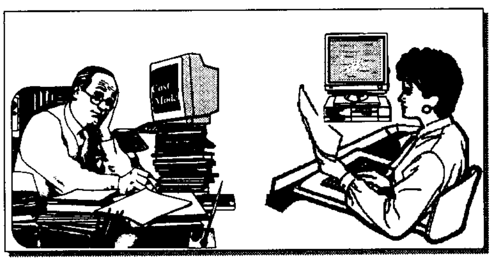

Figure 4 - VECAST Approach Changes the Culture

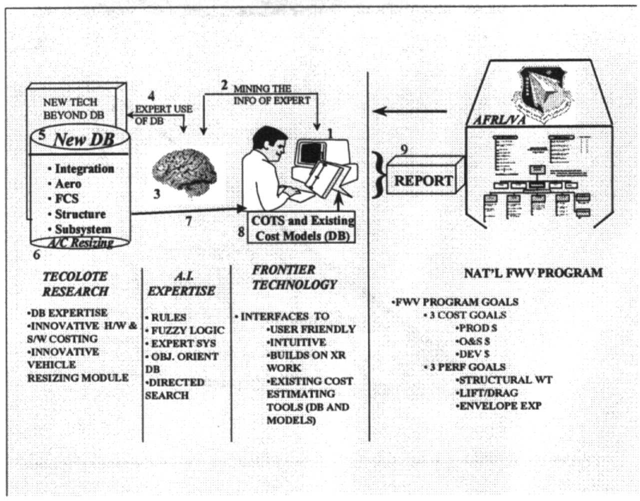

Figure 5 - Integration of Contracted SBIR Cost Efforts

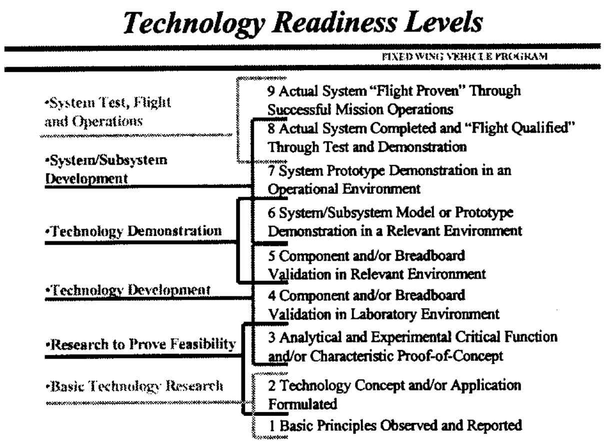

Figure 6 - Technology Readiness Levels

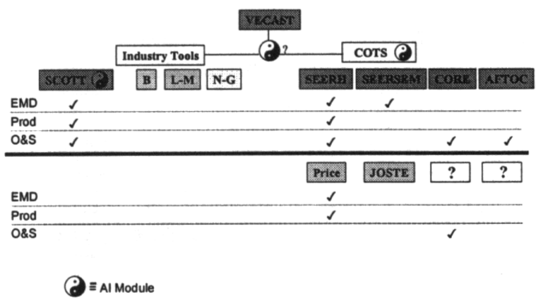

Figure 7 - Virtual Expert Cost Estimator for Air Vehicle S&T

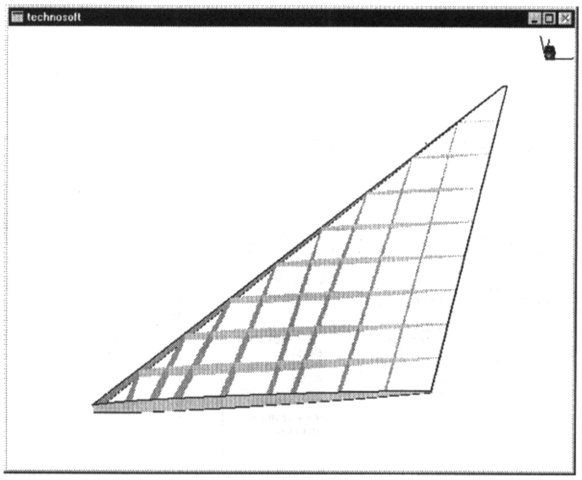

Figure 8 - AML geometry of a Wing Decomposed to Substructure

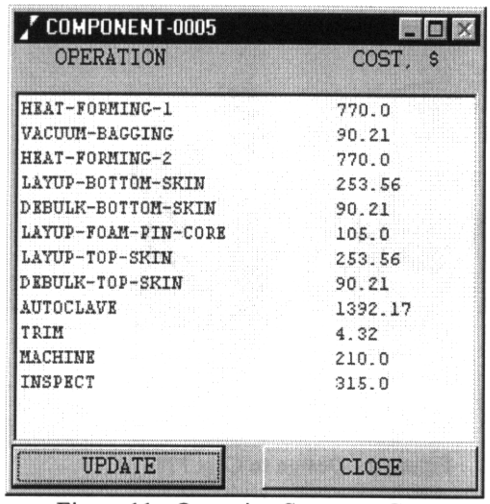

Figure 11 - Operation Sequence Cost

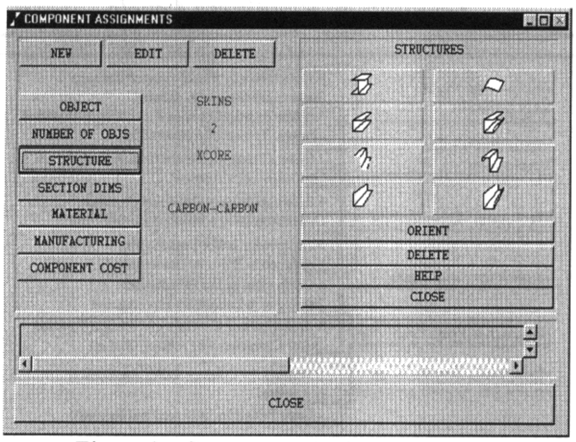

Figure 9 - Component Assignments

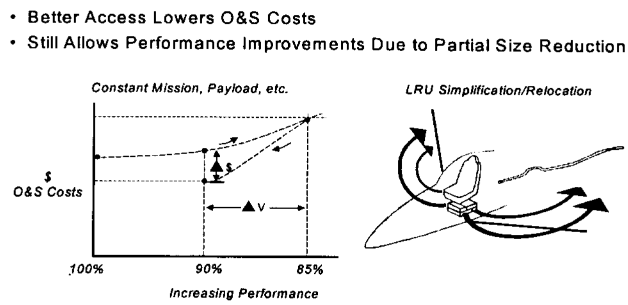

Figure 12 - Performance/O&S Trade Chart

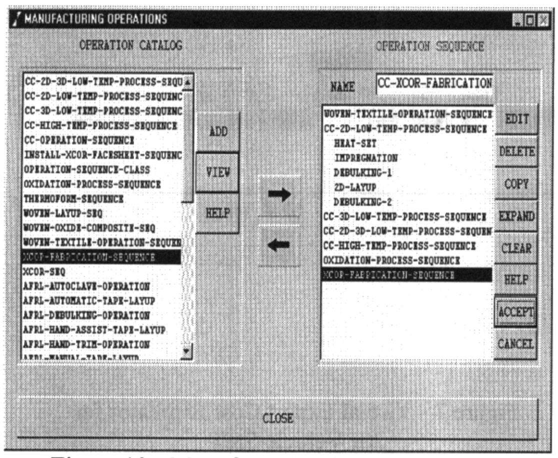

Figure 10 - Manufacturing Operation Sequence

Une expérience de l'ingéniérie concourante de navires de guerre et de leur soutien logistique

Jean-Philippe Carillon
DGA/DPM/MCO
26 Boulevard Victor
00460 Armées
France

1. Introduction

L'article est consacré aux problèmes d'intégration de la conception et de maîtrise du coût global sur la durée de vie des navires de guerre. Quelques voies de solutions simples et immédiates, utilisables quotidiennement, sont proposées. Un exemple illustratif est développé.

Un navire de guerre représente un exemple de " super-système ". Sa mise en œuvre nécessite l'association de plusieurs systèmes complexes, en premier lieu le système de combat. Ces systèmes comprennent eux-mêmes des installations et équipements très divers : transmissions, radars, sonars, contre mesures, armes, propulsion, usines de génération d'énergie, distribution d'énergie, distribution de fluides et d'air, commande de plateforme, sécurité incendie, conditionnement d'air, logements et restauration, etc. Les technologies de ces systèmes, installations et équipements utilisent de plus en plus les logiciels et l'électronique. On peut parler d'une coopération entre l'équipage et des systèmes "intelligents".

L'analogue civil peut être recherché dans la gestion des grandes agglomérations ou dans les grands projets de l'industrie ou de l'ingéniérie. La domotique présente également des similarités, à une échelle différente.

2. Position du problème : l'adaptation au changement continu

Il serait inutile de prétendre que l'ingéniérie concourante, telle qu'elle est décrite dans les manuels, est mise en œuvre quotidiennement dans nos marines. On y trouve, cependant, diverses applications pratiques. On y trouve aussi de la matière à réflexion pour l'avenir, concernant l'utilisation des nouveaux outils de conception proposés sur le marché et la pérennité de la capacité de (re)conception d'un navire au cours de sa période d'utilisation.

2.1. Résumé schématique de l'état de l'art en conception des navires

La conception assistée et la fabrication assistées par ordinateur existent depuis très longtemps dans le domaine de l'architecture et de la construction navales : étude des formes des navires, découpage et formage des tôles, étude des installations, découpage et mise en forme des tuyautages, études de simulation et maquettages de systèmes de combat, etc.

Mais l'intégration des diverses spécialités de conception, pour obtenir un navire qui soit à la fois un bon flotteur, un bon maneuvrier, un bon système de combat, robuste, bien habitable, correctement maintenable, autonome et respectueux de l'environnement.... est restée un art jusque tout récemment. La conception à coût global minimum, qui doit tenir compte de l'intégralité des coûts d'acquisition et d'exploitation, des premières esquisses jusqu'au démantèlement, est restée une discipline indépendante, utilisée seulement à quelques occasions au cours des études et de la vie d'un navire.

2.2. Questions en vue de l'utilisation pertinente de nouveaux outils

Il n'est pas certain que les outils récents de conception, notamment ceux qui calculent et visualisent en trois dimensions, soient facilement maîtrisables en vue d'intégrer les très diverses spécialités qui concourent à la conception puis à l'exploitation d'un navire de guerre.

Dans le domaine du meuble, les fabricants et distributeurs de meubles de cuisine réalisent depuis longtemps des maquettes virtuelles en trois dimensions à l'intention des clients, au moyen de

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logiciels de conception et fabrication par ordinateur. L'intégration avec la fabrication n'a pas toujours été un plein succès et il semble que l'on revienne à des outils différents, bien qu'interconnectés, pour le marketing et pour la fabrication. L'enjeu et les difficultés sont d'un ordre de grandeur encore plus élevé pour des navires de guerre.

Les nouveaux outils intégrateurs doivent donc encore faire leurs preuves.

2.3. Questions relatives à la préservation de la capacité de conception après la livraison

Des outils de conception d'un navire doivent rester à disposition pour réaliser les refontes et évolutions techniques au cours des 25 à 40 ans de la période d'exploitation et permettre de garantir la conservation des performances d'ensemble et des qualités d'intégration.

En effet, une seule refonte à mi-vie du navire, et en particulier de son système de combat, ne suffit plus car la rapidité d'obsolescence technologique oblige, de toute façon, à réaliser des raffraîchissements presque en continu, pas toujours dans l'ordre prévu, souvent avec une amplitude non souhaitée de divers éléments du navire.

Tentons d'être encore plus réaliste : les outils de conception d'origine du navire deviennent eux aussi obsolètes et finissent par disparaître au bout de quelques années alors que la durée de vie d'un navire est de quelques dizaines d'années. Certes, tout n'est pas négatif, car on bénéficie du progrès et on réalise des performances supérieures avec moins d'investissement, mais cet investissement dans l'apprentissage de nouveaux outils de conception est plus fréquemment renouvelé et le facteur humain peut devenir prédominant en tant que facteur limitatif.

Les évolutions du monde industriel, notamment à travers les concentrations, ne facilitent pas non plus la tâche de maintien de la bonne intégration d'un "super-système" tout en restant au coût global minimum. Qu'est devenu le maître d'œuvre intégrateur de conception et de fabrication après dix ou vingt années, à supposer qu'il ait correctement rempli son rôle et que la continuité de ce rôle ait été prévue pour la durée de vie du navire ? Le rôle d'un maître d'œuvre intégrateur du soutien du navire, éventuellement différent du maître d'œuvre de conception, face à des systèmiers et équipementiers, dont certains sont des entreprises régionales, d'autres appartiennent à des grands groupes multinationaux est-il seulement réactif ou bien doit-il anticiper, planifier.... tous les types d'évolutions technologiques, industrielles ? La réponse est certainement oui à la deuxième série d'options, mais quel industriel peut prétendre apporter un tel service et garantir le niveau de qualité de ce service sur longue durée ?

2.4. Importance des outils de management des informations techniques

Dans la perspective d'une continuité de la conception, au moins partielle, tout au long du cycle de vie d'un navire, les outils de gestion des informations techniques prennent une importance toute particulière.

Dans la pratique, les outils traditionnels s'avèrent à peine suffisants. Même les outils récents qui intègrent, par exemple via un workflow, des processus de travail entre acteurs, en s'appuyant sur divers applicatifs, et notamment une gestion de configuration, ne semblent adaptés qu'au traitement des problèmes au niveau des systèmes, mais pas au niveau d'un “ super système ”.

Pour préserver la capacité de (re)conception et d'évolution d'un super-système, il faut une gestion d'un autre ordre de grandeur.

Pour illustrer ce point, prenons l'exemple du soutien des logiciels, qui représentent l'une des technologies les plus répandues et les plus évolutives à bord d'un navire de guerre.

Il n'est pas suffisant de connaître la décomposition des éléments logiciels inclus dans chaque système d'un "super-système" : la gestion à réaliser est par nature “ transversale ” entre les systèmes et un modèle purement hiérarchique des informations de management est insuffisant.

Pourquoi cela ? Il faut savoir rapidement évaluer quels logiciels seront impactés par une modification d'interface matériel - par exemple avec un bus de données-, quels logiciels sont à modifier pour obtenir une fonctionnalité supplémentaire ou améliorer la réalisation d'une fonction opérationnelle. Il faut gérer non seulement les logiciels embarqués, mais les ateliers à terre chez les industriels, d'intégration et de programmation, qui permettent de modifier et valider les logiciels, ainsi que les relations contractuelles avec les industriels, parfois entre industriels, concernant notamment les compétences humaines.

Les difficultés dues à l'obsolescence et aux changements du monde industriel, en l'occurrence non seulement les sociétés de service en informatique mais aussi les producteurs de " logiciels de base ", sont également très présentes. On ne peut espérer, dans le domaine de la configuration des logiciels, figer une situation au-delà de quelques années : les générations d'ordinateurs se succèdent ainsi que les générations de logiciels de base et la compatibilité ascendante n'est pas systèmatique ; elle est même assez systèmatiquement remise en cause à chaque progrès important.

La communication entre le soutien à terre et le personnel spécialement formé à bord est à organiser dans le détail, à la fois pour permettre un enregistrement pertinent et une bonne remontée des faits techniques et incidents, ensuite pour assurer un premier niveau de soutien aux utilisateurs et garantir la configuration actuellement utilisée. Ce dernier point n'est pas un détail lorsque l'essentiel des ordinateurs à bord sont des machines du commerce susceptibles d'être reconfigurées très facilement par des moyens à la portée de la plupart des utilisateurs.

Ainsi, pour un " super système " tel qu'un navire, on doit envisager un système intégré d'informations techniques permettant de traiter chacun des types de problèmes évoqués. Une gestion des informations techniques de type classique ne permet pas de le faire.

2.5. Ingéniérie concourante, ingéniérie du changement

Le vrai problème qui se pose avec une acuité accrue, c'est de maîtriser plusieurs causes de changements continus et concomitants : les besoins des utilisateurs, les technologies mises en œuvre (y compris celles de la conception), le monde industriel qui "supportent" l'ensemble.

Ainsi, l'ingéniérie concourante devient de facto une manière de vivre pour un grand nombre d'acteurs, pas seulement ceux de la conception et de la fabrication initiales, mais aussi tous les acteurs du soutien en service. Le besoin d'outils d'intégration simples, utilisables par des communautés d'acteurs industriels et étatiques, apparaît logiquement, à côté des outils de spécialistes.

Par opposition, il est à craindre que certains nouveaux outils de conception intégrée ne puissent servir à traiter que les problèmes du passé selon une vision plutôt livresque des besoins des acteurs. Le niveau d'investissement nécessaire à l''acquisition et surtout à l'apprentissage de ces nouveaux outils ne permettra probablement pas de se dédire à ceux qui en feront l'acquisition. Cette acquisition ne les dispensera pas d'opérer une récupération et une mise à niveau des informations contenues dans leurs anciens outils. Enfin, il leur faudra réapprendre que, pour espérer maîtriser le niveau de complexité d'un "super-système", il est nécessaire de préserver une flexibilité, des degrés de liberté et des découplages, qu'un outil intégrateur unique ne peut pas offrir, par nature.

Cependant, les leçons du passé peuvent être tirées et utilisées pour ébaucher une ligne de conduite raisonnable en fonction des divers types de changements à maîtriser.

Des solutions " mythiques " ont représenté l'idéal de l'ingéniérie concourante avant l'accélération des besoins d'évolutions continues sur le cycle de vie que nous connaissons actuellement. Il est intéressant de les réexaminer en regard des nouveaux besoins.

Nous commencerons donc par examiner rapidement deux " solutions " mythiques avant de proposer des principes pratiques puis d'exposer un exemple limité mais significatif d'application de ces principes.

3. Examen critique de deux solutions historiques

Pour être exact, les deux solutions examinées ici n'ont jamais été présentées comme exclusives ni exhaustives. Le soutien logistique intégré et la normalisation des échanges de données informatisées sont totalement complémentaires en vue de l'ingéniérie concourante sur la durée de vie des systèmes.

3.1. Le soutien logistique intégré

Le soutien logistique intégré est une discipline d'ingéniérie du soutien, exercée concouramment à la conception.

La méthodologie générique est celle décrite dans l'ex MIL-STD 1388-1A. Elle exige une adaptation particulière à chaque programme, pour tenir compte des problèmes spécifiques à ce programme.

On pourrait penser que le soutien logistique intégré fournirait un bon cadre de travail pour l'ingéniérie concourante au cours de la période d'exploitation des navires.

Mais, en pratique, cette discipline a été exercée par des spécialistes du soutien logistique plutôt que par les concepteurs. Elle a surtout servi à dimensionner des lots de rechanges, et à tenter d'optimiser ponctuellement la répartition des opérations de maintenance entre les divers opérateurs étatiques et industriels.

Au cours de la période d'utilisation en service des navires, la méthode a parfois servi à redimensionner des lots de rechanges en fonction du retour d'expérience. En réalité, on s'est vite aperçu que les rechanges à bord d'un navire de guerre, qui représentent plusieurs milliers de référence, sont pour la plupart des pièces qui ne seront jamais employées. Ces pièces de rechange ont été placés à bord " au cas où " et elles y resteront pour cette même raison d' "essentialité ", quels que soient les analyses et calculs d'optimisation que les logisticiens fassent, si rien ne change par ailleurs.

Une véritable optimisation des éléments de soutien logistique à bord des navires suppose, en réalité, plusieurs actions concomitantes, dont aucune ne fait partie du soutien logistique intégré tel qu'il a été appliqué traditionnellement :

- réévaluer, de manière critique, l'importance relative des systèmes (et non pas de leurs rechanges), dans la réalisation des fonctions opérationnelles exigées le plus souvent en pratique, en tenant compte des redondances architecturales entre ces systèmes ; définir des lots à embarquer seulement pour les missions spécifiques et abandonner le concept " toujours prêt à tout partout à tout moment " au profit d'un niveau de risque raisonnable ;
- mettre en place une communauté logistique efficace entre les navires d'un même type, avec visibilité totale et instantanée des stocks à terre et des en cours de transport des ressources vers les navires, réalisation de transports rapides, fourniture de moyens d'assistance aux équipages pour la maintenance, etc.
- mettre en place une " supply chain " à terre, conduite par une cellule intégrée associant des opérationnels, des techniciens et des acheteurs, de manière à n'approvisionner que le strict minimum et en tenant compte à la fois des facteurs d'obsolescence, de la durée de vie à couvrir jusqu'à la prochaine refonte ou jusqu'au prochain raffraîchissement technologique, des campagnes de production des industriels.

Le soutien logistique intégré n'a pas été conçu pour remettre en cause des organisations et des procédures, ni pour maîtriser le changement en continu.

Maintenant que la coupure entre la période d'étude et de réalisation des navires s'estompe, avec l'augmentation de fréquence des raffraîchissements technologiques et des refontes partielles, on pourrait penser que le soutien logistique intégré va connaître un renouveau. Ce serait logique, mais peu probable. Il faudrait, en effet, qu'il renaisse plus beau et plus intelligent qu'il n'a jamais été, et puisse directement servir à maîtriser les logiciels et les matériels de technologies évolutives. Dans ces conditions, on peut préférer le remplacer carrément par autre chose, qui reste à formaliser et même à nommer, plus proche de l'ingéniérie du vivant.

3.2. La normalisation des échanges par voie informatique

La communication entre les acteurs doit être efficace, aussi bien pendant la conception et la réalisation du navire, que pendant son exploitation et son soutien en service. On a vu que son automatisation était souhaitable. Quelles sont les bases possibles de cette automatisation ?

L'évolution de la signification de l'acronyme CALS, qui désigne à l'origine une stratégie de l'US DOD en matière d'échanges de données informatisées, est caractéristique :

- Computer Aided Acquisition and Logistic Support : l'accent est sur l'ordinateur, les travaux ont porté principalement sur des normes d'échanges entre ordinateurs ;

- Continuous Acquisition and Life-cycle Support : l'accent est sur la continuité, les travaux ont porté principalement sur l'organisation, les procédures, les outils permettant la coopération entre acteurs sur la durée de vie d'un système;

- Commerce At Light Speed : l'accent est sur les affaires, et sur leur accélération.

Il est édifiant de comparer le résultat des premiers travaux avec ceux qui sortent à présent. Les premiers travaux ont produit (parfois simplement reproduit) des normes basiques de détail qui sont actuellement soit périmées, soit tombées dans le domaine public. Les travaux suivants ont permis, entre autres, la réalisation de prototypes de travail de projet en groupe (workflow) à grande échelle entre industriels et organismes étatiques dans le domaine des projets de systèmes d'armes. L'un des enjeux des travaux en cours est la communication directe entre les forces armées et l'industrie, afin que cette dernière puisse efficacement vendre ses produits et réaliser des prestations d'après-vente, y compris des fournitures de faible valeur nominale.

Il est probable que l'époque des normes détaillées très contraignantes au plan de la forme est révolue, au profit de métanormes. Ces dernières sont les plus susceptibles, en effet, de permettre la satisfaction des besoins très divers d'échanges entre acteurs à un coût raisonnable et dans des délais courts, en s'appuyant sur des principes syntaxiques et des dictionnaires de données. Au contraire, l'imposition d'un alignement sur des modalités détaillées ne durerait pas plus longtemps que les produits informatiques commerciaux qui les supporteraient et les coûts de mise à niveau à engager par les divers acteurs seraient forcément importants, donc non synchronisés...

A titre d'illustration, on comparera utilement une métanorme telle que XML et une norme classique telle qu'EDIFACT. On notera que l'industrie automobile fonctionne depuis plus de 15 ans avec des échanges informatisés permettant aux usines de montage de commander les fournitures en flux tendu chez les équipementiers ; l'une des principales difficultés de mise au point a été la prise en compte des cas d'erreurs (exemple : le produit livré par l'équipementier n'est pas le bon bien qu'il porte la bonne référence) ; jamais l'informatique ni la norme d'échange n'ont constitué une difficulté de premier ordre.

Un enjeu très important, dans le cas des systèmes navals, réside dans la capacité d'exploiter d'anciennes bases de données conjointement avec des nouvelles. Il existe, en effet, un décalage entre les générations informatiques mises en œuvre par des programmes sucessifs de navires et les bases propres à chaque programme contiennent un capital considérable. Comme beaucoup d'éléments du soutien logistique, à commencer par la plupart des contrats d'après-vente de systèmiers et d'équipementiers, recouvrent plusieurs programmes, il est indispensable de pouvoir exploiter toutes les données existantes. S'il existe un espoir de faire communiquer efficacement de manière automatisée des "anciennes" bases de données avec des nouvelles, c'est bien en robotisant la capacité de reconnaissance des procédures adaptées d'échange entre agents informatiques, plutôt qu'en tentant d'imposer une modalité unique d'échange ou un modèle unique. Chaque base possède son dictionnaire de données et sa structure, ses protocoles d'accès. Une métanorme peut permettre d'exprimer cela, et permettre les échanges entre des bases existantes en l'état. Bien entendu, un contrat d'échange conclu entre les entreprises industrielles ou organismes détenteurs des diverses bases doit préexister.

Dans le cadre d'une “ supply chain ” du type évoqué au paragraphe sur le soutien logistique intégré, on peut envisager l'échange des faits techniques et des configurations concernant les systèmes en service, l'échange des plannings d'interventions de maintenance des acteurs étatiques et industriels, la communication des campagnes de production des industriels, la communication des niveaux de stocks et en cours, etc. Ces échanges existent déjà de facto pour certains systèmes ou installations navals, de manière formelle ou informelle, mais sans informatique autre que le fax. Il est clair que les acteurs utiliseront l'informatique seulement si elle offre rapidement une amélioration, au moins sur le plan de la convivialité ou de l'apport de fonctionnalités nouvelles, par exemple à travers l'enregistrement à caractère quasi-notarial des échanges. Car l'échange de données par voie informatique n'est pas un but en soi.

Dans la pratique, les informations échangées entre des acteurs, y compris par voie informatique, n'ont qu'une durée de pertinence limitée. Parallèlement, un capital de données informatisées voit sa valeur diminuer automatiquement avec le temps s'il n'est pas mis à jour des évolutions des configurations réelles des systèmes navals en utilisation. Le cœur du système d'informations pour le soutien d'un navire de guerre se déplace vers tout ce qui permet d'assurer la mise à jour rapide du noyau traditionnel (configurations des installations navales, inventaires des ressources disponibles en stock) en fonction des évolutions et de réagir rapidement à une sollicitation opérationnelle imprévue. Ce sont les protocoles d'échanges contractuels avec les industriels réalisant le soutien qui deviennent de facto le nouveau cœur du système d'informations, après avoir été longtemps considérés comme périphériques. On peut même prévoir que le noyau traditionnel sera un jour physiquement réparti entre les industriels, au fur et à mesure que les politiques d'externalisation du soutien logistique se traduisent dans les faits. De toute façon, toute organisation étatique sera incapable, à terme, de justifier le coût de mise à jour du capital des données nécessaires, de l'organiser et de l'effectuer avec la réactivité souhaitable.

Comme au paragraphe consacré au soutien logistique intégré, on peut conclure que la forme ne peut remplacer le fond et que l'outil ne peut remplacer l'intention. Pour chaque acteur étatique ou industriel, la gestion des systèmes d'informations s'assimilera de plus en plus à la gestion des échanges avec d'autres acteurs.

4. Quelques principes pratiques d'organisation pour maîtriser le changement continu

Les principes proposés sont destinés à permettre l'ingénierie concourante des navires et de leur soutien logistique dans un monde en évolution continue. Ils ne sont évidemment pas tous spécifiques au domaine des navires de guerre.

Faire partager aux acteurs une vision commune sur ce qui sera important dans la vie du programme, c'est-à-dire la période d'utilisation qui suivra les études et la réalisation.
Exemple de thèmes à marteler : l'évolution de la répartition du coût global entre l'acquisition et l'exploitation au profit de cette dernière, l'accroîssement de la part des logiciels et des technologies évolutives utilisant du logiciel dans les systèmes, la responsabilisation des industriels systémiers et équipementiers sur leur après-vente, etc. Sinon, comment espérer que le coût global d'un programme soit sérieusement étudié s'il reste traité comme un exercice accessoire sans impact réel sur les choix d'architecture ni l'exploitation ?

Faire travailler en commun, pour des objectifs précis, des étatiques et des industriels, chacun dans leur rôle, dans des cellules de projet.
C'est ce qui est appelé ailleurs l'IPT, Integrated Product Team. Cela fonctionne bien si chacun a une idée précise du résultat attendu et de la nature de sa participation individuelle.

Respecter l'autonomie de chaque cellule de projet selon son horizon temporel, respecter l'horizon temporel des utilisateurs.
Cette évidence n'est pas toujours bien comprise. Un exemple pris dans l'industrie sera plus illustratif qu'un exemple de bureau d'études : un groupe d'emballeuses assure journellement le ramassage et l'expédition de commandes de produits pharmaceutiques ; il y a des grosses et des petites commandes qui induisent une charge très différente dans les différentes étapes du processus ; l'erreur est d'imposer un contrôle détaillé sur chacune des différentes étapes du processus, alors qu'il vaut mieux laisser le groupe d'emballeuses s'organiser de manière autonome; on ne soumet à un contrôle journalier que l'indicateur d'expédition de toutes les commandes prévues pour la journée, c'est-à-dire le résultat final, sans intervenir sur les règles du jeu internes au groupe.
Dans un projet, les jalons de projet délimitent les horizons temporels.
Il peut être nécessaire de refuser un horizon temporel inadéquat. Les problèmes de mise au point des systèmes de commande et automatismes sont parfois imputables à un horizon distendu, entre le moment où les études ont été approuvées et le moment où le système réel est livré. On est alors obligé de traiter sur le tas des défauts de prise en compte des modes dégradés, qu'un maquettage

intermédiaire aurait pu révéler parce que certains facteurs ne peuvent pas être étudiés seulement sur le papier. Les découvertes tardives sont typiquement les suivantes : le système en fonctionnement nominal exige peu de l'opérateur, alors qu'il faudrait dix opérateurs pour espérer traiter certains modes dégradés ; ou bien l'opérateur en situation de prendre des décisions difficiles va être bombardé d'informations vocales et lumineuses qui risquent d'augmenter son niveau de stress jusqu'à l'acte irrationnel.

Assurer la cohérence d'ensemble au moyen de modèles adaptés permettant la communication entre acteurs, entre cellules projets.
Des modèles d'ensemble du navire ou de sous-ensembles importants, simples, interactifs, permettent de visualiser l'influence des divers paramètres. Dans ce type de modèle, on ne doit pas sacrifier une vue globale, même si elle n'est pas totalement exacte, au profit du détail ni de l'universalité. Un exemple est présenté au chapitre suivant.

5. Exemple de modèle global d'un navire de guerre

Le modèle proposé ici comme illustration de modèle global est utilisé dans tous les programmes majeurs de la marine française depuis quelques années. Sa création a été motivée par les considérations développées aux chapitres 2 à 4 ci-dessus.

5.1. Domaine du modèle proposé comme exemple

Le modèle est destiné à montrer l'influence sur la disponibilité opérationnelle du navire

- des choix architecturaux de coopération entre systèmes
- des paramètres de fiabilité et de maintenabilité des systèmes physiques.

Il peut être utilisé à toutes les phases de faisabilité, de conception et de réalisation, ainsi qu'au cours de l'utilisation en service.

Les utilisateurs du modèle sont des opérationnels, des concepteurs, des logisticiens.

5.2. Description du modèle

Chaque fonction opérationnelle du navire est modélisée par un arbre logique développant les sous-fonctions, jusqu'aux systèmes physiques. C'est un arbre des contributions fonctionnelles.

Un porte avions peut être ainsi représenté par seulement une dizaine de fonctions opérationnelles, telles que " lancer les avions ", " récupérer les avions ", " se protéger contre les attaques ", " communiquer avec les autres navires de la flotte ", etc.

L'exemple d'une fonction " préparer les avions pour la mission " donne une illustration commode à la présente description (figures 1 et 2).

Les noeuds logiques dans un arbre sont de quatre types : AND, OR, AND/OR type A0, AND/OR type A1. Ces deux derniers types permettent de représenter les deux types de redondances fonctionnelles entre systèmes.

Le type A0 sert aux cas de coopération entre systèmes de natures différentes à la réalisation d'une sous-fonction ; par exemple, la réalisation d'une sous-fonction de maneuvre et de stabilisation de plateforme suppose le fonctionnement de logiciels de commande et de régulation, d'un gouvernail, de divers systèmes de stabilisation physique, d'un propulseur secondaire à l'avant, etc.; la contribution d'un système coopérant est mesurée par la perte d'efficacité de la fonction lorsque ce système n'est plus disponible.

Le type A1 sert aux cas habituels de redondances partielles ; par exemple plusieurs radars embarqués peuvent, avec un niveau d'efficacité différent, réaliser une sous-fonction donnée. Le niveau d'efficacité mesure la contribution.

Les contributions des auxiliaires, tels que conditionnement d'air, distribution d'énergie, qui apparaissent très souvent dans les arbres fonctionnels, peuvent être recueillies plus facilement dans un tableau croisé avec les divers systèmes physiques présents dans les arbres des contributions fonctionnelles. L'inclusion de ces systèmes auxiliaires directement dans les arbres en est ensuite facilitée.

5.3. Fonctionnement interne

Le but du modèle est l'étude de sensibilité des divers paramètres traités, sur la disponibilité opérationnelle de chaque fonction. Parmi les paramètres traités, les contributions des systèmes dans les divers cas de redondance donnent, eux aussi, lieu à analyse de sensibilité.

Pour chaque système physique, les paramètres sont les suivants :

- MTBCF estimé en cours de mission à la mer (Mean Time Between Critical Failure)
- MDTR estimé en cours de mission à la mer (Mean Down Time to Repair)
- niveau de réparabilité à la mer (qui conditionne le MDTR)
- taux d'utilisation à la mer

Le niveau de réparabilité à la mer représente la probabilité que le système considéré soit, au moment de la fin de mission, dans l'un des états suivants : totalement opérationnel, opérationnel dans un mode dégradé sans panne critique, en panne réparable par les moyens du bord (ce qui suppose qu'il reste à bord tout ce qu'il faut pour réaliser la réparation). Ce niveau de réparabilité induit à lui seul toute la logistique embarquée et la conception du système pour qu'il soit réparable au niveau souhaité.

Le modèle évalue la disponibilité opérationnelle en fin de mission et calcule les sensibilités des paramètres par un calcul analytique. Le temps de calcul est conditionné par le nombre d'apparitions multiples de systèmes dans l'arbre. Les systèmes sont classés, pour chaque analyse de sensibilité, par gravité décroîssante.

On trouvera un exposé des principes de calcul analytique dans la référence suivante :
Une méthode pratique d'allocation des objectifs, J-Ph Carillon, A. Petit, G. Seguin, O. Natta, Dixième Colloque National Fiabilité et Maintenabilité Lambda Mu 1996.

5.4. Logiciel associé

Un logiciel bilingue, français ou anglais au choix par une option de menu déroulant, a été développé pour tourner sur toute machine PC sous un système Windows 9x ou NT. Il permet de saisir les arbres de contributions fonctionnelles, éventuellement en réutilisant des éléments d'autres arbres déjà saisis.

Le logiciel les calculs pour l'arborescence à traiter et fournit les résultats dans un rapport, ainsi que dans chaque élément de l'arborescence traitée. Les résultats peuvent être conservés et rappelés.

La documentation du logiciel présente à la fois les principes de fonctionnement et d'utilisation. Les aides du logiciel rappellent les principes d'utilisation, notamment la gestion des arbres fonctionnels.

L'ensemble logiciel et documentation tient sur trois disquettes, et bien entendu sur un seul CDROM.

5.5. Caractéristiques intéressantes pour l'ingénierie concourante

A. Le modèle est autonome et simple; il utilise très peu de paramètres. Mais ces paramètres ont beaucoup d'implications au plan de l'architecture des systèmes et de l'exploitation du navire. Des outils de spécialistes sont indispensables pour approfondir les conséquences ou étudier les arbitrages en fonction des paramètres détaillés propres à chaque discipline par système ou par technologie.

B. Le modèle s'appuie sur une description fonctionnelle globale établie avec le concours des utilisateurs futurs ou des utilisateurs actuels, selon que l'on traite d'un navire en conception ou en utilisation.

C. Les calculs reposent sur des formules analytiques dont les résultats sont directement accessibles sans besoin d'interprétation par des spécialistes.

D. Le modèle permet et incite à travailler toujours en relatif à partir des analyses de sensibilité sur la totalité des paramètres introduits. Les systèmes physiques sont classés selon leur rang d'impact possible sur la disponibilité opérationnelle, ce qui met en évidence les progrès à faire mais aussi les possibilités de diminution des exigences ; en tous cas, un débat se crée autour d'un raisonnement global, plutôt que sur des bases propres à une discipline ou à une expertise spécifiques.

E. Les arbres fonctionnels et le modèle peuvent être utilisés en exploitation pour rendre compte de l'état de disponibilité du navire par fonction opérationnelle.

Ce modèle est donc, typiquement, un outil de communication et de synthèse.

F. Une dernière caractéristique intéressante : le modèle n'a aucune prétention à l'universalité. Par exemple, les facteurs humains, les études de sécurité, les études de performance des armes et du système de combat... exigent en général d'autres modèles globaux du navire.

6. Conclusion

Sauf à faire une confiance aveugle à des mythes anciens, l'ingéniérie concourante d'un super-système complexe et de son soutien logistique doit s'appuyer sur des modèles globaux complémentaires entre eux, simples, permettant de hiérarchiser l'essentiel par rapport à l'accessoire, et ...d'exploiter intelligemment les outils des spécialistes.

On ne doit pas se tromper dans le choix des outils : ceux qui sont destinés à gérer des systèmes ne suffisent pas à la gestion et au soutien dans la durée d'un super-système qui devra subire des évolutions fréquentes et globalement importantes.

Le facteur humain et la vision d'ensemble sont primordiaux. La technique de l'ingénieur et le management des organisations se traitent ensemble, en continu, sur toute la durée de conception de réalisation et d'exploitation des systèmes.

L'auteur. Jean-Philippe Carillon, architecte naval, après une carrière de 15 ans dans diverses industries civiles de production et de logistique, se consacre depuis 8 ans à la transposition des avancées civiles à la conception et au soutien des systèmes d'armements, principalement dans le domaine naval.
Adresse : DGA/DPM/MCO, 26 Boulevard Victor, 75015 Paris (France).
Le présent article a été rédigé spécialement pour l'atelier « Design for Low Cost Operation & Support » organisé en octobre 1999 à Ottawa par la NATO Research & Technology Organization.

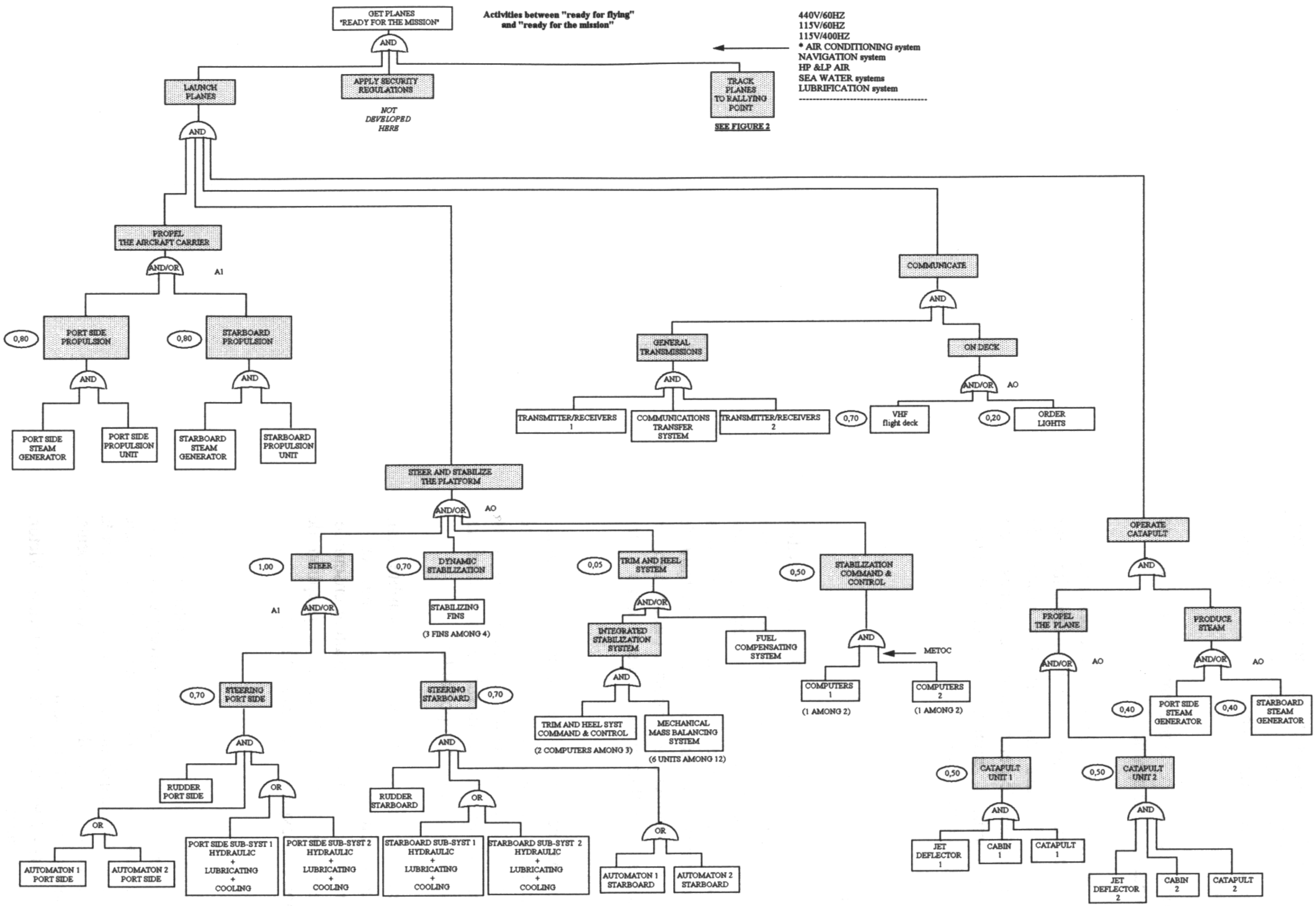


FIGURE 1 : EXAMPLE OF A TREE MODELED FUNCTION (PART 1)

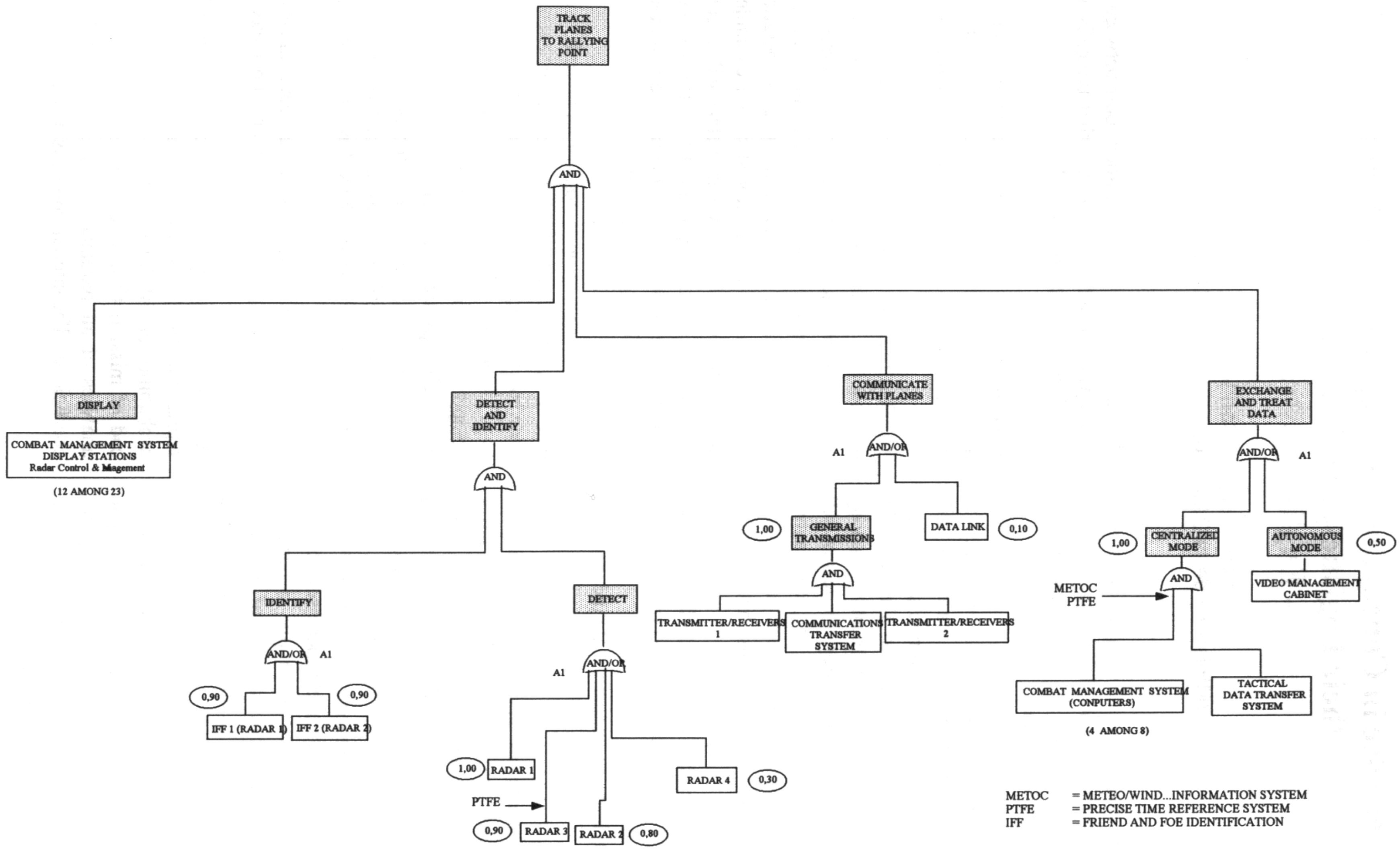


FIGURE 2 : EXAMPLE OF A TREE MODELED FUNCTION (PART 2)

An Experience in Concurrent Re-Engineering of Warships and their Logistics, as a Usual Business - English Abstract -

Jean-Philippe Carillon
(Ministère de la Défense, DGA/DPM/MCO)

A reform in the acquisition of weapon systems is currently in progress in some major countries. But the consequences are still to be derived in the domain of optimization studies.

Really user friendly models to be used by participants in integrated program teams are still lacking. Moreover, as the frontiers between program stages fades away due to the need for continuous technological refreshements - among other reasons - and integrated program teams will have to support the product thru life, continuous reingeneering will arguably become a requirement for survival. The following questions should also be addressed :

- which should be the adequate tools to design then support an "integrated" complex super system thru life,
- by whom (Gov't or industry) should they be operated..

Respected methodologies and strategies such as Integrated Logistic Support and CALS have never been designed for coping with a changing world where both new and legacy design and support tools are to be maintained, operated, sometimes themselves reingeneered. Moreover, as the complexity of newer weapon systems and their cooperative use on the battlefield increases, the aim for support can no longer be simply in terms of maintaining the systems but in terms of delivering the operational capability in various situations thru life.

The paper advocates the use of simple models on Gov't side, that should be based upon representations how the weapon system operates (instead of how it might fail). Dedicated independent simple models should be developed for each major discipline in a given program, for example, safety, availability, human factors, rather than downloading supposedly relevant data from an overall database. The point is that these models should be used as communication tools between the participants in integrated teams, that typically will have different cultures and skills.

Regular detailed models, for example simulation models, would be operated by specialists and experts in various disciplines, mainly in industry.

To illustrate the concept, a modeling tool and methodology is described. It is being used in all major warships acquisition programs in France and also as a reingeneering tool. It aims at relating the operational availability of each top level operational function of a given weapon system, for example an aircraft carrier. Very few parameters will describe the rate of use, the repairability at sea, the mean time between critical failure, the mean down time of each physical major component.

The overall logic of operations of an aircraft carrier can be described with 12 sheets of paper, each one showing the logic of contributions to a given top level function. The logic of contribution of components to intermediate functions then iteratively upwards to each top level function is described by a tree like representation. The contribution coefficients are entered by the sailors since they entirely depend how they use the product.

Various types of partial functional redundancies, as they will show up in real life, can be represented.

A software program allows entering the tree like representation on a PC. It then evaluates the probability of fulfilling each top level function at end of mission time, and computes the sensitivity analyses of all parameters, including contribution coefficients. The internal model is an analytical one.

Recent Combat Aircraft Life Cycle Costing Developments within DERA

Spencer Woodford

Centre for Defence Analysis, Lanchester Building, Defence Evaluation and Research Agency
Ively Road, Farnborough, GU14 0LX, United Kingdom.

ABSTRACT

In an effort to permit the procurement of more cost-effective military equipment, several studies have been performed in collaboration with two leading UK Universities. This paper describes the rationale and requirements of both University programmes, and gives details of the methods and some of the results generated. Rather than a broad overview of many different research activities within the Defence Evaluation and Research Agency (DERA), the purpose of this paper is to give as detailed a view as is possible of two recent studies, and the future developments that will stem from them.

The first part of the paper describes a tool developed for the design and optimisation of combat aircraft for minimum Life Cycle Cost (LCC), whilst the second part explains the evolution and optimisation of a long-range ground-attack aircraft designed for minimum support. The LCC model excludes 'deep overheads', restricting the use of the models to the comparison of similar weapons systems (combat aircraft) with a common set of design objectives and performance constraints. The support estimation methodology of the second part makes use of known aircraft design variables to predict reliability and maintainability of the aircraft. Both research activities, and the subsequent development at DERA, should have a positive effect on the aircraft design process.

INTRODUCTION

The Defence Evaluation and Research Agency (DERA), provides scientific advice, innovative engineering solutions, and a broad range of technical services to the UK Ministry of Defence (MoD). The Centre for Defence Analysis is a sector of DERA, and is primarily concerned with performing operational analysis to provide authoritative and impartial advice to decision-makers within MoD and across the Armed Forces. As part of a larger effort to reduce the cost of military equipment, particularly operation and support cost, a number of research studies were performed in collaboration with Cranfield University and Imperial College, on the conceptual design of combat aircraft for reduced support and LCC.

LCC is a complex subject that is concerned with quantifying options to ascertain the optimum choice of assets and asset configuration. When related to a combat aircraft, this leads to the type of aircraft, its specification, and configuration. In order to provide defensive and strike roles effectively in the face of improvements in the potential enemies' forces, it has been necessary to continually advance the performance, capability, survivability, and support characteristics of the aircraft, its associated weapon systems, and countermeasures. This has resulted in increasing complexity of aircraft and systems and, in most instances, increasing costs, in both absolute and real terms. Clearly, almost any new technology could influence the LCC of the aircraft system. For this reason this paper is not intended to be a comprehensive review of all the LCC research taking place within DERA, but rather an overview of two DERA-sponsored University research programmes, and their intended development.

The US Department of Defence first applied Life Cycle Costing to military projects in the early 1960's. It has become more popular and important in the procurement of military equipment, as the budgets for the World's fighting forces are ever-increasingly tightened. The reasons for this are numerous and highly involved, needless to say that the end of the Cold War, the global recession of the early nineteen-nineties, and the flood of low-initial-cost equipment from the former Soviet Union have all played contributing roles.

With waning public support for defence expenditure, policy makers must be seen to be cutting defence budgets in order to facilitate increases in spending on welfare and other domestic programs. Thus, military equipment must now be shown to present 'value for money' in both the long and the short term. 'Value' is difficult to quantify in the military sense, leading the current research activities to facilitate reductions in through-life costs of aircraft designed for a specified level of capability, mission performance, and operational requirement. In this way, 'value' can be said to be maximised, as a set level of performance is delivered for the lowest total cost.

In most previous studies of military aircraft, the objective function (i.e. the variable subject of the optimisation) was most often mass, either empty, mission, or gross mass. In the civil world, direct operating cost is frequently the figure of most interest to airlines, as it is the figure that allows the operator to decide flight charges, and ultimately calculate profit. In the military environment, 'profit' is not shown, although peacetime costs of operation are still just as important. It would therefore appear that there is a need for a greater understanding of the main contributors to the costs of military equipment, not only for the acquisition phases, but also in their operation and upkeep, and perhaps a re-think in the way that equipment is designed.

The following sections of the paper briefly describe two DERA-sponsored University research studies. The first is a tool for the conceptual design of combat aircraft for minimum LCC, and was performed by the author[1] whilst at Cranfield University. The second describes a minimum support long-range, ground attack aircraft, the Low Support Vehicle (LSV), and was performed by Whittle[2], at Imperial College. There are many similarities between the two pieces of work, but the Low Support Vehicle was optimised for minimum mass, as no discrete measure of support was determined.

The aircraft conceptual design tools used are based on classical design methods, recently adapted and updated, and validated with published data. The engine performance modules consist of detailed thermodynamic models, modified for the current usage. New engine sizing and mass estimation routines were developed for both models. The LCC model is primarily activity-based, and is an amalgamation of several different methods, each written for a different phase in the system life cycle. The LSV methodology makes use of two measures of Support - the calculated levels of Reliability and Maintainability (R&M) for the aircraft, and the number of support aircraft required for a range of offensive missions.

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

PART I - CONCEPTUAL DESIGN OF COMBAT AIRCRAFT FOR MINIMUM LIFE CYCLE COST

AIRCRAFT SYNTHESIS MODEL - The aircraft synthesis and optimisation model is implemented via a large FORTRAN code. Figure 1 gives a schematic representation of the overall operation of the program. It can be seen that the optimiser has ultimate control, and is responsible for altering the aircraft design and engine sizing parameters such that all constraints are met, and a minimum value of the objective function is achieved. For sufficiently accurate LCC prediction, the synthesis model must have an appropriate level of fidelity, and include realistic feature modelling and constraints. This was a difficult balance to strike within the time constraints of the study, and the LCC modelling routines may in future be added to the more capable aircraft synthesis models developed elsewhere within DERA.

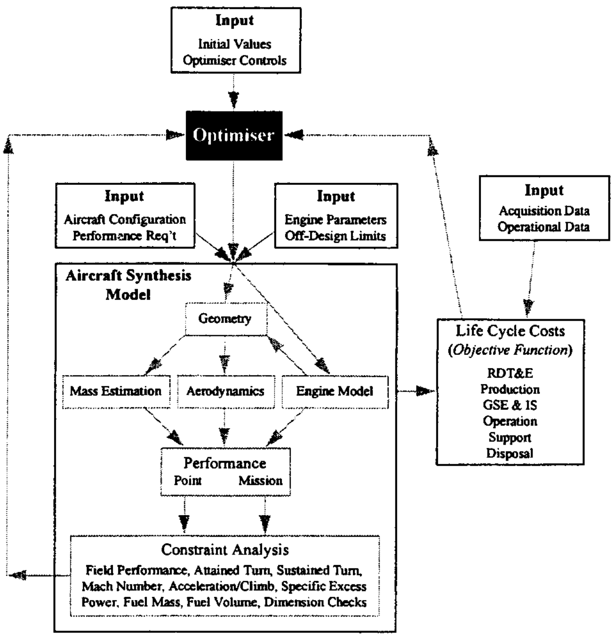


Figure 1. Overall Program Operation.

The first stage in the aircraft synthesis procedure is to read the relevant input data files and set the required parameters. The design options available include the aircraft type, configuration, number of crew, number of engines, etc. Further input data specifies the overall design requirements of the aircraft, including maximum level Mach number, diving Mach number, limit load factor, maximum payload, avionics mass, the number of weapon pylons, and other design drivers.

The parameter initialisation process also calls the engine design program. The engine thermodynamic cycle design is performed using data from the engine input file, which also contains off-design limits for the engine. This adds to the realism of the model by restricting the engine operating envelope. Once the cycle of the engine has been set it is not altered, and all subsequent engine calculations are performed to analyse the engine performance away from its design point. The above actions (i.e. file read and engine thermodynamic design) are only performed on the very first call to the synthesis. All of the following design procedures are performed every time the synthesis is called by the optimiser.

Component Sizing - Although the engine thermodynamic cycle has been specified, the physical size of the engine is yet to be defined. The main parameter used to determine engine size (in terms of both engine thrust and physical dimensions) is air mass flow rate, the value of which is determined by the optimiser. The engine off-design analysis program is called at sea level static conditions, and the values from this run, together with the original engine design data, are used to calculate the physical dimensions of the engine, using a bespoke method. The engine intake area and maximum nozzle area are generated for use in the aircraft geometry, mass, and drag prediction methodologies.

The remainder of the aircraft is then sized so that an overall configuration can be studied. The aircraft sizing process was kept deliberately simple, in order to keep the number of variables to a minimum, and improve robustness of the code. A large number of design variables can cause the optimiser to become trapped in local minima, and reduce the chances of true convergence. Figure 2 shows the overall sizing of the aircraft and the relevant major airframe design variables.

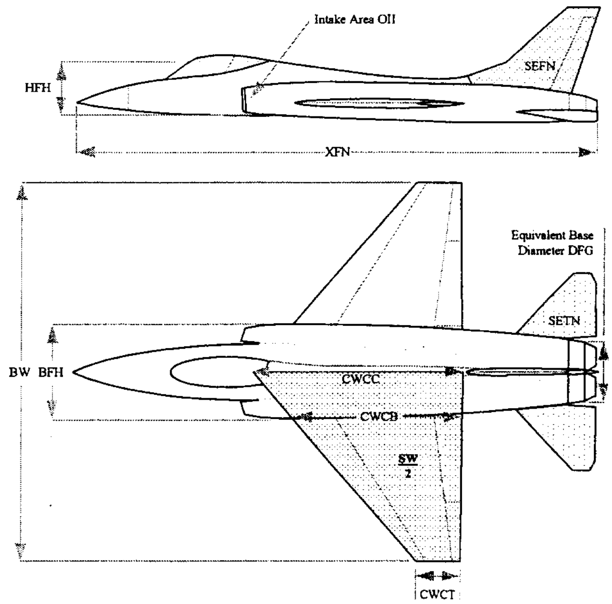


Figure 2. Aircraft Variable Definitions.

The size of the fuselage is determined using the maximum fuselage length, and the maximum effective fuselage diameter. From these two variables, and engine parameters calculated earlier, the remaining fuselage dimensions can be estimated. The width and height dimensions are driven by the maximum effective diameter, whether the aircraft has one or two engines, and the size of the engine(s). Both the height and width could have been varied separately, but a single variable was felt to be beneficial, as explained above. For both single and twin-engine aircraft, constraints are added to ensure that the fuselage cross-sectional area is large enough to accommodate the engine(s), and that the height is at least 20% larger than the maximum diameter of the engine.

The optimiser provides values for gross wing area, aspect ratio, taper ratio, leading-edge sweep, and thickness/chord ratio; all other wing variables, including tip and centreline chords, are found from standard geometry calculations. These values are used in the calculation of aerodynamic performance and wing fuel storage volume. The sizing of the empennage is performed using parametric sizing equations developed for this methodology, and the results are used in the aircraft mass and drag estimation procedures. For both the tail and fin, other parameters are also calculated, namely aspect ratio, thickness/chord ratio, and mean chord. All wing, fin, and tail parameters required by the synthesis have now been generated, concluding the geometric definition of the aircraft.

Mass Estimation and Volume Accounting - One of the most important processes in the design of any aircraft is the estimation of the aircraft mass, which in this methodology, is calculated from the sum of the individual component masses. However, many of the component masses are themselves a power function of the aircraft all-up mass, and the process becomes an iterative procedure to converge on the correct mass of the current design configuration.

The mass estimation method is implemented in such a way as to mimic the historical use of composite materials; the first structural component mass estimated is that for the empennage, followed by the wing, and finally the fuselage. Systems masses are found using semi-empirical methods, with separate parametric equations for each of the major systems. Fuel mass is calculated based on a fuel fraction value supplied by the optimiser. From the mass of structure, systems, and fuel, the aircraft gross mass and mission masses are calculated. Although the above methods are relatively simple, Figure 3 shows that surprisingly accurate results are achieved when the aircraft is treated as a whole system.

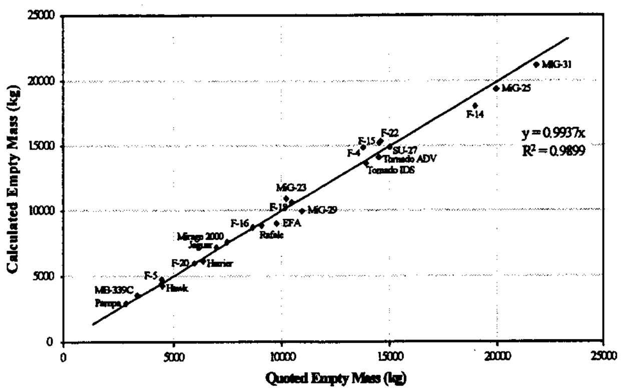


Figure 3. Mass Estimation Correlation.

The final process in this section of the code is to ensure that there is sufficient volume available for fuel carriage. Assumed system densities are used to subtract relevant volumes from the total available in the wings and the fuselage, and is implemented as an optimiser constraint.

Aerodynamic Modelling - The aerodynamics module consists of three models. The first predicts available lift coefficient based on wing configuration and geometry, Mach number, and the presence of high-lift devices. The second calculates the angle of attack from the lift-curve slope, which is based on the clean wing geometry and flight Mach number, and contains a simple correction for the effects of vortex lift. The third section is the largest and most complex of the three, and calculates the drag of the aircraft based on its geometry, lift coefficient, configuration, and the presence of external stores and retractable components. Due to the level of complexity of the models, and in the interests of brevity, the aerodynamic models are not expanded further in this paper.

Propulsion Modelling - Propulsion modelling is performed using two thermodynamic codes, ONX and OFFX, written by Mattingley[3]. The capability of the models has been limited, for the purposes of this study, to reheated turbojets and turbofans, and several improvements have been made from the original codes. Engine design starts with on-design analysis, which presumes that all design choices are still under control and that the size of the engine is yet to be fixed. The performance parameters are given as 'specific' values, normalised with engine size, and each complete set of design choices will result in an engine with its own operating and performance characteristics. ONX performs this section of the engine design, and from relatively simple starting values, the nature of the engine cycle is determined. The user can determine the design cycle of the engine simply by changing the parameters in the input file.

Once the engine cycle and limitations have been set, the engine is analysed away from the design point by the off-design analysis program, OFFX. This program returns all of the major performance parameters for a particular engine and flight condition. From these values, and calculating the installation losses, the thrust available and fuel burn can be estimated at any flight condition and throttle setting. An optimiser constraint has been added to ensure that the thrust available meets or exceeds the required thrust at all flight conditions. The constraint is very useful, as it allows the thrust at every mission phase to be checked using only a single variable. It ensures that the aircraft can complete supercruise and other high-thrust mission legs without the need for extra point performance constraints, for which the aircraft mass will not be known at the mission definition phase.

Once the engine air mass flow rate has been established for a particular application and the design choices and limitations have been set, the mass and physical dimensions of the powerplant are calculated. Continuing a theme suggested by Whittle[2], a new engine dimension and mass estimation methodology has been developed. The new models are based on the major engine design drivers; air mass flow rate, bypass ratio, compressor pressure ratio, number of shafts (although ONX & OFFX only deal with two-shaft engines), and reheat thrust increase. The results are very promising, but there is a question to be resolved over the accuracy of engine mass prediction in the 125-175kg/s air mass flow rate range.

Point and Mission Performance - Point performance calculations are used to compare the delivered performance of the designed aircraft with the required performance figures. They play a crucial role in the sizing of the aircraft, as the performance constraints determine the aircraft wing loading and thrust/weight ratio. The sizes of the wing and engine have a major impact on the overall design of the aircraft, and therefore the point performance calculations must be accurate, if a realistic design is to be produced. The synthesis is able to consider up to ten different point performance constraints; the amount of fuel, payload, engine operation (maximum or military thrust), and the individual point performance level can be specified. Of the ten available point performance constraints, the user has a choice of seven different constraint types. These include take-off and landing, attained turn rate, sustained turn rate (both in either g or °/s), specific excess power, maximum speed, and time-to-climb/acceleration. Maximum height can also be calculated, but is not included as a constraint.

The mission performance calculations work, for the most part, in a similar manner to the point performance constraint analysis methods, many of the algorithms being identical. The main difference in this section is that the major factor being calculated is the amount of fuel burned for each mission leg. The sum of all of these masses, plus a user-defined reserve factor, gives the total mission fuel mass, one of the single most important values in the sizing of the aircraft. Up to thirty mission legs can be specified from eight phase types, those being; engine run, take-off, climb/accelerate/descend, cruise, combat manoeuvres, weapons drop, loiter/CAP, and landing. Range credit is ignored for climb/accelerate/descend and loiter phases. Supercruise legs are specified by setting the cruise Mach number, and restricting the use of reheat.

LIFE CYCLE COST MODEL - The LCC module is based on several models that have been acquired and developed from many different sources, and has been split into the areas most often quoted in the available literature. Those are Research, Development, Test and Evaluation (RDT&E); Production; Ground Support Equipment and Initial Spares (GSE&IS); Operation and Support (O&S), and Disposal. Each life cycle phase model is represented by a subroutine, with all of the data coming either from the aircraft synthesis models, or the LCC input file. This file contains data such as procurement and operation data, production rates, fuel costs, as well as cost factors for security, flight test, and stealth considerations.

Research, Development, Test, and Evaluation - The RDT&E phase covers all areas of research and development prior to full-scale production of the first production aircraft. It includes; concept definition, design studies and integration, wind tunnel models and testing, laboratory testing, production of static and flight test airframes, avionics, software, propulsion development, flight testing, integrated logistics support, and program oversight. RDT&E typically makes up about 10-15% of the LCC of modern, low-production (≈ 500) combat aircraft, but is obviously affected by the number of aircraft over which this cost can be amortised. The method for the calculation of airframe development costs is taken directly from a method developed by Burns[4].

The methodology breaks the development procedure into many different activities, with the effort for each being estimated, and then multiplied by an appropriate labour rate to calculate cost. It can thus be thought of as an 'Activity-Based Costing' (ABC) procedure. The airframe cost model is based on parametric estimating techniques, using airframe mass, and several user-specified or design-dependent factors to allow for differences in the designs. The method used for engine development cost estimation is taken from a model developed by Birkler[5]. It uses thrust, Mach number, and turbine inlet temperature as the main cost drivers, and has been found to be accurate for the limited data available. Avionics and software development costs have proven problematic; avionics cost is based on uninstalled mass, whilst software cost estimation uses the number of lines of code and a number of user-defined complexity factors.

Production - This includes production engineering design, production investment (manufacturing facilities, tooling, jigs and fixtures), manufacturing labour, quality control, material and equipment, profit, overheads, administration, and purchasing of engines and avionics systems. These costs, divided by the number of aircraft make up the Recurring Flyaway Cost. Figure 4 shows a comparison of quoted and calculated recurring flyaway costs.

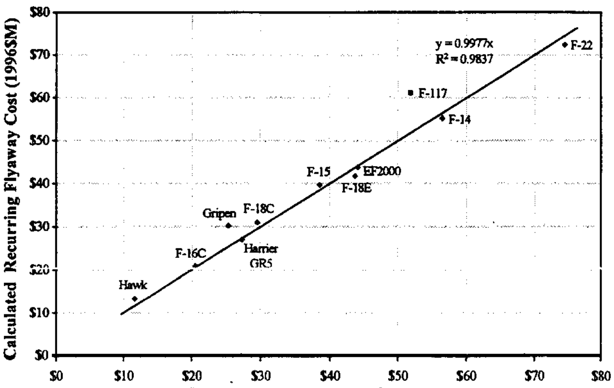


Figure 4. Recurring Flyaway Cost Comparison (FY96).

Production costs typically account for 30-35% of the total LCC of modern combat aircraft; the cost per aircraft decreases with number of aircraft built, as 'learning curve' theory and economies of scale are applied. The airframe production cost models are taken from the activity-based cost model derived by Burns, whilst the engine cost model is taken from a USAF Flight Dynamics Laboratory report[6]. Avionics cost models are based on uninstalled avionics mass. The total of the two major costs above (RDT&E & Production), divided by the total number of aircraft built, is called the Unit Acquisition Cost.

Ground Support Equipment and Initial Spares - This area of LCC is very difficult to estimate because of the equipment requirements for a particular weapon system. In keeping with suggestions made by several members of the costing community, GSE&IS cost is simply a fraction of the aircraft recurring flyaway cost, resulting in about 5% of total LCC.

Operation and Support - Operation and support (O&S) costs for modern combat aircraft can be split into several parts, all of which will be contributors to the cost of using combat aircraft in a peacetime operating regime. In wartime, the cost of operation and support becomes much less important, with all resources made available to win the particular conflict. O&S costs comprise: operation personnel; support personnel; service allowances, personnel support, and training; unit level consumption; contract costs for airframe, avionics, propulsion, and supply; sustaining support funds; and basing overheads and upkeep. The breakdown of O&S costs used follows the methods and structure suggested by the US Office of the Secretary of Defence in their 'Operating and Support Cost Estimating Guide'[7]. The O&S cost is calculated for one Main Operating Base, as this will have a significant effect on the staff requirements for the particular aircraft. This gives the added benefit that the model allows different basing concepts to be investigated, whereas many previous cost models considered the total number of aircraft procured.

One of the largest single O&S costs is that for mission personnel, the vast majority of whom are involved with First and Second Line maintenance. In order to calculate the number of maintenance personnel, the method first estimates the total maintenance effort required by the aircraft, using a parametric method. The number of First and Second Line operation personnel is calculated from the number of aircraft, crew ratio, the annual flying time per aircraft, and the total maintenance effort per flying hour. Support personnel numbers are calculated from the number of operations personnel and the number of aircraft. A separate section of the O&S model estimates the costs of Officer and Enlisted personnel training costs, training funds, and permanent change of station allowances. The models were adapted and updated from a US Navy report[8], and the values were calibrated against RAF Cost Of Support Spreadsheet data.

Unit Level Consumption attempts to capture the costs for all consumables used in operating the aircraft, including fuel, oil, lubricants, maintenance materials, miscellaneous support supply, depot level reparables, and temporary additional duty. Contract costs for the aircraft comprise what was thought of as Third and Fourth Line maintenance. With the potential re-structuring of the RAF, it was advised that it might be more applicable to treat these values as annual contract costs. The costs can be split among the three main aircraft systems - airframe, propulsion, and avionics - and supply. All of the contract cost models need updating, and work is currently underway to improve accuracy and increase the number of cost drivers. Supply contract costs capture the cost of shipping airframe, engine, and avionics components between the base and the contractor, and some of the costs for the supply of unit level consumption materials. The final two O&S cost models deal with Sustaining Support, and Installation Support Funds. Sustaining support includes the cost of replacement support equipment, modification kit procurement, and sustaining engineering support. Installation support costs are made up of personnel pay and allowances, material, and utilities needed for the maintenance of the base.

The sum of all of the previously calculated values gives the total O&S cost for one year in 'then-year' dollars, which is then multiplied by the number of years in service, and can be 'discounted' using standard techniques. The model does not currently contain timescale estimates for development and production, making the discounting process slightly inaccurate, as a lack of discounting applied to the acquisition phase will result in those costs appearing to be larger than they really are. The discounted O&S costs for a life of thirty years at a rate of 6% per annum is found to be only 13.765 times the first annual cost, as opposed to the 30 times that would be applied if discounting were ignored. The cost calculated by the LCC model, for the individual aircraft, contains the total then-year O&S cost divided by the number of aircraft on the base. The O&S phase typically contributes about 50% of the LCC for modern combat aircraft, and it is in this area that the largest LCC savings can be made. Reduction in O&S costs can be achieved by reducing one of many contributing factors, e.g. maintenance effort, fuel burned, aircrew numbers, etc.

Disposal - This could amount to a wholly negative cost if the aircraft were sold intact at the end of its useful life. As this is very unlikely, the disposal cost model consists of the following contributors; disassembly labour, disposal of non-reusable material, sale of scrap material, and resale value of on-board equipment. Depending on the relative values of these different components, the total disposal figure could be positive (i.e. a cost), or negative (a credit). The resale of systems, such as the engines and avionics, is thought to be unlikely, as technology in these areas changes so quickly that, for the moment, the value of these items has been neglected.

Total Life Cycle Cost per aircraft is simply the sum of the different cost phases already calculated, apportioned to different numbers of aircraft, depending on the Life Cycle phase. Figure 5 gives an example then-year LCC breakdown for a modern combat aircraft, having a large composite materials content, which has the effect of increasing disposal costs. Encouragingly, O&S costs now appear to make up a smaller fraction of the total LCC compared with the last generation of combat aircraft, where operation and support costs typically contributed 60-70% of total LCC.

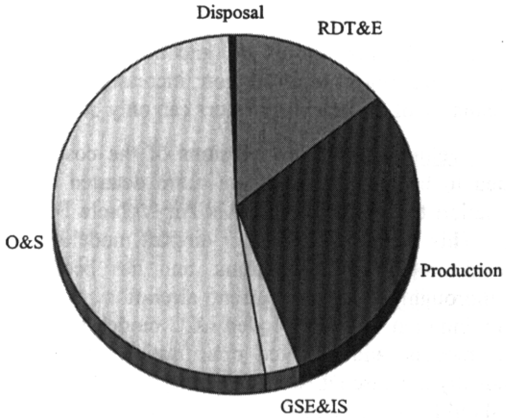


Figure 5. Approximate Then-Year LCC Contributors.

EXAMPLE RESULTS - In order to demonstrate the model capabilities, a number of aircraft solutions to a single mission specification were generated, optimised for minimum LCC. Aft-tail, delta, and delta-canard designs were produced with single and twin engines, and with options for crew and fin numbers. A notional air-intercept and combat mission was used, shown in Figure 6, together with rigorous point performance parameters, to produce a range of conventional semi-stealthy high-performance combat aircraft.

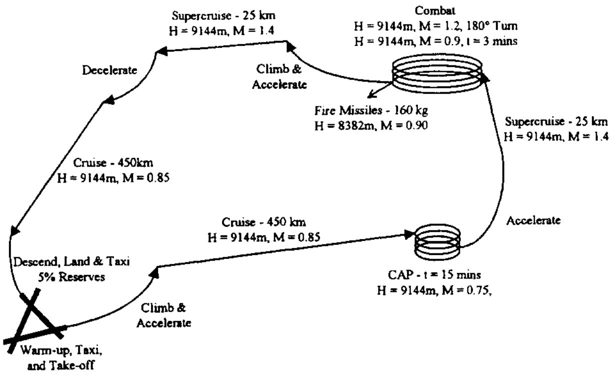


Figure 6. Aircraft Mission Performance Requirements.

Ground roll was limited to 250m for take-off and 500m for landing with full mission payload (475kg) of external weapons, and 95% fuel. Two attained turns were set; 7g at 12750m, M = 1.4, and 7.5g at 10805m, M = 0.9. Two sustained turns with reheat were specified; 5g at 6050m, M = 0.8, and 3g at 12825m, M = 1.6. All turn constraints were said to have full mission weapons load and 50% fuel remaining. Excess thrust values were checked at 11500m, M = 2, and sea level, M = 1.2, with full weapons load, and 50% and 80% fuel respectively. The final point performance constraint was for a time to climb. Initially, the aircraft was at sea level and M = 0.25, climbing to 9144m and M = 1.5 in 90 seconds; mission weapons mass and 50% fuel were assumed at the start.

The aircraft is assumed to be built by a collaborative group of two major and two minor partners, with a total buy of 620 aircraft and a production rate of 4.5 per month. FY2000 was assumed as the accounting year. The aircraft is to be operated from dispersed main operating bases of three squadrons (39 aircraft) per base, with a three-tier maintenance strategy - First and Second Line on the base, as well as Third Line contracts. It is to have a life of 25 years, at 240 flight hours per year, giving a total flying life of 6000 hours. 'Deep overheads', such as the cost of fighter control, are ignored, as are other costs not affected by the design of the aircraft.

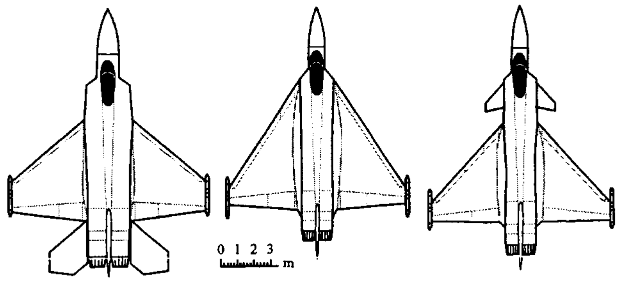
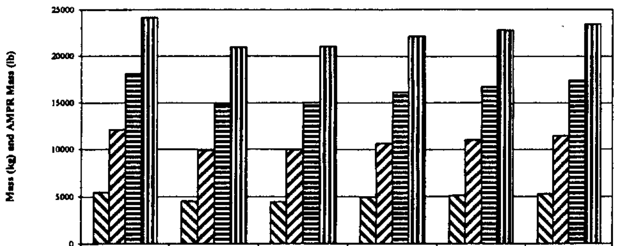


Figure 7. Twin-Engine Configuration Solutions.

Visualisations of the resulting one-crew, twin-engine, single-fin, configurations are shown in Figure 7. As can be seen, the delta and delta-canard designs are smaller than the equivalent aft-tail aircraft, although the delta will have lower agility than the other two. The aft-tail aircraft can probably be the most 'stealthy' with the least compromise from near-optimum placement of control surfaces, which would most significantly affect the delta-canard. Thus, all of the proposed solutions are viable designs having particular strengths and weaknesses.

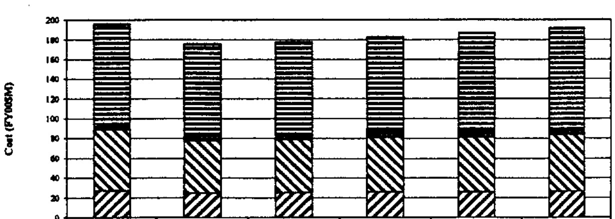
Fuel, empty, mission, and gross masses are shown in Figure 8, where mission mass is the mass of the aircraft, including crew, fuel, and weapons payload. The mass figures confirm the relative sizes of the aircraft, with the delta and canard-delta aircraft seen to be the lightest.



	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Fuel Mass	5475	4509	4457	4921	5095	5304
Empty Mass	12113	9880	10001	10632	11003	11470
Mission Mass	18162	14964	15033	16127	16773	17449
Gross Mass	24187	20989	21058	22152	22798	23474

Figure 8. Twin-Engine Mass Breakdown.

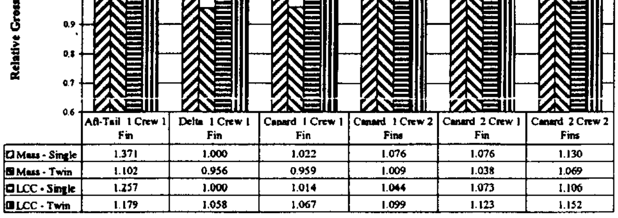
The costs for the various configuration options are shown in Figure 9. As expected for aircraft of similar technology levels, the costs change roughly in proportion to the mass, with all proportionate mass increases being greater than the relevant cost increases, except for the delta-canard design. This is due to a change in the driving performance constraints between the delta and canard-delta solutions, resulting in only a very small mass increase, but a larger cost increase, due to the increased complexity of the canard-delta aircraft.



	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Total	196.188	176.063	177.682	182.975	186.927	191.830
Disposal	0.973	0.776	0.798	0.838	0.831	0.884
O&S	99.948	92.247	92.662	95.122	99.058	100.812
GSE&IS	6.243	5.352	5.436	5.643	5.646	5.872
Production	61.542	52.756	53.587	55.627	55.657	57.876
RDT&E	27.481	24.932	25.199	25.744	25.736	26.385

Figure 9. Twin-Engine LCC Breakdown.

A comparison of the relative mass and cost increments relative to the single-engine delta (the lightest and cheapest aircraft) is presented in Figure 10.

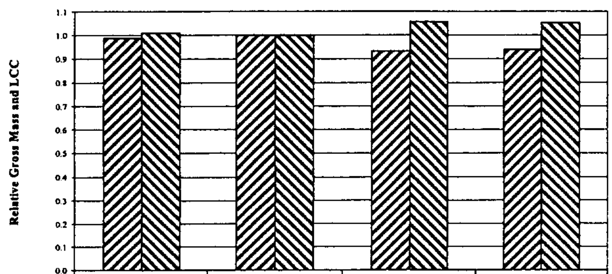


	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Mass - Single	1.371	1.000	1.022	1.076	1.076	1.130
Mass - Twin	1.102	0.956	0.959	1.009	1.038	1.069
LCC - Single	1.257	1.000	1.014	1.044	1.073	1.106
LCC - Twin	1.179	1.058	1.067	1.099	1.123	1.152

Figure 10. Relative Mass and LCC – Single vs. Twin Engine.

It can be seen that for every equivalent aircraft configuration (except the single engine aft-tail aircraft, which is not a fully converged solution), the mass of the twin engine aircraft is lower, but the LCC has increased. This result is interesting for two reasons. Firstly, it questions a commonly held perception that, for a given set of requirements, a single-engine aircraft will be smaller and lighter than a twin-engine configuration. Secondly, it shows that for significant configuration changes cost is not proportional to mass.

This second observation prompted further research in to the differences between aircraft optimised for mass and LCC. For both single and twin-engine canard configurations (which had previously been judged to offer a good balance of cost and combat effectiveness), solutions were produced with gross mass as the optimiser objective function. The results of the comparison appear in Figure 11, where the relevant objective function is minimised in all cases.



	Single Engine Mass-Optimised	Single Engine LCC-Optimised	Twin Engine Mass-Optimised	Twin Engine LCC-Optimised
Gross Mass	0.987	1.000	0.933	0.939
Total LCC	1.009	1.000	1.057	1.053

Figure 11. Relative Mass & LCC – Mass vs. LCC-Optimised.

Although the differences are small when presented as above, the total savings for an aircraft programme, with no loss of capability, are significant. The savings above correspond to a monetary value of FY00$M970 for the single-engine aircraft, and to FY00$M435 for the twin-engine solution. These savings increase once discounting is included, due to the reduced influence of the slightly increased O&S costs. In future, the difference between aircraft optimised for mass and cost will increase as the R&M and LCC models are improved to reduce their dependency on mass.

Other studies have also been performed to investigate the effects of internal weapons carriage, composite materials usage, and more electric aircraft (MEA) technologies on aircraft mass, performance, and cost. The LCC model requires further development, particularly for the R&M model, and the manpower scaling from it. This will improve accuracy and confidence in the models, and should produce greater differences in aircraft optimised for mass and LCC. Long-term, this will allow greater savings in through-life cost, as aircraft become closer to true minimum-cost designs. What the objective function should be, and the confidence that is placed in it are subject to discussion; increased modelling and understanding of the real cost drivers can only be of benefit.

Future developments – New versions of the cost model are intended to be included with the more detailed design and optimisation tool used by DERA's Air Vehicle Performance group. This model offers higher aircraft modelling fidelity, improved propulsion calculations, and has been validated more thoroughly than the current aircraft synthesis model. The combination of the improved LCC model, higher fidelity aircraft models, and up-rated optimisation software should dramatically increase DERA's capability to 'Design for LCC'. This should enable significant improvements in the cost-effectiveness of future British/European combat aircraft.

PART II - THE LOW SUPPORT VEHICLE

OVERVIEW - A fresh approach to solving the problem of affordability of future combat aircraft was proposed[9], involving the formulation of a Low Support Vehicle (LSV) concept, specifically directed at minimising through-life operating and support requirements. The outline specification for the concept design of the LSV, and a description of the principal characteristics of the LSV, was established[10], so that a single detailed concept formulation could be produced. The Department of Aeronautics, Imperial College, London undertook the study, under a three-year contract. The purpose of the study project was to demonstrate the effects of aiming for drastic reductions in support costs for all parts of a combat aircraft design, so allowing a better trade-off to be made between support characteristics and other features.

This section of the paper summarises the evolution of the LSV design and indicates some of the supportability features incorporated. The method developed for the prediction of the reliability and maintainability (R&M) of the LSV is described, together with the outcome of the predictions. A separate assessment of the cost-effectiveness, design attributes, and supportability features of the LSV has been conducted, but is outside the scope of this paper.

Supportability - For the purpose of the study, a supportable aircraft was defined as one with low support requirements; a minimum expenditure of equipment, effort, and, ultimately, money is required for the aircraft to fulfil its assigned role. Supportability of the aircraft alone was considered as a fundamental consequence of R&M. This was derived from the assumption that everything that affects the direct support of a system, other than consumables, can be linked to the inherent R&M characteristics of the system. For the study therefore, supportability is the quality possessed by a supportable aircraft.

The usual perception of supportability is that it is simply the consequence of the R&M characteristics of the aircraft under consideration. However, this view can be broadened to encompass the supporting systems required by the aircraft to complete its mission. This brings in such systems as in-flight refuelling tanker aircraft, or escorting fighter aircraft. This idea of total system support requirement reflects the aircraft's capability as well as its R&M characteristics, and is dependent upon the aircraft's mission.

It was considered that a total system support approach would be used to evaluate the supportability of the LSV in comparison with other combat aircraft. A framework for the method of comparison was developed during the study, which could be completed with the application of the appropriate analysis tools. The concept formulation for the LSV took into account the direct influence of R&M. It also considered the impact on the total system supportability in terms such as the ability to operate from short or damaged runways, the need for air-to-air refuelling, and the deployability of the aircraft by provision of systems that would reduce the need for an extensive logistics tail.

Evolution of the LSV design - The LSV was intended as an exploration of the effects of designing to minimise the aircraft support requirement. The specifications[10] called for the design to be formulated for the offensive role, with key performance specifications being equivalent to the Tornado GR4. Deviations from the performance requirements were only to be made to reduce the support requirement without significant reduction in capability. The essential features of the Tornado GR4 adopted for the LSV are shown below:

Mission:	hi-lo-lo-hi penetration
Payload weight with max. fuel:	4000 kg
Max. low-level speed with stores:	Mach 0.92
Maximum load factor:	7.5g

The LSV was initially specified to have a hi-hi mission radius of 1400nm, compared to the published Tornado combat radius (un-refuelled) of 750nm, although this was subsequently modified to a more representative hi-lo-lo-hi profile of 1130nm. Take off and landing distance of 1565m was specified on the grounds that a supportable and deployable concept such as the LSV should be capable of operating from many different bases - published data shows 36 British civil airfields with runways of adequate length for this performance. Such performance is comparable to that of modern mid-sized civil aircraft such as the Boeing 757 and Airbus A319, indicating that a similar distribution of suitable airfields should be found elsewhere in the world. Although an unclassified study, the LSV project took into account open literature information on low observables and considered them as part of the design.

DESIGN PROCESS - It was appreciated that the LSV would be a novel configuration in many respects, so that it was not appropriate to design just a single aircraft using existing methods; several different solutions might be possible for some areas of the design. However, without actually reaching the final design process for the aircraft it was not possible to identify which features should be included, and where new methods would be required. To resolve these problems, a scheme was established for developing several configurations leading to the ultimate design. New methods were developed in parallel with the development of the configurations, so that the final configuration would incorporate not only the best design features, but also the most refined calculations.

The design philosophy of the LSV was intended to maximise supportability, but the approach leads to some significant impact on the overall design. Inherent component reliability, although obviously desirable, cannot ensure reliability of a complex system due to the large number of individual components. Improving the operating environment for sub-systems and even systems can significantly improve the reliability of an aircraft, but such improvements can only be achieved if they are considered early in the design process. For example, providing a better environmental control system and planning the layout of all systems to provide a favourable operating environment can only be done by giving supportability a high priority early in the design process. Similarly, de-rating systems, particularly the engines, may provide a more benign environment, thus improving reliability. However, to achieve the same performance targets, de-rated engines must be larger than those operating at their maximum rating, affecting much of the design.

The LSV philosophy also stresses simplicity and integration as means to improve reliability. The use of integrated avionics systems, capable of re-configuring to take over functions of failed units is one example, but the concept of integration and simplicity can be applied to a much more basic level. For example, the weapons bay door on the LSV combines many functions, facilitating the release of internally carried weapons, and providing access to refuelling points and other internal systems. The complexity of the weapon bay doors is not increased, but the increased functionality eliminates the need for extra doors for refuelling and maintenance. Accessibility of systems for maintenance is emphasised in the early design phases; an inadequate initial basic configuration and layout of systems can never be recovered in the detailed design phase. Finally, the LSV design philosophy avoided reliance on the use of unproven or speculative technologies, the failure of which to realise their potential would fundamentally undermine the ability to achieve the LSV aim.

From the target specifications, a baseline configuration was formulated. The designations LSV A and LSV B were used during the baseline formulation so that the first configuration to be designed was called the LSV C. The LSV C is a single seat, flying wing aircraft with wing-tip fins and a short nose. It is predominantly constructed of composite materials. Internal weapons bays flank the single non-afterburning, de-rated engine. The LSV C was developed from the baseline configuration, and has a 50° leading edge sweep with leading-edge root extensions. The trailing edge is kinked, and supports four control surfaces - a pair of rudders and a pair of elevons. The aircraft is slightly statically unstable.

As a result of the experience gained during the design of the LSV C, in both configuration and methodology, two further LSV configurations, the LSV D and the LSV E, were produced. The LSV D is a low aspect ratio delta wing design with no horizontal or vertical tail and no protruding nose. A single chin engine intake leads to the single non-afterburning turbofan engine. The LSV E has a planform similar to that of the LSV C, but without the wing tip fins, being a flying wing with no protruding nose. The trailing edge has a pronounced kink around 40% of the semi-span. Two engine inlets are positioned on the upper surface of the wing, each feeding a non-afterburning turbofan engine.

Analysis of the LSV-D and LSV-E showed that both met their targets, and could be developed into extremely supportable aircraft. The LSV-E was considered a more operationally flexible design, so this configuration was chosen for optimisation, to produce the final LSV configuration, the LSV-F. The computerised methods used to design the LSV C, LSV-D and LSV-E were combined in an automated design synthesis very similar to the one described in Part I of this paper. Many of the aircraft design models, particularly mass and aerodynamic estimation methodologies, had to be updated to allow for the unconventional design, although the thermodynamic engine models were derived from the same source. Figure 12 shows the optimiser evolution of the configuration, with drawings of the aircraft at the start, after 14 and 28 iterations, and at the end of 42 iterations.

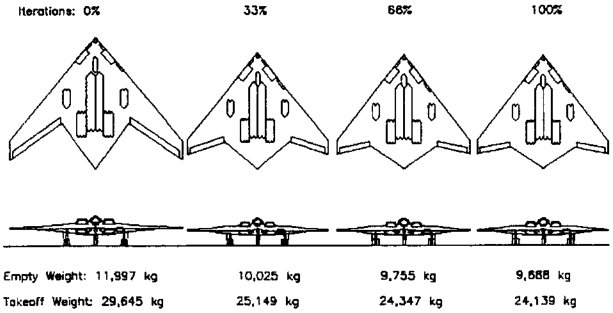


Figure 12. Optimiser Evolution of the LSV-F.

The LSV-F is a twin-engine flying wing, of almost pure delta planform, with a trailing edge kink at just under 50% semi-span. Two split elevons are the only control surfaces, and the aircraft is slightly unstable in pitch. It has a single centreline weapons bay with two doors, as well as the provision to carry external stores. The LSV-F configuration is illustrated in Figure 13, and by a computer generated image in Figure 14.

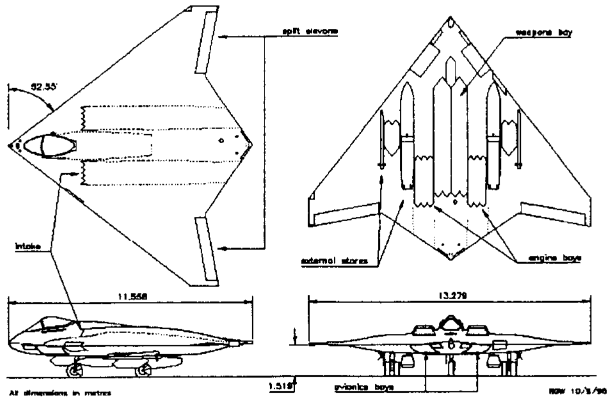


Figure 13. Final LSV-F Configuration.

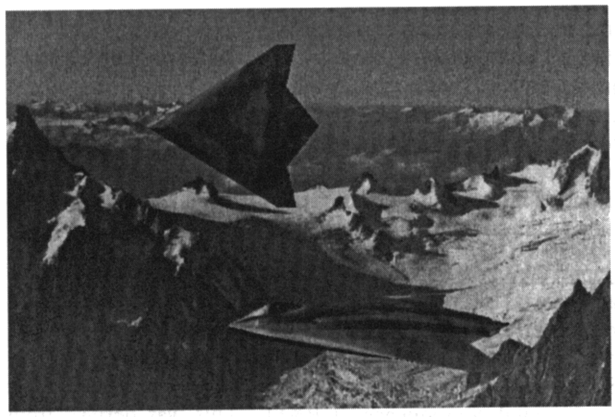


Figure 14. LSV-F in Flight.

LSV-F SUPPORTABILITY - The LSV concept design is driven by the need to reduce support requirements. Aircraft supportability is achieved mainly by simplification, systems integration, redundancy, and by commonality of parts. The need for supporting systems is reduced by making the aircraft capable of autonomous operation; long range without refuelling, low-observable features, comprehensive electronic counter-measures, high speed at low level, and self-defence weapons all contribute to this. For maintenance purposes, all important systems can be accessed from the ground, without downloading weapons, via either the avionics bay, the cockpit, the undercarriage bays, or the weapons bay. On-board oxygen and inert gas generators (OBOGS/OBIGGS) and a multi-function integrated power unit reduce the need for ground support equipment.

The LSV-F structure employs composite materials to reduce fatigue, corrosion, and weight. A modular structure is used, possibly incorporating a damage sensing system, to allow on-condition maintenance and to reduce peacetime operating costs, through reduction of third and fourth line maintenance and no-fault-found (NFF) reporting. Many structural components are common, and there are no leading and trailing edge high-lift devices. The engines are de-rated, and do not have reheat capability. Engine installation and removal is achieved by means of a special trolley, and all maintenance actions can be effected from below, so avoiding damage to the upper wing skin. Due to the position of the intakes, there is little danger of foreign object damage (FOD) to the engines.

The main undercarriage is very simple and robust, the units being interchangeable between the left and right sides of the aircraft. Oversized tyres operating at low pressure give increased tyre life, and two wheels per main undercarriage strut reduce the kinetic energy per wheel, allowing simpler brakes. The nosewheel uses the same type of tyre as the mainwheels, and the oleo shock absorbers are identical for the main and nose undercarriage. A titanium matrix composite could be used for the undercarriage, eliminating the need for corrosion inspection.

Whole fuel tanks are formed from composite material, to reduce leakage at tank joins. The tanks are foam-filled, and can be pressurised from the inert gas generating system. The weapons bay provides a benign environment, improving the reliability of weapons that may be carried on a number of missions without being expended. The gun is positioned to prevent interference with other aircraft systems and minimise the effects of vibrations from gun firing and ingestion of gun gas by the engines. A disposable cover is fitted over the gun port, and ammunition replenishment is carried out via the starboard main undercarriage bay. The avionics bays are easily accessible, and the windshield may be opened to access cockpit avionics. All sensors are readily accessible from ground level. Avionics reliability is enhanced by a closed loop environmental control system for the avionics bays.

The hydraulic system is of simple configuration, employing electro-hydrostatic actuators. The ultimate goal is to eliminate hydraulics to further reduce support costs. The on-board multifunction power unit provides engine start, emergency power, and auxiliary ground power. The power unit replaces ground support equipment, as does the on-board inert gas generator. The main utility locations are positioned to prevent any compromise to system accessibility if more than one maintenance task is being carried out simultaneously. Except for the cockpit (which has its own access ladder) and upper wing surface, all points can be reached from the ground without ladders or stands.

The supportability measures identified for the LSV-F are summarised in Table 1.

Structure	simple modular construction
	composite fatigue-resistant airframe
	only four multifunction control surfaces
	self-testing structure
Propulsion	non-afterburning, de-rated engines
	full-length engine access doors
	simple engine removal concept
	fixed geometry air intakes
	reduced likelihood of FOD to engine
Alighting	interchangeable undercarriage components
	single tyre and oleo types for all wheels
	corrosion-resistant undercarriage
	low pressure tyres
	simple brakes
Systems	integrated avionics and sensors
	low number of hydraulic system functions
	replacement of secondary hydraulic actuators with electrical systems
	multi-function integrated power unit
	on-board oxygen generating system
	on-board inert gas generating system
Maintenance	very simple configuration
	access-driven design
	accessible avionics bays, >50% growth space
	easy radar access
Operational	capable of operation from civil airfields
	stealth and advanced electronic counter-measures allow operation with minimum support
	single crew
	in-flight refuelling if required
	integrated weapons loading/launching arm
	internal weapons carriage
	self-defence capability
	long range with internal fuel

Table 1. Supportability features of LSV-F.

RELIABILITY AND MAINTAINABILITY - Two quantitative measures of aircraft reliability and maintainability are generally available. These are the defect rate (DR), usually expressed as defect occurrences per 1000 flying hours, and the defect man-hour rate (DMHR), which is the number of man-hours spent rectifying the defects, again expressed per 1000 flying hours. The term 'defect', in the context of this study, refers to a failure or a fault, requiring corrective maintenance action (referred to as 'rectifying' the fault).

The defect rate is a measure of reliability; more reliable aircraft will have a lower DR. The DMHR is often described as a measure of maintainability. However, the DMHR cannot be taken as an independent measure of maintainability, since the man-hours spent rectifying the defects in a given number of flying hours will depend not only on how easy it is to repair the system, but how many times it needs to be repaired. An independent measure of maintainability is found by dividing the DMHR by the DR, to give the mean time to repair each defect (MTTR), in man-hours per defect. If the reliability (DR) and maintainability (MTTR) are known, the unscheduled overall maintenance requirement (OMR) can be found.

The approach of separating reliability and maintainability measures and then multiplying to find the overall maintenance requirement, rather than attempting to predict the DMHR directly, was considered to lead to a more accurate and robust prediction method. The two aspects of the OMR are driven by different factors. Reliability is dependent on factors such as complexity, loading, and component reliability, whereas independent features such as accessibility and test methods determine maintainability. The three measures of merit (DR, DMHR, and MTTR) were used as part of the overall LSV supportability assessment method, the most important part of which was the prediction of the LSV R&M.

Different R&M analysis and prediction methods are appropriate for different stages of an aircraft design process. Several existing reliability and maintainability prediction methods were examined during the study to determine their applicability to the LSV design process. It was concluded that insufficient data was available to use detailed design methods for the supportability analysis of the LSV. Further, existing methods for conceptual design analysis were too old and too simplistic. It was therefore necessary to develop a new method for the prediction of the LSV reliability and maintainability for use in the supportability assessment.

R&M Prediction - For the purposes of the study, aircraft were considered to consist of twelve systems: air conditioning; flying/operational controls; fuel system; hydraulic power and pneumatics; alighting/arrestor gear; oxygen; miscellaneous utilities; structure system; propulsion systems; armament systems/tactical avionics; navigation and communications systems; electrical and instrument systems.

The R&M prediction method used consists of a set of statistically derived equations, based on work by Harmon[11], and updated by Serghides[12]. The equations predict, separately, the reliability and maintainability of aircraft systems, which can then be combined to give total aircraft figures and an overall figure for the support requirement in man-hours per flying hour. Data for ten aircraft in current or past RAF service, plus two US-operated aircraft (used to derive only the reliability equations) were collated, mainly from official sources. All aircraft are jet-powered combat aircraft from advanced trainers through interceptors and strike aircraft to a long-range strategic bomber, although the results should be treated with caution for such a large aircraft.

The purpose of the prediction equations is to relate measurable physical parameters describing the aircraft to observed measures of R&M. The accuracy of the method depends very much on the consistency of the data. In addition, there are other factors affecting R&M that will not be accounted for in the equations, but which could cause errors. Such error sources include the data collection procedure, definition and capture of variables and data, aircraft reliability growth, inconsistent maintenance policies, differing operating and environmental conditions, small sample size, and the use of few parameters to reflect complex design effects. It has been assumed that the influence of these factors is relatively small.

Derivation of prediction equations - Equations for all twelve aircraft systems were derived using multiple regression analysis of the defect rate and mean time to repair data with various parameters, alone and in combination with others. Over 90 parameters were tested, of which 28 and 19 were finally selected for the reliability and maintainability equations respectively. Several possible forms of equation were investigated in each case, some incorporating the influence of time on reliability (called time improvement factor, TIF) resulting from different technology standards and design practices. Prediction equations were only accepted if there was sound engineering basis for the inclusion of the parameters, and the trends produced were logical. Points that did not fit an otherwise clearly defined trend, either as a result of known exceptional features or as a result of a known error source (known as outliers), were discarded. For example, Lightning landing gear data was discounted, as the aircraft was notorious for its poorly sized tyres, which were very narrow in order to stow within the thin wings of the type.

Total aircraft defect rates - The total aircraft defect rate is found by adding the system defect rates. The accuracy of the total defect rate prediction is well illustrated by using the reliability equations to compare the predicted and recorded reliability of a number of aircraft. The results of the comparison, together with a best-fit line and 'goodness of fit' metrics are shown in Figure 15.

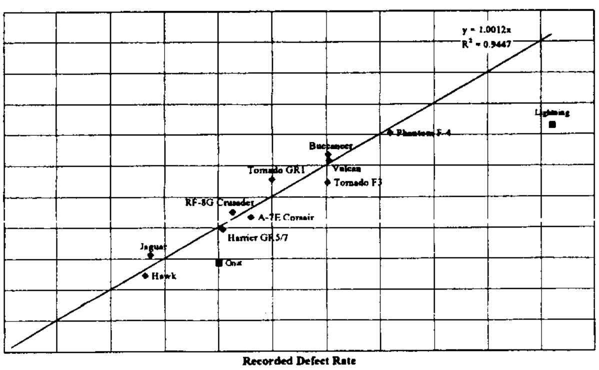


Figure 15. Predicted vs. Recorded Defect Rates.

Only the results for Lightning and Gnat are poor predictions; these were both significant outliers in some of the derivations and were excluded from the derived equations. The policy of excluding outliers tends to increase the total error of the excluded aircraft, but the resulting equations better represent engineering trends, and thus should have superior predictive ability. Plotting of actual and predicted rates for each aircraft by system (see Figure 16 for the Harrier GR5/7 as an example) indicate that the accuracy of the prediction is a consequence of good system level prediction, rather than fortuitous cancellation of system errors.

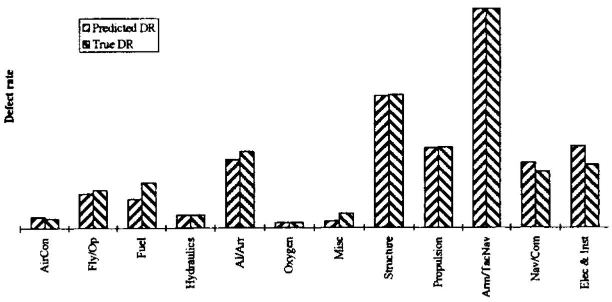


Figure 16. Predicted and Recorded Defect Rates, By System.

Maintainability prediction equations - As noted above, the maintainability equations were derived using data for the ten aircraft in the database operated by the RAF. Maintainability equations for the MTTR of each of the twelve aircraft systems were derived using the same multivariate regression process as used for the reliability predictions. Time improvement factors are not used in the maintainability prediction equations, since maintainability is not dependent on component design to the same extent as reliability. However, factors are employed to account for 'design for maintainability', and the resulting improvement in the accessibility of systems.

The total aircraft mean time to repair is defined as the total of the defect man-hour rate divided by the total defect rate. The results from the R&M prediction equations may be combined to generate an overall defect man-hour rate (man-hours per flying hour). Figure 17 shows a comparison of predicted and recorded defect man-hour rates for various aircraft.

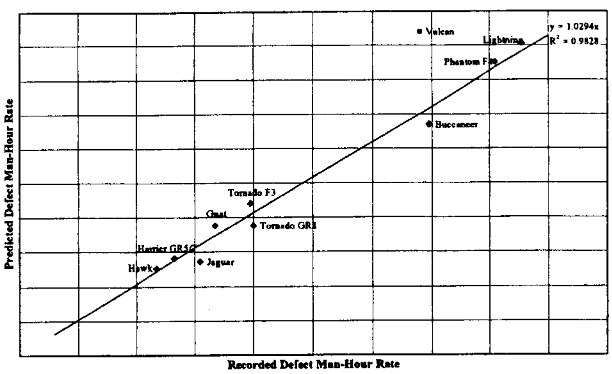


Figure 17. Predicted vs. Recorded Defect Man-Hour Rates.

LSV-F PREDICTIONS - The R&M forecasts for the LSV-F were produced using the prediction equations, and drawing upon 47 available inputs. The inputs ranged from the date of the first flight of the aircraft type, through empty weight, to whether the aircraft carried a primary radar. It should be noted that the outputs from some of the prediction equations were modified to account for special features of the LSV-F, such as additional effort expected in the detailed design stage to reduce support requirements. If no adjustments to the predictions are allowed, the DMHR is increased by 9%.

It would be misleading to compare the predicted defect man-hour rate and its components, the defect rate and the mean time to repair a defect, for the LSV-F with published data available for other aircraft. The LSV-F predictions are based on the maintenance policies and data collection standards of the RAF. Other aircraft operators use figures derived from a different base; some include planned as well as corrective maintenance, or consider on-aircraft maintenance time only. The study compared the predicted rates for the LSV-F with the predicted rate of other combat aircraft. Figure 18 shows the results of the comparison, scaled relative to the predicted values of Tornado GR1.

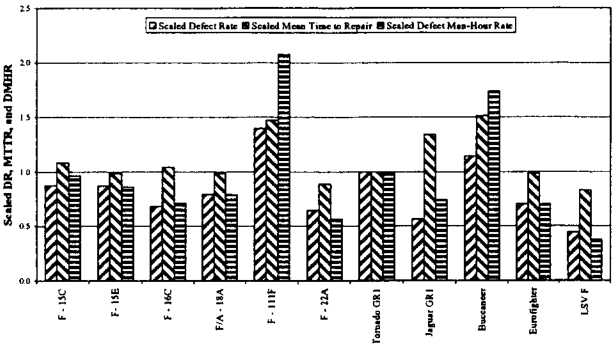


Figure 18. Predicted R&M Quantities.

The comparison shows that the defect-related maintenance requirement (the DMHR) of the LSV-F is considerably lower than that of all the other aircraft, being nearly half of that predicted for Eurofighter and nearly a third of that predicted for Tornado GR1. The maintainability prediction for the LSV-F structure penalises the use of composites and the relatively poor accessibility due to the low aspect ratio all-wing configuration. Except for the structure system, the maintenance requirement of every system of the LSV-F is less than that of each of the other aircraft. The relative advantage of the LSV-F over the other aircraft is less pronounced in maintainability (the MTTR) than in reliability (the DR). It is likely that some maintainability advantages of the LSV-F are not reflected in the maintainability prediction equations.

Influence of technology - The LSV-F (and F-22 and Eurofighter) predictions benefit from the increased reliability of modern systems reflected in the Time Improvement Factors in the reliability prediction equations. By eliminating this factor it is possible to judge whether the LSV-F and its 'contemporaries' are the most supportable simply because they use newer technology, or whether the designs are fundamentally superior. Setting the technology datum to 2002, the assumed first possible flight date of the LSV, results in an overall flattening of the distribution of the results, although the pattern is very similar. The LSV-F remains best by a considerable margin, but its nearest competitor becomes the Jaguar, a far less capable aircraft. F-22 slips to fourth in the ranking, being overtaken by the less capable F-16. The implication of this is that the supportability advantage of the LSV-F derives partly from the application of new technology, but mainly from the fundamentals of the design.

Future Developments - As the LSV-F was single point design for a given mission specification, it is unlikely that the actual design will progress further than at present. However, the design philosophy and many of the models will be taken forward and updated for use with other DERA aircraft design and analysis tools. Of particular interest are the mass and aerodynamic estimation methods for the flying wing configuration. The R&M prediction equations will form the basis of an updated model, which will be compatible with the LCC model described in Part I. This will contribute to a powerful and flexible suite of aircraft design and analysis tools, capable of designing and optimising for either minimum mass, LCC, support effort, or eventually, availability-cost.

CONCLUSIONS

This paper has described the methods and results from two DERA-sponsored University research programmes. The first, performed by the College of Aeronautics, Cranfield University, developed a computerised design and optimisation tool to minimise the Life Cycle Cost of combat aircraft. The tool and the results from some studies were presented in Part I of this paper. The second research programme, performed by the Department of Aeronautics, Imperial College, produced a similar tool to investigate the supportability gains that could be achieved by an aircraft designed for maximum supportability. The resulting aircraft, the Low Support Vehicle, and the methods used to assess its supportability were described in Part II of this paper.

Both research programmes have shown that design for reduced cost is possible, but that quantifying the benefits is difficult and requires extensive modelling effort. The LCC model has shown that reduced through-life cost will not always be achieved by reducing support costs. Although O&S contributes approximately 50% of the through-life cost, the economic impact of increasing reliability and compromises to the design may outweigh, in life cycle terms, the benefits of reduced O&S costs. This matter is further complicated by the difference between discounted and non-discounted costs.

The design characteristics resulting from the cost and support design drivers are considered to improve future aircraft supportability, and therefore improve future combat aircraft peace time and war time availability, whilst reducing through-life costs. This in turn should lead to aircraft capable of delivering a set level of performance for reduced cost, maximising 'value' in the military sense, and leading to a situation that will be beneficial for both customer and manufacturer alike.

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Supportabilité en conception et faible coût global : l'exemple du MIRAGE 2000
Supportability in Design and low Life Cycle Cost (LCC) : the MIRAGE 2000 example

Louis Lemaignen, Franck Huet, Maleck Rajabaly
DASSAULT AVIATION
78, Quai Marcel Dassault
CEDEX 300
92552 Saint-Cloud Cedex
France

Résumé : Bien qu'il n'ait pas été complétement conçu, comme le RAFALE l'a été ultérieurement, à travers la démarche Soutien Logistique Intégré (SLI), le MIRAGE 2000 a bénéficié d'une forte implication de ses futurs utilisateurs dès le début de sa conception et a tiré profit du retour d'expérience opérationnelle des programmes précédents de Dassault Aviation pour lui donner les "aptitudes" d'un avion à disponibilité élevée et à très bonne maintenabilité.
L'approche globale de la "Supportabilité en conception" est présentée et la façon dont les "aptitudes" de l'avion ont été introduites au cours de sa conception est mise en relief. Les principaux choix techniques et leurs qualités de "Supportabilité" sont présentés. Les caractéristiques de soutien démontrées opérationnellement montrent comment les objectifs ont été satisfaits.
Pour une définition technique donnée, il existe plusieurs solutions logistiques pour optimiser le coût global selon les moyens du client et la taille de sa flotte sans gêner l'emploi opérationnel de sa flotte. Une optimisation de ce type à partir de simulations de coût global est présentée.

Summary : Though not fully designed, as later the RAFALE was, through a true Integrated Logistic Support (ILS) methodology, the MIRAGE 2000 received, during its design phases, a strong involvement of the future Users and took benefit of Dassault Aviation's experience and operational feedback from previous programmes to give it the "abilities" of a highly available and maintainable aircraft.
The overall approach of "Supportability in Design" is presented and the way the "capabilities" have been incorporated in the A/C definition and its evolution are highlighted. The major technical choices and their "Supportability" aspects are presented. The field-demonstrated Support characteristics show how the objectives have been met.
For a given design, different logistic solutions are possible, depending on the specific Customer and the size of his fleet, to reduce the Life Cycle Cost (LCC) without impairing the operational use of the fleet. Such an optimisation, using an LCC tool, is presented.

1 – The Integrated Logistic Support Approach

For the operational people, the quality of Support is measured through the **Availability** of the fleet (the number of aircraft ready for a mission compared to the initial number and the time it takes to perform servicing or maintenance tasks) and the amount of resources (hardware and personnel) necessary to operate them (deployed means or **Logistic Footprint**).
For the program deciders, the quality of Support is measured through the overall cost of the function : the Life Cycle Cost (**LCC**).
In both cases, what is judged is not the Support alone but the efficiency of the overall System : Flying **and** Support Systems. Therefore, a good design has to consider both aspects simultaneously : it is the commonly accepted approach of Integrated Logistic Support. As Weapon and Support systems are interdependent, the process needs to be iterative and because the main choices affecting the LCC are made in the early phases of design, it is essential to apply the ILS methodology to the Preliminary Definition phases in order to incorporate Supportability into Design.
The main Measures of Effectiveness for Support are Availability , Logistic Footprint and LCC, as seen above ; they are Mission Efficiency and Vulnerability for the Flying System. Figure 1 represents the principle of the ILS process.

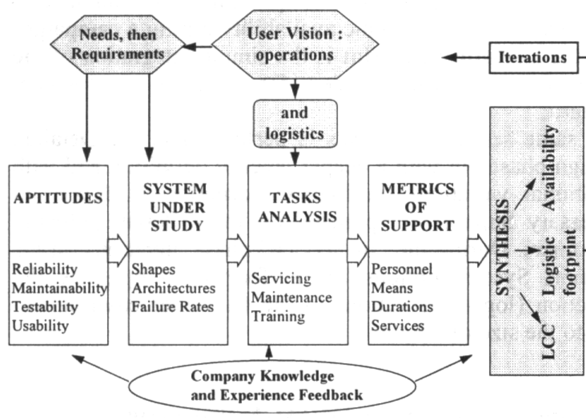

Figure 1 : The iterative process of ILS

The initial loops of the process analyse the Customer vision in terms of **needs** and **aptitudes** (or qualities) of potential systems to satisfy them with the highest Measures of Effectiveness (MoE). The next iterations, in which the needs start to become **requirements**, try to define concepts (virtual products) which could satisfy these requirements and to quantify the consequences of the technical choices on Support. The integration of the Support metrics of this virtual product allows to calculate its MoEs and to iterate either on the concept (optimisation) or on the requirements (when not achievable).
The aptitudes are the recognised **Reliability**, **Maintainability**, **Testability** (which is becoming more

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important with the increasing complexity of the weapon systems) and **Usability** which is the aptitude to an easy training of the pilots and of the technicians (it affects the amount of resources, skills and time needed to be able to operate the system).

The **System under study** is a Virtual Product (digital product assembly) containing a definition of the shapes, main structural elements, floors and doors and a preliminary definition of the subsystems architectures (with reliabilities of the envisaged technologies).

The **Tasks Analysis** consists in analysing all the actions needed to operate and maintain the system. The Servicing tasks include the mission preparation and the weapon loading or replacement ; they set the product in a condition of Operational Readiness. The Maintenance tasks restore this readiness condition. The training tasks include all necessary actions to allow the personnel to properly operate the system and maintain it with the dedicated hardware. This Tasks analysis generates the **Metrics of Support** (durations of the tasks, skills of personnel, Ground Support Equipment and consumables, training means and services) allowing their integration with the proper tools into the Measures of Effectiveness **to assess the Supportability** of the concept.

The **Company knowledge** and experience feedback is used to introduce the proper Support aptitudes in the product concept and then the design rules in the product definition. Ideally, simplified formulas, based on past programs experience and on technology evaluations, should allow a fast estimation of the complexity (needed resources) and duration of the different tasks and of their costs. We are presently working on such a modelling.

Finally, the **LCC** is calculated from the list of necessary hardware, consumables and salaries established in the tasks analysis and from costs data bases ; the **Availability** is calculated from the architectures definition and the critical reliabilities (the logistic flow of spares must be simulated to have access to the dynamic availability during a campaign) and the **Logistic Footprint** is the simple integration of the resources and skills needed for a given deployment scenario.

The same sequence of tasks is performed in the Detailed Design phase but with a deeper level of definition and with additional variations on logistic scenarios to define all necessary Support components for the different potential customers. During the “In-Service” phase, iterations on the Support System options are performed to optimise the selection (logistic solution) to the Customer environment and to the size of his fleet.

2 – Supportability in the MIRAGE 2000 design :

When the MIRAGE 2000 was designed, the methodology described above was not yet formalised (and the tools necessary to perform a fast assessment of a virtual product were not available) but, in its principle, it was applied in the key decision process as shown below.

In complement to the usual involvement of the Operational pilots, as seen in the previous programs, to tailor the program requirements to the "Armée de l' Air Française" (AAF) needs, the MIRAGE 2000 program received a much stronger involvement of the Support specialists (for the requirements definition and the development), thus achieving a different balance between Performance and Support requirements.

2.1 - The needs and the aptitudes : MIRAGE 2000 program started in 1976 after the MIRAGE F1 had cumulated a significant operational experience and after the preliminary studies of the Avion de Combat Futur (ACF) which, in fact, were the feasibility studies allowing to transform the needs into requirements. Based on a different aerodynamic concept and an improved engine (the ATAR 9K50), the MIRAGE F1 had inherited most of the reliable vehicle systems of the famous Delta wing MIRAGE 3. Its operation, including the use of an Automatic Failure Localisation System called SDAP (Système de Détection Automatique de Pannes), had shown the advantages and drawbacks of different technologies and Support concepts. The needs for the new aircraft, based on the new M53 SNECMA engine, were bright performances (among which **Agility** was at the first row) but also **Robustness** (like the MIRAGE 3), **Ease of handling** (like the MIRAGE F1), **Flexibility** and variety of stores, **Reliability** and **Ease of maintenance**, including **on-board Testability** of the Weapon Delivery and Navigation System and (already !) **Affordability**. For this last essential parameter the ACF study was stopped (the AAF considered it could not afford a fleet of big twin-engines) and the specification evolved towards an agile single engine airplane. The MIRAGE 2000 development program was starting with an integration of AAF pilots and technicians and Ministry of Defence engineers in the industrial team.

2.2 - The aptitudes in the Design :

The Airframe : To satisfy these new requirements, the well proven robust and versatile Delta configuration was selected (the 58° leading edge angle selection taking benefit of the variable geometry MIRAGE G8 flight tests). Owing to the mastering of a carefree handling Fly-by-Wire flight control system able to cope with an unstable platform and to allow ease of flight and landing, an aerodynamically unstable definition was selected to give the aircraft bright manoeuvering characteristics. This platform was able to carry the required variety of loads without difficult flight envelope extension tests and able to be the basis of different versions to meet the various mission requirements, thus giving the AAF a **common affordable core for its different needs** (later the RAFALE approach will be even more ambitious allowing the replacement of different aircraft by one single versatile platform). Twin-seater versions were decided at the beginning of the program for the purpose of training or complex missions requiring a crew of two (tactical nuclear version). Structural design and doors arrangement gave a good **accessibility** to the main equipment (see figure 2 below) based on their frequency of

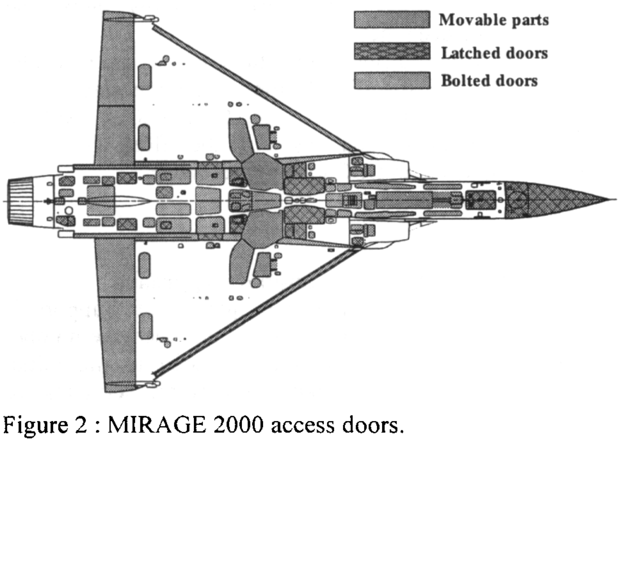


Figure 2 : MIRAGE 2000 access doors.

removal (linked to reliability) and taking into account the compromise of a low wing concept.
For the first time also the Manufacturing team was involved in the design with the first simultaneous use of CATIA in design and in manufacture, thus leading to a structural design much **cheaper to produce** than the MIRAGE 3 which looks similar in shapes. The structural dimensioning rules and the corrosion protection plan (company **robustness** tradition) gave the airframe a good Safe Life expectancy. In the prototype phase, the integrated team simulated the potential maintenance tasks and reoriented the design for an improved serviceability and maintainability. A specific effort was performed for a good **repairability** through access doors and interchangeability of major subassemblies. Later, in the flight test phase, Visits of Aptitude to "Mise en Oeuvre" (=servicing) and Maintenance (called **VAMOMs**) were performed to optimise the Supportability of the production aircraft.

The Engine : The single core/double flow M53 engine is modular by design and its replacement on the A/C had to be shorter than 2 hours with three technicians (in fact trained mechanics have demonstrated not more than 1 hour - it happened recently in a foreign country where a presentation was made).
The modular design allows a reduction in cost of spares and allows to perform most of the maintenance at O/L and I/L levels. The modules are geometrically and functionally interchangeable.

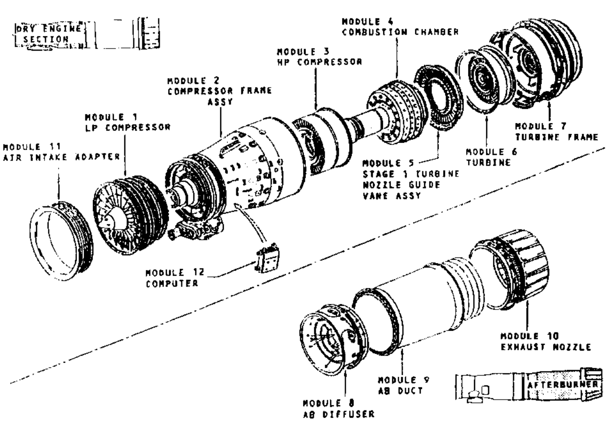


Figure 3 : Exploded view of SNECMA M53 engine

The Vehicle Systems : They were designed with the fundamental Dassault Aviation philosophy of robustness "Safe and Simple, Reliability first!" and with mostly NATO **Interoperability** requirements. The main choices are linked to a single engine configuration and the classical distribution of the primary energy source (here hydraulics for high manoeuvrability) on the engine itself and on the AMAD (Aircraft Mounted Accessory Drive).
Autonomous engine start by a Turbo-Starter mounted on the AMAD.
Hydraulic redundant servoactuators for all primary flight controls (elevons and rudder) and servomotors on secondary controls (slats) with quadruplex, triplex or duplex redundancy (depending on the criticity) for the Electrical Flight Control System (EFCS) and its electrical generation.
Hydraulic system based on two 4000 PSI pumps and an electrical emergency pump and electrical shutoff valve on ancillary functions ; one circuit is dedicated to the flight controls and nose wheel steering with a purely hydraulic irreversible emergency landing gear extension (as it is the tradition for all Dassault Aviation fighters).
Carbon brakes with hydraulic progressive control valve and redundant antiskid servovalves.
AC current delivered by two 25 kVA variable speed constant frequency (400 Hz) alternators (Varioalternators) and a standby inverter. The varioalternators take benefit of many improvements from the previous programs (MIRAGE 3, MIRAGE F1, JAGUAR, etc.). Their reliability has reached a good level though they remain complex electromechanical machines (two differential gear boxes and an Eddy current clutch to insure constant speed of the alternator). Note that, for RAFALE, as the speed ratio of the engine was smaller, a technology step was performed with the use of the variable frequency (very reliable alternators).
DC current delivered by a 40 A/hr battery and two transformer-rectifiers.
Fuel system using two forms of energy to feed the engine (electrical pumps and pressurisation) and using pressurisation for transfer. The hydro-pneumatic principle of most refuelling and transfer valves was kept from the previous programs because of its demonstrated very high reliability and safety of operation. The aircraft can carry three drop tanks and flight refuelling is performed via a STANAG 3105 refuelling probe.
Physiological protection system based on Liquid Oxygen converter (LOX) for breathing and Anti-g with purely pneumatic demand regulators (excellent demonstrated reliability). At the time, it was the only credible choice for long duration flights with refuelling. Today, to improve the maintenance aspects (logistic footprint and LCC) an On-Board Oxygen Generating System (OBOGS) is the proper choice and is the standard on RAFALE. The study of its adaptation to future versions of MIRAGE 2000 has been performed recently (the difficulties to find the proper pressure conditions to feed an OBOGS have been overcome).
Escape system based on a Martin-Baker Mk 10 seat fitted with the very good GQ Aeroconical parachute and operated by a Dassault pyrotechnic Sequence System together with the zero-delay fragilization of the transparency. Its maintenance aspects are fairly good but primary desarming is still needed for seat removal. This constraint has disappeared on RAFALE with its specific version of Mk 16 having Dassault Patent "Autoconnectors" (including pyrotechnic transfer - see Ref. 2) allowing the removal or installation of the seat with just the Safety lever raised (no connection to perform).
Environmental Control System derived from the MIRAGE F1 with the classical well proven "bootstrap" design and using as cold sources Ram Air (precooler, primary and secondary heat exchangers) and the water of an evaporator (for topping at high Mach number). Cockpit pressurisation based on purely pneumatic redundant pressure regulators. For RAFALE a much higher power demand will lead to the choice of a better performance "High Pressure water separation" principle.
To reduce the ground diagnosis time of electronic equipment, an On-board Integrated Maintenance (automatic self tests) was selected for the WDNS and for the EFCS computers as explained below. Interestingly, it was not considered necessary for all Vehicle Systems (except EFCS) in reason of the technical choices (reliability, comprehensive flight alarms, pilot reporting) and of the

previous programs experience (testability more difficult for "physical" systems and avoidance of false defects).

The Weapon Delivery and Navigation System (WDNS) : As in any other program, it is by far the most evolutive system and the description of the different versions and their evolution towards the up-to-date MIRAGE 2000-5 and 2000-9 Systems would require a specific presentation. Without being an expert, it is obvious that the performances and mission capabilities of the initial MIRAGE 2000 C with RDM RADAR and the MIRAGE 2000-9 with RDY RADAR are very different. What is common, in terms of Supportability, is the use of Multiplex Data exchange Bus (MDB), the **On-board Integrated Testability** of the system, decided from the beginning to avoid the need of the SDAP, the Maintenance principles and organisation with 2nd level Automatic Test Equipment.
The Integrated Testability principles are the following :
-using integrity checks for every component of a unit or a functional link, rather than operation simulation
- using a centralised process to enable real-time or delayed localisation of faulty elements for on-line maintenance and, through the use of specific procedures for some I/L maintenance.
These principles have allowed :
- a drastic reduction in specific ground means for O/L maintenance (limited now to sensors and open loops)
- a very quick localisation of faulty LRUs with a very low false diagnosis rate
Two different phases can be distinguished in this Integrated "Maintenance" :
- real-time monitoring, during operational functioning, which is focused on self-tests in the units without disturbing normal operation
- on-ground complementary tests, with a specific functioning mode, allowing the execution of tests which would be too disturbing during flight.
These complementary roles of integrated maintenance have proven to be very efficient.

3 - The Maintenance Program :

3.1 - The Maintenance Development : its aim was to offer the User the maximum Availability at a minimum Life Lycle Cost by reducing the ground logistic Support through a better use of the on-board systems.
This Maintenance development was performed in four steps :
a- **Maintainability study** including analysis on drawings and equipment of the potential maintenance actions and checking the User's rules and with operations performed on the mockups and on the prototypes (as explained above). It is the most important phase because it incorporates Supportability in the Aircraft itself (accessibility, interchangeability, removability, trouble-shooting, etc.). It allows also the specification of the Support equipment.
b- **Analytic study** of the **maintenance program** : It is based on the MSG3 methodology and was called MAPIE (Méthode Analytique de définition du Plan Initial d'Entretien).
For the systems and the engine, it consists in classifying each failure consequence (depending whether it is visible or not) as critical for safety or mission or as only economic and in specifying an efficient maintenance action to prevent the failure with a given probability if it is needed and in programming this action with a periodicity in relation with the probability of occurrence. Today we use the same methods except they are Computer Assisted (CECILIA failure Trees coming directly from the safety analyses and MAPIE AO).
For the Airframe, the study is based on Fatigue Tests (airframe and samples), on measurements and fatigue Index calculations on the aircraft and periodic inspections with Non Destructive Testing (NDT). For corrosion, the principle is similar except the theoretical projection on the future is more questionable and periodic inspections are probably unavoidable (the trick being to associate them with other maintenance actions, thus becoming nearly "transparent" for the user). The tolerance to accidental damage approach is applied mostly beyond the "Safe Life". Each type of main structural element has its inspection logic. As an example, the diagram below shows a grid for selecting the periodicity of NDT on a carbon composite structure as a function of criticity and exposure.

		Impact Susceptibility		
		1	**2**	**3**
Margin after impact	**1**	1	2	3
	2	2	2	3
	3	3	3	3

⇩

		1	**2**	**3**
Criticity	**1**	1	2	3
	2	2	2	3
	3	3	3	4

⇩

		1	**2**	**3**	**4**
Level of Exposure	**1**	1	2	3	4
	2	2	3	3	4
	3	3	4	4	4
	4	4	4	4	4

⇩

NDT periodicity	**1**	Every 4 years
	2	Every 8 years
	3	Every 12 years
	4	No inspection

Inspections to apply on 10% of the fleet.

Figure 4 : Selection grid for impact damage

c- **Experimentation** by the AAF on the first production aircraft : it essentially validates the equipment and procedures.
d- **Program update** through technical monitoring of the customers fleets : as seen above, the maintenance program is relying on probabilities of occurrence, condition monitoring and aging studies. **Experience feedback** is a fundamental factor in its validation and improvement. The high number of flight hours in different countries and climatic conditions has led to a significant improvement of the Maintenance Program by reduction of its cost without impairing the safety.

3.2 - The Maintenance Plan :
The maintenance operations are performed at three levels :
- Organisational Level (O/L) : inside the squadron
- Intermediate Level (I/L) : specialised workshops on the Air Base
- Depot or industry Level (D/L)

Depending on the customer fleet size and existing facilities the distribution of work between I/L and D/L can be varied to optimise the LCC (see §5). The O/L activities are always flight inspections, daily servicing, operational check-out, lubrication, trouble-shooting and replacement of Line Replaceable Units (LRUs).
The I/L, which is mostly dependent on Logistic concept choice, deals with periodic inspections and minor structural repairs and replacement of Shop Replaceable Units (SRUs) or consumables.
The Maintenance Program is divided into two categories of tasks :
-"Hard Time" maintenance which is essentially preventive and which is progressively reduced with the experience feedback
-"On Condition" maintenance which is corrective and takes more and more the first place. It requires the evidence of a defect (wear, deterioration or failure) either by visual checks or by On-Board Integrated Testability or measurement of significant parameters. As explained before, for the MIRAGE 2000 vehicle systems the "Integrated Maintenance" was not selected : fault localisation is performed from alarms, indicators, the pilot's flight report and a good knowledge of simple reliable systems in which the types of failures are now well known. On RAFALE, because of different technical choices (computers for all vehicule systems, increasing pilot workload requiring an automatic management of the platform functions- see Ref.2) the On-board Integrated Maintenance is applied to the whole flying System.
Airframe maintenance : with the experience feedback from all our customers and internal studies (showing the excellent airframe behaviour), its organisation (basic, minor and reinforced inspections) has evolved to better fit the specificity of foreign customers. The inspections are performed at Intermediate Level (**not** at D/L). The figures below show the **present** schedule of inspections .

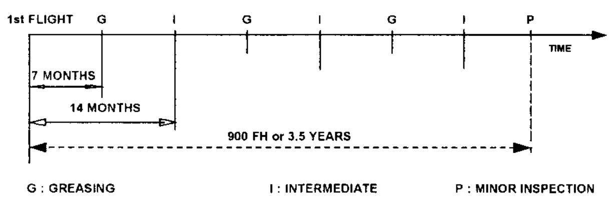


Figure 5 : Basic and minor inspections

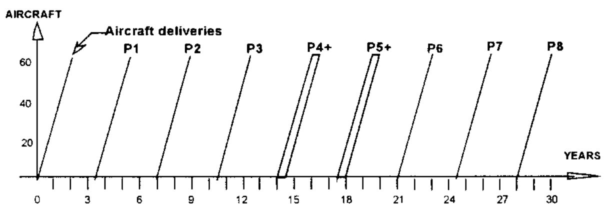


Figure 6 : Split of minor and reinforced inspections

An other important evolution under way is the transition from "fixed periodicity" P visits to flight hours related P visits, the calendar inspections being distributed on the different basic inspections.
Systems maintenance : its organisation can be varied according to customer needs. Because of their needed limited investment and their frequent use, the minimum shops are : wheels and brakes, batteries, oxygen and flight equipment, escape system and weapons. Additional shops are : FCS and hydraulics, ECS, Fuel systems, Electrical systems and turbostarter.
An Automatic Test Equipment (ATEC) can be proposed for trouble-shooting and SRU replacement and repair validation of Electronic equipment.
Engine maintenance : it consists in visual inspections on the installed engine at O/L every 150 operating hours and periodical inspections on modules at I/L (engine workshop) at 600 operating hours and then every 300 hours. The modules are replaced according to their **condition** or their remaining potential.
Engine life monitoring computers (HUMS) are now offered to take benefit of the maximum potential of the modules (and not the "safe potential" independent of what they have actually experienced). This option is clearly a cost saver. The potential is computed as a function of the mechanical fatigue, the thermal fatigue and the oligocyclic fatigue. Such a computer not only allows a reduction of maintenance cost (reduced consumption of spares), but also gives a warning of expiring potential to the mechanics.
The depth of maintenance performed by the Customer is adapted to his requirements and facilities. It includes at least engine overhaul and repairs using conventional equipment but repairs with advanced or sophisticated equipment can be proposed with SNECMA approval and confidentiality agreements.

4 - The field - proven Supportability characteristics :
Traditionally, the Air Forces do not like to see their operational parameters published. Similarly the AAF takes part to NATO exercises or joint operations which have stringent confidentiality rules . Therefore we are obliged to give only anonymous synthesized information to simply show how our systems behave. This paragraph is the shortest of the presentation but by far the most important because it gives **demonstrated** results.
After more than 750 000 hours flown, we can state that **Safety** , **Reliability** and **Maintainability** are the most obvious qualities of MIRAGE 2000 :
- Attrition rate smaller than 0.5 for 10 000 flight hours, which is excellent for a single engine aircraft. Within this rate, **only 25%** of the accidents are due to **technical** reasons, the remaining 75% being due to Human Factors (surprisingly, this distribution is similar on Civil Aircraft).
-Mean Flight Hours Between Failures MFHBF = 6.8
-Mean number of sorties without failure (France) : 5
- Direct Maintenance Hours/Flight Hour for O/L and I/L DMMH/FH= 8 to 10 depending on the exact definition of the maintenance cycle applied (about 11 demonstrated in the AAF with its organisation - see Ref 1- but with A/C towing tasks included in the servicing, 8 with the new Export Maintenance Plan based on the same tasks durations).
Another obvious measure of the overall MIRAGE 2000 Supportability is the small volume of Hardware and People deployed to operate it . Without revealing military secrets, the MIRAGE 2000 behaviour in RED FLAG exercises is

our main pride : the highest number of laurels with the smallest team and logistic footprint.
Several above figures largely exceed the qualitative Supportabilty Requirement which was to improve by 50% the MIRAGE F1 characteristics. They compare favorably with what we know about the competing aircraft of similar performance. They are not in contradiction with some comparisons made in open publications but the hypothesis of which must be checked carefully. For instance we saw a comparison of DMMH/FH for the highly respectable F18 and the older design MIRAGE 3 : they are simply not of the same generation and not in the same Supportability Requirements class.

5 - Optimisation of LCC :

5.1 - LCC approach

Many manuals, including LSA guides, describe the Life Cycle Cost analysis tasks, and everybody agrees on the following general decomposition of program costs :

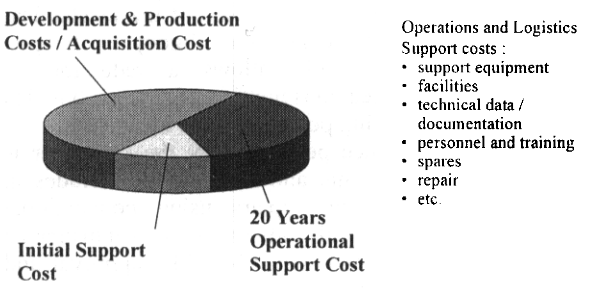


Figure 7 : Life Cycle Costs

Nowadays, most Air Forces need the cheapest operations and logistics support during the operational phase of the aircraft life without impairing the operational readiness. This is achieved with a progressive Life Cycle Cost approach through each stage of the product development.
During the predevelopment phase, the operations and logistics support costs are estimated to determine at least the trends in costs evolution. Feedback of in-use systems support costs and technology evaluations are used for such an analysis.
This assessment of the system supportability would mainly call the specified aptitudes in question again. So, both the main system and its support are optimised.
At the detailed definition level, the architecture, testability and maintainability of equipment are optimised and some detailed cost models can be used for the critical equipment, mostly the less reliable.
Finally, models are used to achieve a better optimisation of the support solution for specific customer's operations and organisation in order to reduce the support costs.

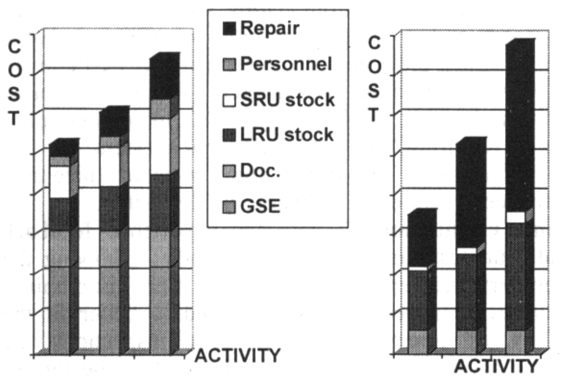
5.2 - Customer Support Solution optimisation

We try to use COTS tools or models when they are not dealing with our core activity. CESAR model (Coût Efficacité du Soutien d'un système d'ARmes), developped by the "Délégation Générale pour l'Armement" (part of French MoD), is such a model.

One potential use of this steady state model is to assess **the trade-offs** between the cost of Intermediate Level facilities (electronics workshop,...) and the cost of spares and industrial services (repair, inspection,...) **allowing the user to have the same availability level**.
Entries for the calculation are :

- the aircraft logistic tree : Line Replaceable Units (LRU), Shop Replaceable Units (SRU), components,... with their aptitudes (default rate, discard rate, inspection rate,...),
- the support tasks at Organisational, Intermediate or Depot Level with their metrics (ground crew, ground support equipment, documentation, training, durations, costs,...),
- the user operations and logistics environment : aircraft's activity, aircraft's and workshops' organisation with their metrics (movement time, turn-around time,...).

It computes the level of stocks according with a security rate, the mean availability according with the average waiting time due to spares shortage and the support costs per flight hour.
The following figures show the study of trade-offs between a workshop cost and other support costs.



Costs **with** workshop   Costs **without** workshop

Figure 8 : Electronic equipment support costs on a 15 years period

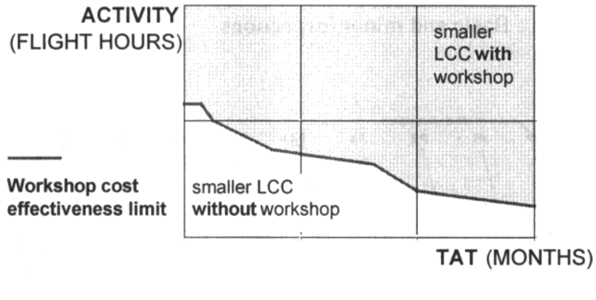


Figure 9 : Workshop cost effectiveness limit on a **15 years** period

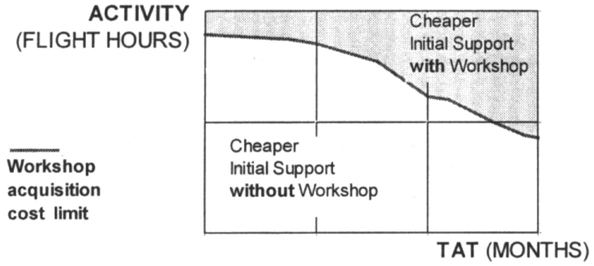


Figure 10 : Workshop acquisition cost limit for **initial** support

The following figure shows the study of trade-offs for different configurations of a workshop.

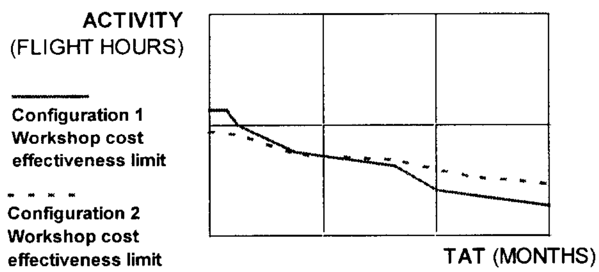


Figure 11 : Workshop's options cost effectiveness limit on a **15 years** period.

With these figures, the program managers are able to decide the better purchase within economic constraints and operational needs :

- to implement the workshop as soon as possible,
- to postpone the acquisition of the workshop until a second batch of aircraft,
- to choose the best configuration of a workshop,
- or to buy industrial services.

5.3 – Cost modelling limitations.

The modelling quality depends heavily on support and costs data base.

Support data are compiled from the tasks analysis study, but you can't afford to wait for detailed data to analyse costs in the first design phases.

Likewise some approximation is used for costs because it's difficult, and expensive, to maintain up-to-date costs for all items.

For those reasons, two types of models are used :

- complete model to analyse the main factors for costs (with low level of details).
- detailed (but limited) model to optimise the important costs for the customer, among others the expense in foreign currency as opposed to local costs (personnel,...).

6- Conclusion :

Theoreticians of Logistic Support Analysis will have the satisfaction to see that this presentation does not contradict the MIL - STD - 1388-1A methodology for ILS. It has shown the importance of the user involvement and of the Support consideration in the early phases of Specification and Design. Though the methodology was not strictly formalised in documents, MIRAGE 2000 **took benefit** of this involvement for a **good Supportability in design** which has been **demonstrated** on the operational field. It has also shown that a Maintenance Plan is a living document which receives its value from experience feedback allowing to reduce the Maintenance costs without impairing safety and that further cost reductions are coming from the optimisation of the Logistic Solution to the Customer needs.

Today, owing to these actions, **MIRAGE 2000 is a proven low LCC** weapon system with superb **Availability**. Tomorrow, taking benefit of a true ILS Methodology, MIRAGE 2000 experience feedback and improved technologies, the twin-engine **RAFALE will rank better** in terms of Supportability. And for the day after tomorrow, as **Affordability** has to be proven before the program starts, we build the **tools** to prove the Customer that our virtual flying objects are their best future investment.

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2 - The safe pilot environment of the RAFALE fighter (French Aerospace 90 conference -Washington June 1990)

Design Optimization using Life Cycle Cost Analysis for Low Operating Costs

Khalid A. Khan (P. Eng., MCASI)
Graeme D. Houston (P. Eng., DAR)

Bombardier Aerospace, 123 Garratt Boulevard, N46-11, Downsview, Ontario, Canada M3K 1Y5

With the increase competition among airlines to capture the customer base, more and more airlines demanding the aerospace industry to produce aircraft with high reliability and low maintenance costs. Similarly, aircraft manufacturers that once had the monopoly in various sectors, that is, small & large jets, propellers, business jet are now facing fierce competition. In response to airline industry, manufacturers are increasingly paying more attention to optimize new and current designs to improve reliability while low operating cost aircraft. This paper covers one of several methodologies available to optimize the design of an aircraft. The Life Cycle Cost (LCC) analysis is a powerful tool that has been used extensively on two new designs at Bombardier Aerospace. Several publications are available in public domain covering theoretical aspects of Engineering Economics, including Life Cycle Cost.

The Life Cycle Cost analysis is a systematic approach in applying engineering economics to determine the best solution for a design over the useful life of the aircraft, from an economic standpoint. There are may approaches available in the academic media, however, some of the economic variables that are used in almost all LCC analyses are:

Cost of borrowing money
Present Value
Depreciation
Break-even point
Discount Rates
Interest Rates
Insurance costs
Taxes
Etc.

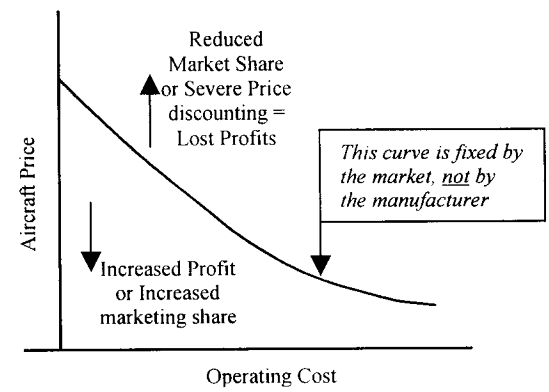
This paper covers a practical approach to LCC analysis and an in-house developed model is presented here using an example to illustrate the construction and use of the methodology in aerospace industry. However, the computerized model is developed in such a way that minor modification to the model can lead to many other applications outside the aerospace industry.

The LCC analysis methodology and model was developed in 1988 at de Havilland, a division of Bombardier Aerospace, by Reliability & Maintainability Engineering for use in a multi-disciplinary design environment. It provides a rigorous analysis methodology to evaluate relative merit / benefit and manage risk. In addition, it provides a means of comparing effects of parameter that are normally not compared (For example, weight Vs MTBF).

Life Cycle Costing is a systematic process for identifying the most cost-effective utilization of available resources over the entire product life cycle, that is womb to tomb. The methodology used in the LCC model also allows a systematic process for evaluating and quantifying the cost impacts of various alternative courses of action for the decision makers in engineering, finance and program management.

In order to fully appreciate the value of LCC analysis, it is important to look at the economic evaluation of a product. For a new design project, from conceptual stage, Marketing performs product analysis to determine the type of aircraft and the features for which airlines are willing to pay. The requirements are developed by Marketing and presented to Engineering where the marketing requirements are converted into design requirements and objectives. The market base is also established by Marketing in terms of units that are likely to be sold at a baseline price and corresponding operating costs. From the LCC point of view, for equivalent financial productivity, aircraft price can be traded off against the operating costs as shown below:

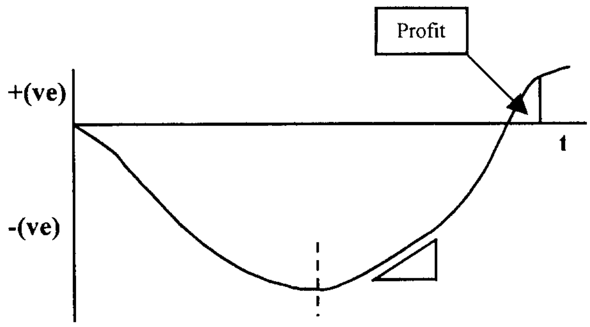
Figure 1: Aircraft Price Vs Operating Cost



It is apparent from the above chart that as the operating cost increases, the company has only two options, that is, either to discount the price of the aircraft or to improve the operating costs. The operating cost consists of Ownership, Fuel, Crew, Insurance, Maintenance Cost, etc. The ownership costs include financing, spares holding equipment acquisition, etc. The Maintenance Cost is normally 14% to 22% of the operating cost and can be controlled by a cost-effective design.

In order to fully appreciate the usefulness of the LCC analysis, it is important to understand the economic benefit. Cash Flow analysis is perhaps one of the most important tool in the decision making process. The following is a portion of a Cash Flow chart from a program.

Figure 2 – Program Cash



At the onset of a new design or a modification of the existing design, non-recurring costs will drive the negative cash flow. In addition, if recurring costs are not understood and managed properly, the negative cash flow will impact the profitability of the program. Therefore, the slope of the curve is a function of:

Aircraft Price – Cost

Where cost consists of:

- Manufacturing costs
- Bill of Material
- Support

Therefore, in order to maximize the profit, design must be optimized. To have a good and cost effective design, it is imperative to consider all costs from womb to tomb of a product. There are three major areas of costing that covers the entire life cycle of the product. These are:

1. Acquisition Cost

Acquisition costs consists of items such as Research & Development, which includes Initial Planning, Marketing Analysis, Feasibility Study, Engineering Design, etc. Also included in acquisition costs is Production Construction costs such as, Operation Analysis, Facilities, Logistics Support, Customer Support, etc. Some or all of the variables are used in the model depending on the project requirements.

2. Operation and Maintenance Costs

Operation costs are related to the activities required to produce the product for the end user. Typical costs include Production, Marketing & Sales, transportation etc. On the other hand, Maintenance costs are those costs that are incurred in supporting the product. It consists of, Customer Service, Maintenance, Spares, Support Equipment, Modifications, Training, etc.

3. Retirement and Disposal

These costs also fall under product support and consist of costs related to Non-Repairable Items, System/Product Retirement and Material Recycling.

METHODOLOGY

The LCC analysis used at Bombardier provides a rigorous "Bottom Up" work statement driven analysis, that can be compared with program objectives to:

- Close the loop
- Assess Risk
- Determine if further work is required

The methodology allows engineers and program managers to reconcile with program financial analysis to make sound design and/or investment decision.

Application

The basic LCC analysis is applied when:

- There is a requirement to spend money due to some technical or operational requirement and several options are available.
- There is a "Status quo" or existing condition and an investment can be made for some recurring benefit (i.e. Current Cost Reduction Exercise).
- The alternatives are complex and the cost / benefit is unclear, or risk is high.

Normally, the benefits of LCC analysis are most prevalent where large sums of money is involved and several variables, such as procurement cost, manufacturing costs, maintenance costs, etc. can influence the outcome. If the design change is minor and the benefits can readily be identified, an LCC analysis is not required. However, engineers with training in economics, in particular LCC analysis, are known to produce well-balanced design.

LIFE CYCLE COST MODEL

The LCC model requires several steps and inputs from various functions within the organization. For simplicity, the model presented here is for an existing Engine Instrument System consisting of 30 components. Three options are available, each with different recurring and non-recurring costs. The objective of the analysis was to reduce the operating costs and improve the reliability of the system. The benefit was deemed to be increased market share and profit for the aircraft type.

MODEL INPUTS

The following is a list of aircraft and economic variables used in this model and are applicable for the commercial aircraft design.

Base Year: The year project starts. Used in the Cash Flow Analysis.

Market Base: Number of aircraft expected to be sold during the economic study period. Used in the model to calculate Total Program Cost.

Average Fleet Size: The number of aircraft an airline will buy on an average. Is used in the spares cost calculation.

Annual Utilization: Average flight hours per year used in MTBUR, MTBF, NFF and DMC calculations.

Cost of Money: Cumulative effect of elapsed time on money value of an event, based on the earning power of equivalent invested fund. This factor is used to discount the costs to their present values

Economic Study Period: Number of Years the life cycle cost analysis is based on.

Manufacturing Labour Rate: Labour Cost ($/MH) used in the calculation of non-recurring cost and manufacturing installation.

Flight Test Rate (years): Cost of performing a flight test to verify the installation/operation of a component or system ($/Flt hr). Used in non-recurring cost calculation

Spares Holding Factor: Used to calculate the cost of holding the inventory. This cost is part of the operating cost.

Insurance Factor: A factor used for held inventory.

Repair Turnaround Time: Average time in days for an item send to a repair facility, repaired, and returned to the owner. Used in spares requirement calculations.

Airline Labour Rate: Specifically, the labour rate ($/MH) for the maintenance personnel. Used in direct maintenance cost calculation.

Cost of Flight Delays: The cost incurred by airlines to accommodate the passenger due to a delay or cancellation. The information can be obtained from Customer Support.

Annual Inflation Rate: Annual inflation rate expressed as percentage. The inflation rates are available from US Bureau of Labour Statistics on the internet.

Airline Income Tax Rate: Airline income tax rate expressed as percentage. Used to calculation the tax amount that can be deducted from the operating cost.

Depreciation: Percentage decline in value of a capitalized asset for each year. Used to calculation the tax amount that can be deducted from the operating cost.

Cost of Weight: Impacts the performance of the aircraft resulting in lower payload and increased fuel consumption.

Cost of Fuel: Used in the calculation of "Cost of Weight".

Non-Recurring Period: The length of the project including planning, design, certification, manufacturing, installation and delivery of the product.

Spares Margin: Markup on the spares in terms of percentage.

Aircraft Delivery Schedule: Used in the Cash Flow Analysis and to determine the break-even point.

Design Hours: Direct cost by engineering staff for each discipline such as Electrical, Avionics, Hydraulics, etc. Used in the calculation of Non-Recurring costs.

COMPONENT DATA

In addition to the variables listed above, component data is required to calculate the Recurring and Non-Recurring costs. The integrity of the data is important in the LCC analysis to arrive at good results. Sanitized historical data is available from airlines and agencies collecting and processing airline data to produce data/analysis for publications. Most large companies will collect data on an on-going basis to monitor their products. Following is a list of the data used and/or calculated in the model.

Weight: The weight of each component used in the calculations of the operating costs over the economic life of the aircraft.

Purchase Price: The acquisition cost normally has a higher weight on the outcome of LCC analysis. The source of this information is usually the procurement department or can be obtained directly from the supplier.

Spares Price: The spares price is one of the important costs to the end user since the procurement cost is only available to the Original Equipment Manufacturer (OEM). The markup on the spares could be substantial and must be carefully evaluated and designed to maximize the use of the component in the field.

Mean Time Between Failures (MTBF): This is a calculated value using statistical methods and is based on the component failure and utilization data. An exponential distribution is assumed. This is used in the DMC calculations. MTBF is calculated as follows:

$$MTBF = \frac{\text{Total Flying hours in a period}}{\text{Total Failures}}$$

Mean Time Between Unscheduled Removals (MTBUR): This is a also a calculated data using statistical methods and is based on the component unplanned removal due to a malfunction and utilization data. This data is used in the DMC calculations. MTBUR is calculated as follows:

$$MTBUR = \frac{\text{Total Flying hours in a period}}{\text{Total Unscheduled Removals}}$$

Repair Cost: The average repair cost to restore the component to its design specification. Used in calculating the operating costs.

No Fault Found Cost: This type of expense by the user of the product can be controlled by a good design where Build-in test circuit can avoid removing a good unit from the aircraft. Good troubleshooting techniques built into the maintenance manual can also minimize this cost.

Delay Rate (DR): The number of flights that were delayed beyond the actual departure time plus 15 minutes versus the total scheduled flights. This information is used in the calculation of Delay cost. The delay rate is calculated as follows:

$$DR = \frac{\text{Total Flights delayed in a period}}{\text{Total Flights; same period}}$$

Downtime Rate (DTR): The time aircraft is not available for revenue service due to a component malfunction causing delay. The downtime rate is calculated as follows:

$$DTR = \frac{\text{Total Downtime in a period}}{\text{Total Delays; same period}}$$

Spares Exposure (SE): The spares exposure is based on the Poisson Distribution and is used to calculate the spares required by the airlines to operate their fleet. The spares exposure is calculated as follows:

$$SE = \frac{TAT * AU * AFS * QPA * 1/MTBUR}{365}$$

Where,

- TAT= Turnaround Time (days)
- AU = Annual Utilization (Flight Hours)
- AFS = Average Fleet Size (No. of aircraft)
- QPA = Quantity Per Aircraft

Note: If the MTBUR is infinite then spares exposure is zero.

Manufacturing/Installation Cost (MIC): The time required by production labour to manufacture and/or install the component on the aircraft. MIC is calculated as follows:

MIC= Manuf/Installation time (hours) * Labour Rate

Spares Required (SR): The spares required to support the continuous operation of the product. In an ideal situation, if the component life is equal to the economic life of the product where the aircraft will be scrapped, then spare requirements will be zero. Also, If the MTBUR is infinite and the unit does not malfunction until the scheduled maintenance, then the spare requirement will also be zero.

Using Poisson Cumulative Distribution Chart, for 95% probability and spares exposure "SE", the spares required can be read off the chart. Alternatively, the following computer sub-routine can be used to have the model calculate the spares requirement:

$S = 0$ (Number of Spares)

$R = 0$ (Probability)

$$R = R + \frac{\text{Spare Exposure}^S \times e^{-\text{Spares Exposure}}}{S!} \quad (1)$$

if ($R > 0.95$) then Spares = S, otherwise $S = S + 1$ and goto (1)

where

$$\text{Spares Exposure} = \text{Repair Turn Around Time (Days)} \times \text{Annual Utilization (flts-hrs)} \times \text{Average Fleet Size} \times \text{Quantity per Aircraft}/365$$

and

assuming that 95% of time, all spares requirements can be satisfied.

Direct Maintenance Cost (DMC): The cost resulting from all direct maintenance performed on the component to restore it to its functional state. DMC is calculated as follows:

$$DMC = \left\{ \left(\frac{1}{MTBF} \times \text{Repair Cost} \right) + \left(\frac{1}{MTBUR} - \frac{1}{MTBF} \right) \times \text{NFF Cost} + \left(\frac{1}{MTBUR} \times \text{Line Labour Manhours} \right) \times \text{Airline Labour Rate} \right\} \times QPA$$

Delay Cost (DC): The cost of delay is significant to the airlines due to lost revenues and customer base. The delay cost is calculated as follows:

DC = DR * DTR * Expenses due to delay

Spares Cost (SC): The cost of Spares is calculate as follows:

SC = SR * Spares Price

SUMMARY OF COSTS

In general, the LCC model uses inputs typical of those generated by the functional departments in response to defined work statement such as non recurring man-hours and material, equipment purchase costs including the cost of spares, manufacturing labour costs, equipment reliability and repair costs, etc. at the system / component level. In addition, there are inputs that have a more global effect, and tend not to vary much for any given program. These are typically things like the cost of money, number of aircraft in a program, anticipated delivery rate, etc. Note that all inputs are treated as variables in the model. The total Life Cycle Cost in the model is summarized in Figure 3 and 4 by aircraft and by program respectively.

Figure 3 – Life Cycle Cost Summary by Aircraft

COST ELEMENT	Baseline	Option 1	Option 2	Option 3
Non-Recurring Program		$350,000	$250,000	$450,000
Non-Recurring per Aircraft		$1,750	$1,250	$2,250
Component Cost per Aircraft	$56,656	$45,440	$40,360	$50,520
Labour Cost per Aircraft	$18,880	$7,200	$7,200	$7,200
Initial Spares Cost per Aircraft	$7,816	$5,240	$4,640	$6,040
INVESTMENT COST/AIRCRAFT:	$83,352	$59,630	$53,450	$66,010
Direct Maint. Cost per Aircraft (Yr 0)	$11,814	$3,911	$3,911	$3,911
Delay/Cancellation Cost/Aircraft (Yr 0)				
Spares Holding Cost per Aircraft (Yr 0)	$782	$524	$464	$604
Insurance Cost per Aircraft (Yr 0)	$378	$272	$244	$300
Fuel Cost-Weight per Aircraft (Yr 0)	$2,508	$914	$914	$914
Miscellaneous (Yr 0)				
TOTAL OPERATING COST/AC (YR 0)	$15,482	$5,621	$5,533	$5,729
15 YR OPERATING COST/AC ($)	$132,518	$48,112	$47,360	$49,036
Depreciation ($/Yr)				
Tax Adjustment (Yr 0)				
TOTAL LIFE CYCLE COST/AC	$215,870	$107,742	$100,810	$115,046

The total operating cost per aircraft in Figure 3 is distributed over the life of the product (15 years in this example) and discounted to convert yearly cost into present dollars, that is, Present Equivalent Value (PEV). Standard financial formula (Cost of Money – see Inputs) is used to calculate PEV in this model. An example is presented here in Figure 4

Figure 4 – Operating Cost Analysis

	Baseline:	Baseline System			
YEAR	YEAR 'n' ($)	CUMULATIVE P.E.V ($)	DISCOUNT FACTOR YEAR 'n'	OPER COST YEAR 'n'	TAX ADJ. YEAR 'n'
0	83,352	83,352	1.0000	0	0.00
1	14,335	97,687	0.9259	15,482	0.00
2	13,273	110,961	0.8573	15,482	0.00
3	12,290	123,251	0.7938	15,482	0.00
4	11,380	134,630	0.7350	15,482	0.00
5	10,537	145,167	0.6806	15,482	0.00
6	9,756	154,924	0.6302	15,482	0.00
7	9,034	163,957	0.5835	15,482	0.00
8	8,364	172,322	0.5403	15,482	0.00
9	7,745	180,066	0.5002	15,482	0.00
10	7,171	187,238	0.4632	15,482	0.00
11	6,640	193,877	0.4289	15,482	0.00
12	6,148	200,026	0.3971	15,482	0.00
13	5,693	205,718	0.3677	15,482	0.00
14	5,271	210,989	0.3405	15,482	0.00
15	4,881	215,870	0.3152	15,482	0.00
TOTAL	132,517.67		8.5595		

In order to launch a program, the investment costs and operating costs must be clearly understood at the program level by business and financial mangers. Therefore, the program cost is calculated by multiplying the number of aircraft (as dictated by the program) by the aircraft level costs as shown in Figure 5.

Figure 5 – Life Cycle Cost Summary by Program

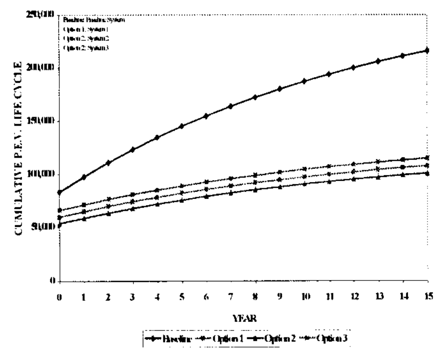
COST ELEMENT	Baseline	Option 1	Option 2	Option 3
Non-Recurring Program		$350,000	$250,000	$450,000
Recurring: Program:				
Component Cost	$11,331,200	$9,088,000	$8,072,000	$10,104,000
Labour Cost	$3,776,000	$1,440,000	$1,440,000	$1,440,000
Initial Spares Cost	$1,563,240	$1,048,000	$928,000	$1,208,000
TOTAL INVESTMENT COST:	$16,670,440	$11,926,000	$10,690,000	$13,202,000
TOTAL OPERATING COST - FLEET:	$26,503,533	$9,622,473	$9,471,998	$9,807,187
TOTAL PROGRAM COST:	$43,173,973	$21,548,473	$20,161,998	$23,009,187

ANALYTICAL MODEL OUTPUTS

1. Life Cycle Costs

Based on the input values, the model computes the Life Cycle Costs from the aircraft Operator's standpoint on a "per aircraft" basis. The model attempts to capture the costs of particular options from "womb to tomb". A typical example is shown in Figure 6.

Figure 6 – Life Cycle Cost Comparison



The "Year 0" value on the graph represent the operator's investment, including the appropriate share of the non-recurring, the cost of equipment and installation, and the cost of initial provisioning. The graph displays the investment cost and the cumulative operating costs. The 15 year values represent the total Life Cycle Cost for the particular option, in "present value" dollars, since this is the only way to fairly compare options where investment and operating costs can vary significantly.

2. Cash Flow

The Cash Flow Analysis has been designed specifically for the situation described earlier, where there is a baseline (status quo), (existing instrument system with approximately 30 components), and we are considering investing in a new instrument system for some benefit. The model has been designed to compare three alternatives to the declared baseline in a manner such that for any given option, non-recurring costs are evenly distributed over a specified period, and then the investment is recovered (or not) as a function of the cost savings per aircraft of the new system.

For the cash flow analysis, aircraft recurring and program non-recurring costs are used and distributed over the cash flow analysis period. A sample of the cost distribution worksheet is presented in Figure 7.

Figure 7 – Cash Flow Analysis Worksheet

	Baseline	Option 1	Option 2	Option 3
NON-RECURRING/PROGRAM:	0	350,000	250,000	450,000
RECURRING/AIRCRAFT:	72,957	50,911	46,029	55,727
NON-RECURRING MONTHS:	0	12	12	12

Baseline:						Option 1:							
MON	PLANNED DELIV	ACTUAL DELIV	CUM DELIV	CASHFLOW BY MONTH	YEAR END TOTAL	MON	PLANNED DELIV	ACTUAL DELIV	CUM DELIV	CASHFLOW BY MONTH	DELTA CASHFLOW BY MONTH	CUM DELTA CASHFLOW BY MONTH	YEAR END TOTAL
1	2.00	2.00	2.00	-145,913		1	2.00	0.00	0.00	-29,167	-29,167	-29,167	
2	2.00	2.00	4.00	-145,913		2	2.00	0.00	0.00	-29,167	-29,167	-58,333	
3	2.00	2.00	6.00	-145,913		3	2.00	0.00	0.00	-29,167	-29,167	-87,500	
4	2.00	2.00	8.00	-145,913		4	2.00	0.00	0.00	-29,167	-29,167	-116,667	
5	2.00	2.00	10.00	-145,913		5	2.00	0.00	0.00	-29,167	-29,167	-145,833	
6	2.00	2.00	12.00	-145,913		6	2.00	0.00	0.00	-29,167	-29,167	-175,000	
7	2.00	2.00	14.00	-145,913		7	2.00	0.00	0.00	-29,167	-29,167	-204,167	
8	2.00	2.00	16.00	-145,913		8	2.00	0.00	0.00	-29,167	-29,167	-233,333	
9	2.00	2.00	18.00	-145,913		9	2.00	0.00	0.00	-29,167	-29,167	-262,500	
10	2.00	2.00	20.00	-145,913		10	2.00	0.00	0.00	-29,167	-29,167	-291,667	
11	2.00	2.00	22.00	-145,913		11	2.00	0.00	0.00	-29,167	-29,167	-320,833	
12	2.00	2.00	24.00	-145,913	-1,750,960	12	2.00	0.00	0.00	-29,167	-29,167	-350,000	-350,000

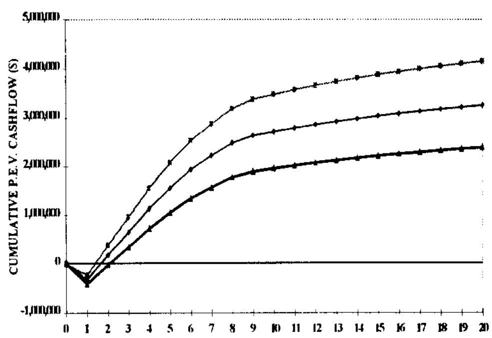
The yearly cash flow for each option is then compared with the baseline and the delta Present Equivalent Value is calculated for each year in the cash flow study periods shown in Figure 8. These values are then used to construct the cash flow chart for analysis.

Figure 8 – Cash Flow Comparisons

YEAR	Baseline: YEAR END TOTAL	Option 1 vs Baseline YEAR END DELTA	Option 2 vs Baseline YEAR END DELTA	Option 3 vs Baseline YEAR END DELTA	Option 1 vs Baseline DELTA P.E.V.	Option 1 vs Baseline DELTA CUM P.E.V.
0	0	0	0	0	0	0
1	-1,750,960	-350,000	-250,000	-450,000	-324,074	-324,074
2	-1,969,830	595,238	727,052	465,206	510,321	186,247
3	-1,969,830	595,238	727,052	465,206	472,519	658,766
4	-2,188,700	661,376	807,836	516,896	486,131	1,144,897
5	-2,042,786	617,284	753,980	482,436	420,113	1,565,010
6	-1,969,830	595,238	727,052	465,206	375,101	1,940,111
7	-1,605,046	485,009	592,413	379,057	282,998	2,223,109
8	-1,605,046	485,009	592,413	379,057	262,035	2,485,144
9	-1,021,393	308,642	376,990	241,218	154,398	2,639,542
10	-583,653	176,367	215,423	137,839	81,692	2,721,234
11	-583,653	176,367	215,423	137,839	75,641	2,796,874
12	-583,653	176,367	215,423	137,839	70,038	2,866,912
13	-583,653	176,367	215,423	137,839	64,850	2,931,762
14	-583,653	176,367	215,423	137,839	60,046	2,991,808
15	-583,653	176,367	215,423	137,839	55,598	3,047,406
16	-583,653	176,367	215,423	137,839	51,480	3,098,886
17	-583,653	176,367	215,423	137,839	47,666	3,146,552
18	-583,653	176,367	215,423	137,839	44,136	3,190,688
19	-583,653	176,367	215,423	137,839	40,866	3,231,554
20	-583,653	176,367	215,423	137,839	37,839	3,269,393

Figure 9 below displays the non-recurring expenditure, until the new system cuts in, at which point, the graph displays the cumulative difference in recurring costs between an option and the baseline. The graph depicts the net present value of a given investment at any point in time, and the break even point is indicated where a curve crosses the x-axis. In the example below, all three alternatives represent the new instrument system, however, each used a different non-recurring cost, and a different procurement cost.

Figure 9 – Cash Flow Comparisons



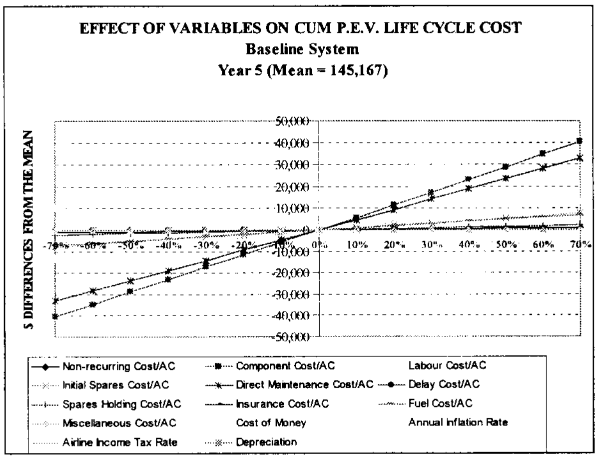
THE POWER OF ANALYTICAL MODELLING

The true power of the model becomes evident once the inputs have been entered. Although the inputs are treated as "hard" numbers, at the conceptual / preliminary phase of the program, they are anything but hard numbers. In fact, apart from existing configurations with established historical data, the inputs are predictions, each with its own degree of uncertainty.

Sensitivity Analysis

The model has a built in sensitivity analysis where iterative process is used to change one variable at a time while holding the rest constant. In this particular example, the program goes through approximately 92,000 iterations to generate Cash Flow charts for each year against the variation criteria used, such as ± 0% to 70%. An example is presented in Figure 10, below:

Figure 10 – Sensitivity Analysis



Depending on the end result of interest, it is relatively straightforward to determine cost driving parameters. As a matter of practice, it is prudent to explore a range of input values for the cost drivers in order to test the sensitivity of the result to that variation. In addition, this should be repeated for inputs with the highest degree of uncertainty. The cash flow example in this paper exemplifies this type of exploration where a ± 30% variation in non-recurring costs exerts little influence on the result, but ± 10% variation in the procurement cost of the new instrument system has a marked effect.

Depending on the desired level of savings, a "must not exceed" purchasing cost can be established. On the other hand, if a cost driver had a high degree of uncertainty, it may be worthwhile to conduct a more detailed evaluation to reduce the uncertainty. In any event, the model has been designed to cater to "what if" types of exploration at the push of a button, permitting efficient assessment, and management of risk.

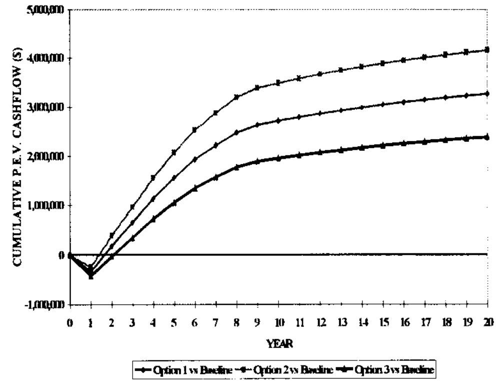
Note that the model has been described in terms of a "systems" level analysis. However, any number of these can be rolled up to a program level analysis.

RISK ASSESSMENT

In its present form, the model treats the inputs as exact values, and computes an exact output. In reality, each input represents a "point estimate", or mean value, with its own variation. However, it is possible to use the model as a foundation for numerical risk assessment, as follows:

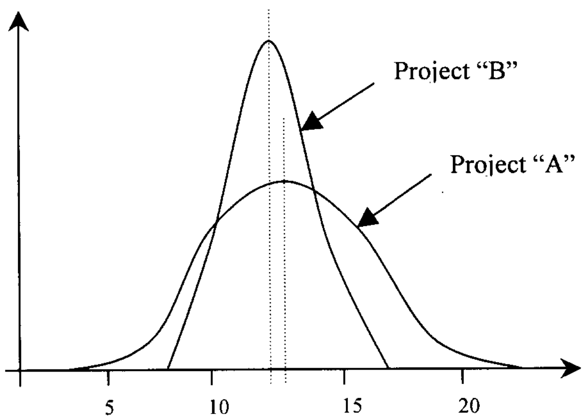
For each input, three values are obtained; optimistic, expected, and pessimistic. These inputs are used to create three scenarios, that is, most favourable, expected, and least favourable. These can be considered analogous to +3 sigma, mean, and −3 sigma for a normal statistical distribution. While at first glance this might appear to be a crude approximation, it matches the precision of the inputs one is likely to receive, and as long as the "mean" lies in the middle of the distribution, the assumption of a normal distribution has merit. It is now possible to generate an output distribution for a particular project or opportunity. For example purposes, the distribution is superimposed on the Engine Instrument example in Figure 11 below

Figure 11 – Cash Flow Comparisons



This process can be applied to several different projects and the results superimposed on one another as shown in figure 12 below. Since the curves for the two projects are mathematically defined, numerical assessment of risk is possible once consequences are established.

Figure 12 – Risk Assessment



CONCLUSION

Life Cycle Cost Analysis is a powerful tool used to optimize the design for increase profitability and market share. It is a structured process that allows the user to collect and analyze all aspects of the design and financial variables to realize a well-balanced product.

In Aerospace industry, Life Cycle Costing is becoming increasingly important since airlines are no longer willing to pay for inefficient design and high operating costs.

Engineering can play a major role in increasing profit through LCC analysis. At the conceptual design stage, this type of study can be used to select a most LCC efficient configuration. That is lowest Bill of Material for the best economic value.

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AIRCRAFT DESIGN TO OPERATIONAL COST

Stéphane Gosselin
Aérospatiale Matra Airbus
316 Route de Bayonne, P.O. Box M9132
31060 Toulouse Cedex 03
France

COMPANY BACKGROUND

Aerospatiale Matra Airbus is a subsidiary of the Aerospatiale Matra group which was created in 1999 from the merge between Aerospatiale and Matra Hautes Technologies. Aerospatiale Matra Airbus is involved in the design, production and support of Airbus products within Airbus Industrie.

Airbus Industrie is a European consortium of industries from four different European nations: Aerospatiale Matra Airbus from France , DaimlerChrysler Aerospace Airbus from Germany, British Aerospace from Great Britain and CASA from Spain.

Airbus Industrie is involved in other partnership within Europe for the development of a military transport aircraft.

INTRODUCTION

The method that will be presented to you is used on Airbus products.

The aim of this presentation is to give you an overview and some indications on the process and the associated tools that we have developped to ensure that the design of our products is coherent with the operators expectations in term of operational costs.

The presentation will first show the evolution of the market and of the operators expectations that drove the emergence of the Integrated Logistic Support concept. This will be followed by a description of how we have adapted this concept in a very pragmatic procedure applicable to military transport as well as commercial aircraft design. The five steps of the procedure will then be detailed. An overview of the existing tools and of the environment in which this procedure is applied will follow.

OPERATORS EXPECTATIONS AND ILS CONCEPT

The basic operators objectives when they choose an aircraft are to transport a specified number of passengers or materials loads (CAPACITY) on defined routes (RANGE) with a minimum acceptable level of availability of the aircraft (MISSION & DISPATCH RELIABILITY). The aircraft must be certified with an expected level of SAFETY. It should provide a high PASSENGER COMFORT, produced low emissions and noise (ENVIRONMENTAL IMPACT) and have a low FUEL CONSUMPTION. The evolution of the market toward a very concurrential situation between the operators have brought an additional very important requirement from the operators for low OPERATIONAL COSTS. This is a major issue in their financial success and the aircraft itself is driving a large portion of these costs. Direct Operating Costs (DOC) is thus a major criteria for operators in their purchasing decision.

Direct Operating Costs (DOC) are those expenses supported by the operators directly for the operations of the aircraft. They exclude indirect expenses such as facilities amortization and indirect administrative personal. They include the following costs:
- Acquisition & financial costs related to the purchase of the aircraft, engine, spares initial provisioning and specific maintenance tools.
- Maintenance costs related to direct labor and materials expenses induced by scheduled and unscheduled maintenance activities whatever the location they are performed (line, base, shop or contractor). It also includes the indirect burden induced by maintenance activities, such as management, planning, storage, engineering, energy and customs.
- Insurance costs related to aircraft, spares and tools.
- Fuel expenses required to operate the aircraft.
- Crew wages (technical and cabin crew).
- Landing and navigation charges.

Maintenance costs are the portion of DOC where the aircraft manufacturer has one of the greatest potential field for improvement in reducing the DOC. Maintenance cost represents approximately 13 to 18% of the direct operating costs of a commercial aircraft. Maintenance costs induced by an aircraft are highly related to the aircraft design, engine selection, vendor selection and maintenance concept.

Integrated Logistic Support (ILS) is a concept of program management, initially developed for military program. It aims at integrating up front in the development of the aircraft the tasks that will ensure that the final product (the aircraft and its support elements such as spares, technical publications, maintenance, tools, GSE and training) will be optimized in term of operational costs and will fulfill the operators requirements regarding operational reliability and safety. ILS concept is as well formalizing the planning and management tasks for the development of the support elements.
This approach was a clear evolution from the past approach when maintenance and support elements design were considered once the aircraft design was frozen. The final product was not at that time optimized against operational objectives.

The ILS concept was adapted to military transport aircraft and commercial aircraft development. The adaptation of the concept is what we call the "Design to Operational Cost Process". The objective is to provide guidance to the designers in order to ensure that the estimated operational cost induced by the design choices will be within a predetermined target.

DESIGN TO OPERATIONAL COST PROCESS

The Design to Operational Cost Process is split into five steps: The first steps are conducted up front of the design and their results are to provide inputs to the designers (design requirements). The procedure starts with the settlement of a global target operational cost for the aircraft (Step 1) which is broken down to the lowest level required to match the design responsibility breakdown (Step 2). Then design requirements

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

should be selected in accordance with the target to be met and transmitted to the designers (Step 3).
The next steps are conducted down stream of the design activities. It starts by a maintainability analysis which is verifying that the choices are in accordance with the target (Step 4). The last step closes the loop in validating the achievement or in modifying the allocation of targets (Step 5).

The presentation that will follow is mainly describing the application of the procedure to a new aircraft. However this procedure is as well applicable for a modification to an in-service aircraft.

The operational cost data gathered from the field on in service aircraft are the "raw material" for most of the steps of this procedure. Without this feedback it is very difficult to ensure that this approach will result in real significant benefits for the operators.

The knowledge and collection of in service aircraft operational costs allows:

- To define a global operational cost objective for a new aircraft by comparison to the known position of other aircraft (Step 1).

- To split up this global objective from the experience of operational costs distribution on previous aircraft (Step 2).

- To identify the design requirements that would ensure that the objectives will be met (Step 3).

Without this feedback it is very difficult to ensure that this approach will result in real significant benefits for the operators.

STEP 1
The global DOC target has to be set and broken down to isolate the maintenance cost portion which is one of the areas where the aircraft manufacturer has the strongest impact.

STEP 2
Then from the new aircraft general characteristics and the experience of in service aircraft, an estimated baseline is issued and compared to the global operational cost target. If the estimated baseline is not matching the global target it may be indicating that the target is not achievable with the proposed general aircraft characteristics and that a review of these characteristics may be required. If both the baseline and the target are equivalent, we have a first breakdown of detailed objectives by ATA.
The method we use to estimate a baseline for a new design is based on parametric relations between operational costs and aircraft general characteristics. These relations were established from the data gathered on in-service. A relation has been defined for labor costs and for material costs for system and for the airframe based on a total of around 20 parameters for the whole aircraft. In the example shown on the bleed air system, operational costs are evaluated from a relation with the total thrust. The dots on the graph are plotting the operational costs of this system for different aircraft of different total thrust. In this case we have chosen a linear regression.

The predicted operational costs of any new aircraft may be estimated with this type of relations for every system and for the airframe. In order to control the impact of the flight length, the annual use, the sharing between on and off aircraft maintenance, the labor rate and efficiency, we are using adjustments factors that allow us to tune all costs to similar operational and environmental conditions.

The depth to which the global target must be broken down depends on the design activities and commercial work sharing. For example:
- For system designers or global subcontractors, a breakdown to the ATA chapter level is acceptable.
- For equipment purchasers, a breakdown at equipment level for off aircraft work is expected.
- For maintenance engineering a breakdown by maintenance level is required.
- For program management a target by top cost drivers items is required.

STEP 3
This step is an engineering activity in close relation with the designer. The objective of this task is to translate the quantitative operational cost target into "words" (technical targets, commercial targets, design rules or recommendations) that are understood and applicable by the designers or the purchasers.

The technical targets are mainly linked to the interval to which a maintenance action will have to be performed and to the duration of the task. These targets may be on the mean time between unscheduled removals (MTBUR), the mean time between failures (MTBF), the mean time to repair (MTTR), the scheduled task interval, the BITE definition, the balance between the on-board maintenance system and the ground maintenance system.

The commercial targets are mainly related to the parts price and to the guarantee related to product support (DMC, spare price, MTBUR).

The requirements are related to accessibility of the items, maintenance test equipment and specific maintenance tools, level of repair, drainage, corrosion protection, repairability, interchangeability and standardization.

STEP 4
This step is the first one of the bottom-up approach: it starts from a design proposal and it consists in analyzing the associated reliability, maintenance and repair costs characteristics and evaluating the operational cost result. The maintainability analysis may also be conducted qualitatively in providing guidance to the designers to improve maintainability.

This step may also be conducted to compare two or many proposals to highlight the benefit of one solution compared to the others and initiate a trade-off on DOC to select the solution that will offer the greatest advantages. This trade-off may be performed for example between different concept maintenance, between different technical solutions or to optimize the balance between reliability and repair costs.

STEP 5

The last step of the procedure is a comparison of the estimated operational costs resulting from the maintainability analysis with the detailed targets. If the detailed objective at a lower level can not be reached, a decision to reallocate the objective at the next higher level may allow to match the global objective. The aim of this step is to monitor the objective consolidation process in order to ensure a clear follow-up of the achievements all along the aircraft development.

The first step of the procedure which is the settlement of a global target should be launched as soon as the project is launched as it is one of the high level program decision and that the challenge is to influence very up front the design decisions. The detailed target breakdown are derived from the global target and should be set prior to the selection of product concept. The maintainability design requirements are established from the detailed targets. As soon as a target is set, the associated requirements should be defined and we have considered that all requirements have to be set before the first metal cut. The maintainability analysis are linked to the design solutions and will start from the definition of the basic concept up to the end of the development. The objectives consolidation is linked to the results of the maintainability analysis and is in line with it on the milestone plan.

TOOLS AND ENVIRONMENT

This procedure is supported by many tools and methods and by a qualified staff. The in service experience is recorded in databases collecting data on operational interruptions, operational costs, reliability and pilots reports from the operators and/or from the suppliers. From this experience we have established operational costs baselines and an associated derivative method. We are recording all the supportability design requirements in a data base in order to record them for new programs. As for the contract we have harmonized in a standard format all the product support guarantees in order to better monitor the achieved results. An operational cost evaluation model was developed to perform analysis on proposed new design solutions. We are as well using level of a repair analysis model and a qualitative analysis model.

Most of our design office staff were trained to strengthen the customer oriented mindedness in their design tasks. We are working in teams integrating design engineers, purchasers, product support specialists, suppliers and customers. A concurrent engineering team is developing the tools to manage a program workflow linked to our CAD (computer aided design) system.

CONCLUSION

Direct operating costs are a major issue for operators in their purchasing decision and industrials must focus on this concern to remain competitive. The maintenance costs are a major contributor to operational costs and it has been demonstrated that design improvements can reduce maintenance costs. This can be performed during design by a formalized approach called "Design to operational cost". This procedure relies on the data on good and bad experience that operators are feeding back to the industrials. The results are to the benefit of the operators that will gain in profit margin and competitiveness.

AEROSPATIALE MATRA AIRBUS

AIRCRAFT DESIGN TO OPERATIONAL COST

Stéphane GOSSELIN
AEROSPATIALE MATRA AIRBUS

AEROSPATIALE MATRA AIRBUS

AIRCRAFT DESIGN TO OPERATIONAL COST

CONTENT OF THE PRESENTATION

- 1. EVOLUTION OF OPERATORS EXPECTATIONS
- 2. DESIGN TO OPERATIONAL COST PROCESS
  - 2.1 Global target
  - 2.2 Detailed target breakdown
  - 2.3 Maintainability design requirements
  - 2.4 Maintainability analysis
  - 2.5 Objectives consolidation
- 3. TOOLS AND ENVIRONMENT
- 4. CONCLUSION

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AIRCRAFT DESIGN TO OPERATIONAL COST

1. EVOLUTION OF OPERATORS EXPECTATIONS

BEFORE

- HIGHEST SAFETY
- REQUIRED RANGE and CAPACITY
- LOW ENVIRONMENTAL IMPACT
- HIGH PASSENGER COMFORT
- HIGH DISPATCH RELIABILITY and MISSION RELIABILITY
- **LOW FUEL CONSUMPTION**

NOW

- HIGHEST SAFETY
- REQUIRED RANGE and CAPACITY
- LOW ENVIRONMENTAL IMPACT
- HIGH PASSENGER COMFORT
- HIGH DISPATCH RELIABILITY and MISSION RELIABILITY
- LOW OPERATIONAL COSTS

DIRECT OPERATING COSTS ARE A MAJOR ISSUE FOR OPERATORS IN THEIR PURCHASING DECISION

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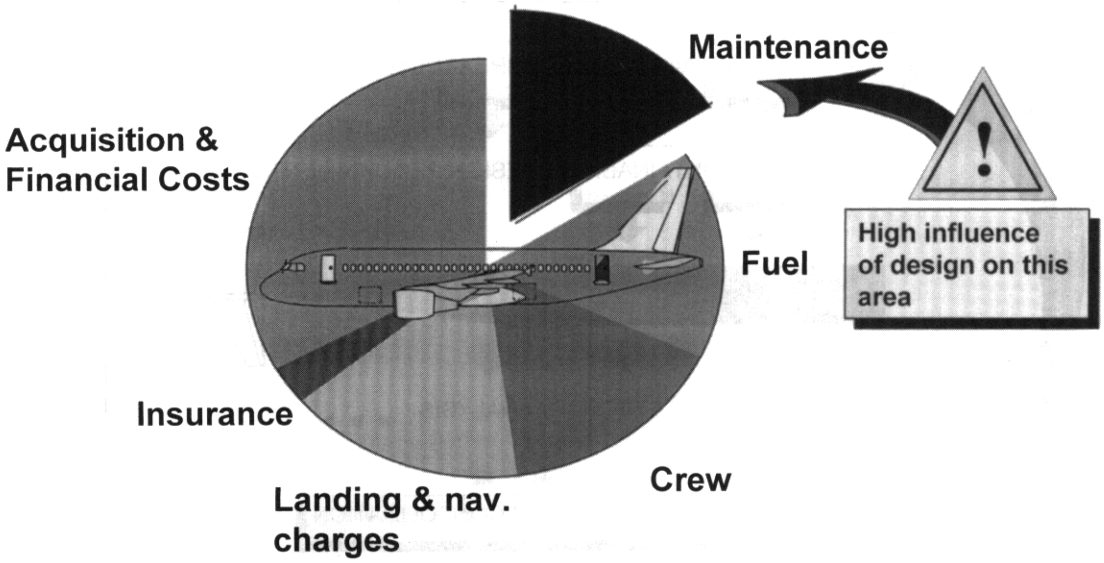
AIRCRAFT DESIGN TO OPERATIONAL COST

1. EVOLUTION OF OPERATORS EXPECTATIONS (Cont)

DIRECT OPERATING COSTS BREAKDOWN



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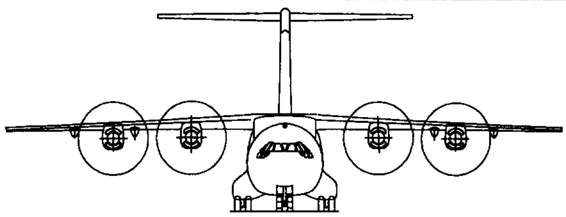
3. DESIGN TO OPERATIONAL COST PROCESS

CONTROL THE OPERATIONAL COST (and more specifically maintenance cost) BY INFLUENCING THE DESIGN TO REACH THE COST OBJECTIVE FOR THE OPERATORS



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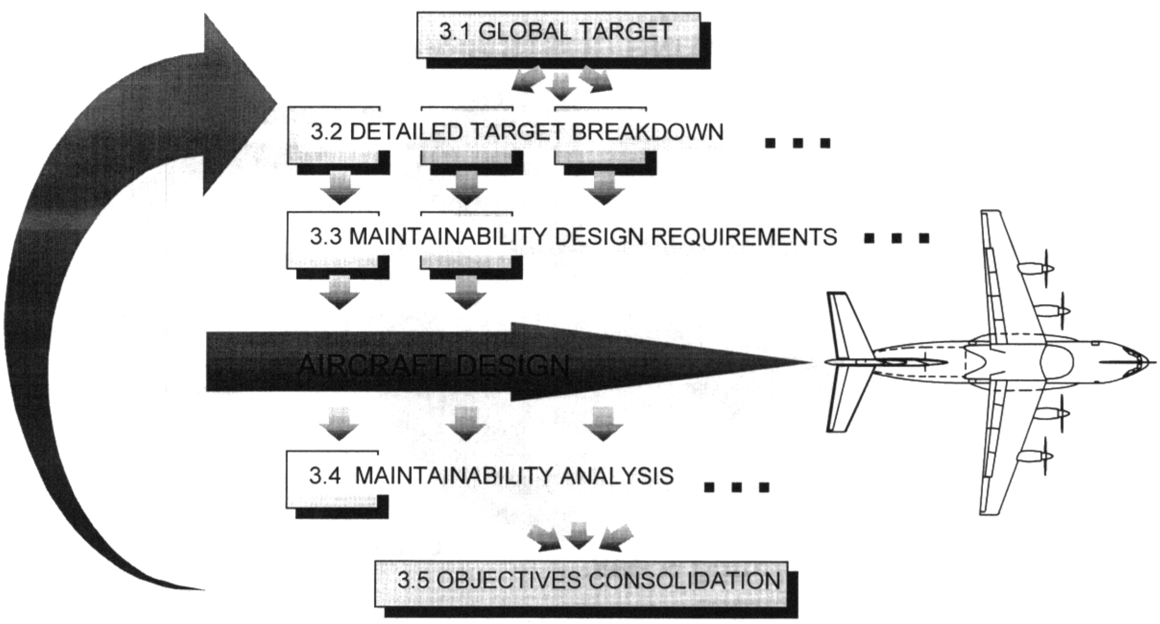
3. THE PROCESS STEPS



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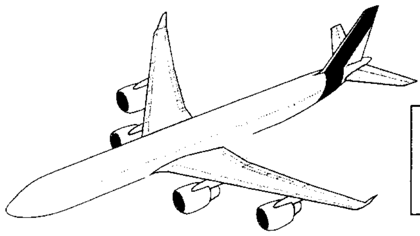
AIRCRAFT DESIGN TO OPERATIONAL COST

3.1 GLOBAL TARGET

Aircraft A: D.O.C. OBJECTIVE: -25% PER SEAT- MILE COMPARED TO Aircraft B



Aircraft A PROGRAM TARGETS:
- **TOTAL QUALITY (A/C & SUPPORT ELEMENTS)**
- **- 15% D.O.C. PER TRIP COMPARED TO PREVIOUS TYPE**

Aircraft A SUPPORT TARGETS: "MUST REQUIRED LESS THAN X MAINTENANCE MAN HOURS PER FLIGHT HOUR »

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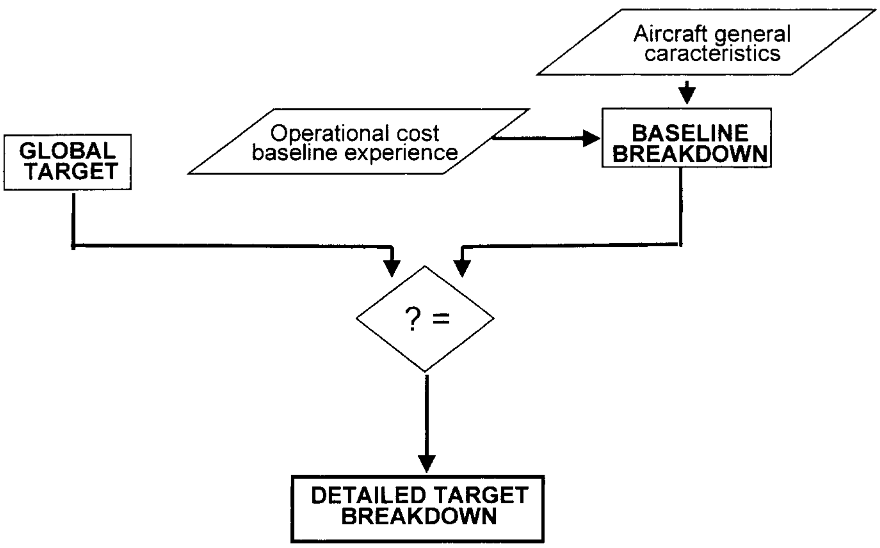
AIRCRAFT DESIGN TO OPERATIONAL COST

3.2 DETAILED TARGET BREAKDOWN



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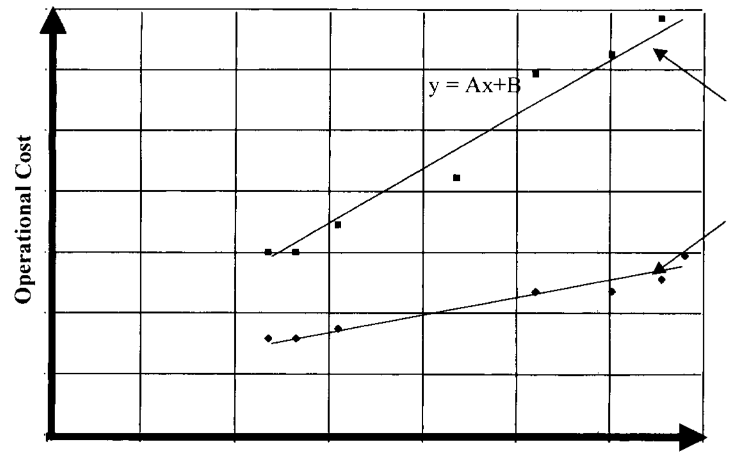
3.2 DETAILED TARGET BREAKDOWN (Cont)

Example of parametric approach: ATA 36 Bleed Air System



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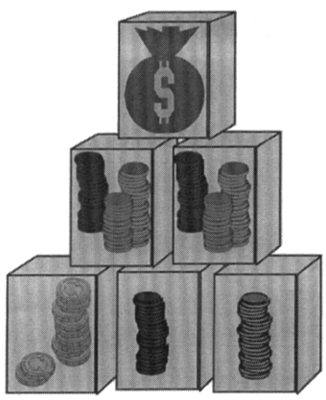
3.2 DETAILED TARGET BREAKDOWN (Cont)

Example of breakdown views for direct maintenance costs (DMC):



- DMC by ATA for labor, material
- DMC by maintenance level (A to C checks, higher checks, line...)
- DMC by manufacturer (industrial worksharing, GCP for vendors)
- DMC for cost drivers

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3.2 DETAILED TARGET BREAKDOWN (Cont)

BASELINE:

		LABOR			
ATA description	ATA	On A/C%	Hourly%	Use%	AT
AIR CONDITIONNING	21				2
AUTO FLIGHT	22				2
COMMUNICATIONS	23				2
ELECTRICAL POWE	24				2
EQUIPMENT/FURNIS	25				2
FIRE PROTECTION	26				2
FLIGHT CONTROLS	27				2
FUEL	28				2
HYDRAULIC POWER	29				2
ICE/RAIN PROTECTI	30				3
INSTRUMENTS	31				3
LANDING GEAR	32				3
LIGHTS	33				3

DOC breakdown by ATA chapter

Average sector	X	FH
Annual util =	Y	FH
Labor rate =	Z	$
Labor Eff =	W	
Material usage :	V	

	BASELINE			BASELINE	
ATA	Labor	Mat.	ATA	Labor	Mat.
Line	$$	$$	52	$$	$$
21	$$	$$	53	$$	$$
22	$$	$$	54	$$	$$
23	$$	$$	55	$$	$$
24	$$	$$	56	$$	$$
25	$$	$$	57	$$	$$
26	$$	$$	71	$$	$$
27	$$	$$	72	$$	$$
28	$$	$$	73	$$	$$
29	$$	$$	74	$$	$$
30	$$	$$	75	$$	$$
31	$$	$$	76	$$	$$
32	$$	$$	77	$$	$$
33	$$	$$	78	$$	$$
34	$$	$$	79	$$	$$
35	$$	$$	80	$$	$$
36	$$	$$	36	$$	$$

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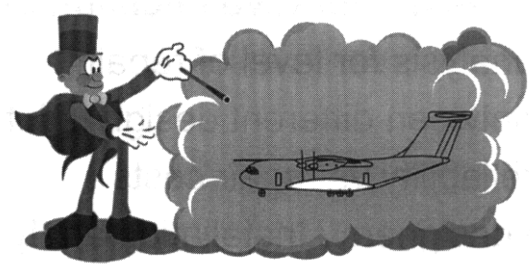
AIRCRAFT DESIGN TO OPERATIONAL COST

3.3 MAINTAINABILITY DESIGN REQUIREMENTS

- **Translation of the detailed cost targets into requirements applicable by the designers:**
  - Technical targets
  - Commercial targets
  - Design rules or recommendations



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3.3 MAINTAINABILITY DESIGN REQUIREMENTS (Cont)

- Technical targets:
  - MTBUR, MTBF, MTTR, scheduled maintenance tasks interval, BITE performance, global performance of on board + ground maintenance system, ...
- Commercial targets:
  - DMC, spare prices, repair prices, ...
- Design rules or recommendations:
  - Accessibility, associated tools and test equipment, repairability, drainage, corrosion protection, interchangeability, standardisation, physical breakdown (repair level), ...

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3.4 MAINTAINABILITY ANALYSIS

- **Evaluation of maintainability / maintenance costs**
  - Bottom-up approach for operational cost evaluation from reliability, maintenance program and repair costs data
  - Maintainability qualitative analysis
- **Trade-off for design iterative decision process:**
  - Trade-off analysis for level of repair
  - Trade-off between different design solutions
  - Trade-off reliability vs repair costs
  - Support to designers / Installation analysis

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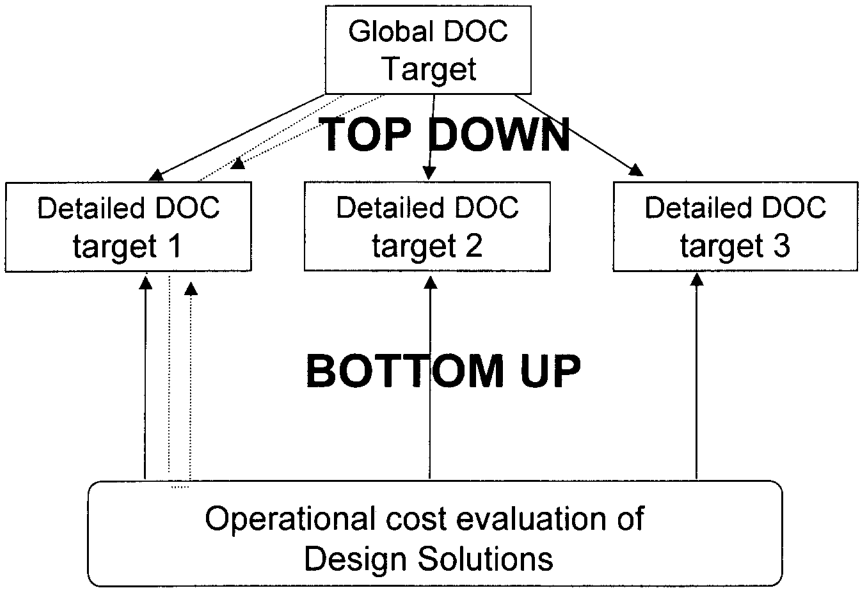
3.5 OBJECTIVE CONSOLIDATION



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4. TOOLS AND ENVIRONMENT

- In service experience database (Operational interruptions, Maintenance Costs, Reliability, Pilot reports)
- DMC Baselines
- Derivative method
- Design requirements database
- General conditions of purchase
- Operational cost evaluation model
- Level of repair analysis
- Qualitative maintainability analysis

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AIRCRAFT DESIGN TO OPERATIONAL COST

5. TOOLS AND ENVIRONMENT (Cont)

- Training / concurrent environment
  - Development of customer oriented behaviour by sensibilisation training of all staff on customer mindedness
  - Integrated teams: customers / design engineers / purchasers / product support / vendors
  - Concurrent engineering workflow

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AIRCRAFT DESIGN TO OPERATIONAL COST

6. CONCLUSION

- Aeronautical industries must focus on operational cost to remain competitive
- Design can have a major impact on maintenance cost which is a significant element of operational cost
- There has been success in reducing maintenance costs by a formalized consideration of them during the design phase
- Operators gain in competitiveness

"REQUIREMENTS, DESIGN FEATURES AND MANUFACTURING TECHNIQUES LEADING TO REDUCED OPERATIONAL COST FOR ADVANCED MILITARY AIRFFRAME STRUCTURES"

M. Voglsinger
E. Mennle
G. Blas

DaimlerChrysler Aerospace AG,
Military Aircraft Division
P.O. Box 80116
81663 München, Germany

0 Introduction

Reliability has a key role to play in successful deployment of the Eurofighter/Typhoon, because its air force customers are relying on improved availability rates, and therefore buying fewer aircraft than would previously have been required.
A set of M, R + T-requirements derived from previous in-service-aircraft-programmes has been established, amended by new technology potentials and airforce customers demands.
Selected design criteria, design features and manufacturing techniques supporting the goal of reduced operational cost are detailed below.

1 Requirements affecting operational cost

Life Cycle Costs (LCC)
Life Cycle Cost assessment plays a increasing role in the acquisition of aircraft both for military and commercial operators.
Military and commercial customers emphasise the need to optimise cost and benefit ratios from the feasibility phase up to the in service phase.
An extrapolation of Life Cycle Cost of existing aircraft over a 30 years in-service period shows an impact of Logistic Support Costs of about 60 %.
(see fig 1.1) Extrapolation of LCC

Consequently a main aspect of the Life Cycle Cost optimisation process is the reduction of Costs for Logistic Support. This fact is reflected in an appropriate product support concept which is based on qualitative and quantitative requirements.

RM&T requirements
The consideration of following qualitative requirements has a substantial influence on the aircraft downtime, the necessary maintenance effort, the number and complexity of required Ground Support Equipment and the amount of spare parts.
Reliability requirements:
- Safe Life Design
- Fail Safe Design / Damage Tolerance
- Optimisation of defect rate by
  - Corrosion prevention / protection
  - Selection of adequate materials
  - Analysis and assessment of stress profiles

Maintainability Requirements:
- Accessability (on and off aircraft), (structure + equipment)
- Ergonomic aspects
- Repairability
- Modularity
- Standardisation
- Interchangeability
- Replaceability
- Simplicity of design

Testability Requirements:
- Structural Health Monitoring (service life vs. design life)
- Onboard data processing capability
- Parameter exceedance monitoring capability

The realisation of those requirements by application of logistic support methods from the beginning of the concept

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

phase leads to significant reduction of logistic support costs.

The quantification of specified requirements in comparison to logistic parameters of existing aircraft provides target features to be met.
(see fig. 1.2)

Quantification is performed using mathematic models and comparable data of aircraft already in service. Allocation of different aircraft parameters (e.g. defect rates, maintenance man hours / flying hour etc.) are a measurement for the reliability and maintainability features of an aircraft and their impact on the Life Cycle Costs. Those figures show the expected aircraft parameters in an early stage of the aircraft development phases.
(see fig. 1.3) M-Allocation

2 Design Principles and Criteria

As already mentioned above the operational cost of an A/C play a significant role especially in the environment of restricted military budgets.
By the time the design of a combat aircraft is frozen a large percentage (about 80 %) of the life-cycle costs have been predetermined. Therefore, to meet the challenge of low in-service costs, consideration to the above must be given at an early stage in the design phase.
Product support considerations are already included in the structural design criteria and are covered by the applied design principles.
Developing and designing a high performance aircraft itself is a complex process with inputs and requirements from many disciplines. In opposition to this, the operational cost considerations are providing conflicting requirements. The final product is a compromise between all inputs and aspects from technical and support disciplines.
Life-cycle costs are directly related to fatigue and damage tolerance calculations. In addition to these also the accurate definition, establishment and simulation of design loads within the flight envelope, the consideration of aeroelastic effects and in general the accuracy of the analysis methods that are used influence the operational cost of a combat A/C.

2.1 Damage Tolerance (Composite Structure)

The general damage tolerance requirements are considered in the A/C design by adopting the following measures:

- Structural redundancy
- Selection of materials and methods of design with low sensitivity towards external effects and with good resistance to damage growth
- Design methods assuring that details are not prone to damage by impact, environment or abnormalities in manufacture

In addition, the specified Bird Strike capability has to be guaranteed.
Since a large extent of the outer surface is designed and built from CFC material, it is necessary that impact damage is considered in the design of these structural items.
The primary problem of composite structures is that a damage caused by a low velocity impact may not be visible. This means a delamination caused by the impact cannot be seen with naked eye but needs detection by NDT.
Visible damage on a monolithic structure will generally be repaired and the strength of the structural part will be restored.
Non-visible damages will remain in the aircraft structure and it has to be ensured that these damages never lead to failure of the structure within the service life of the A/C.
The visibility threshold for composites may lie around 0.2 mm indentation depth but nevertheless depends on the surface properties. Generally it is not deemed suitable to base a damage tolerance criterion for monolithic structures on the visibility of impact damages. A better approach therefore is to identify the potential impact risks within individual zones of the structure and then design the airframe accordingly.
For sandwich structures with their typical thin skins however, a low energy impact, e.g. 8 J, may already produce indentations of about 1mm depth that are well visible.
The possible impact energies have to be established by assessing risks resulting from normal routine, everyday servicing of the A/C and normal operating threats.
Table 2.1 presents the established impact energies based on an assessemten as mentioned above.

In order to cover the effects of these occurrences, damage tolerance design allowables have to be established accordingly. They are considerably lower than the laminate strength and are based on compression

after impact test results. The compression after impact allowable depend on both the impact energy and the laminate thickness.
For tension strength, the reparability requirement already covers the damage tolerance requirement.
The damage tolerance allowables are used to design the structure. The qualification of the structure and the validation of the damage tolerant design is performed by static and fatigue testing.
This is done by incorporating representative impact damages in structural test components. A schematic "Route to Impact Resistance Verification" is shown in Chapt. 5.1

2.2 Fatigue Design (Metal Structure)

The fatigue behaviour of an A/C during the whole in-service life is influencing the operational costs to a large degree. A good fatigue design covering all the different requirements and considering the operational usage, as specified in the contract, of an A/C is therefore very important.
The requirements regarding fatigue are established in the Durability Criteria which form an important part of the Weapon System Specification.
The important requirements are specified as *Flight Hours, Number of Landings, Service Life and Mission Profiles.*
In case of Eurofighter/Typhoon a "Safe Life " Design is required .
In order to meet this requirement safe fatigue endurance curves (SN-curves) have been used by applying a scatter factor of 3 on life at the low endurance/high amplitude region of the SN-curve and a factor of 1.4 on strength at the high endurance/low amplitude region of the SN-curve .
Very early in the design process, fatigue allowable stresses based on the specified life/spectra for different metallic structural features (stress concentration factors and materials) have been generated.
Detailed fatigue calculations are performed to recognise and understand at an early stage the possible problematic areas and to guarantee the endurance of the A/C. At fatigue critical areas detailed FEM investigations are performed to identify local load paths and stress concentrations.
The fatigue life analysis is supported by fatigue testing of structural items.
All identified problems and damages are leading directly to a redesign of the affected structural part.
The validation of the fatigue design is based on the fatigue analysis and on the result of the extensive fatigue test programme. The final fatigue strength qualification is demonstrated by a full scale fatigue test (MAFT) and associated major fatigue tests. It has to be demonstrated that the full static strength (100 % D.U.L.) can be achieved after testing for twice the required aircraft life additionally the structure must sustain 80 % D.U.L. after completion of the fatigue test of 3 aircraft lives.
The fatigue verification including a schematic "Route to Fatigue Verification" is treated under Chapt. 5.2.

Operational costs can also be reduced by fulfilling the Inspection-free Concept which requires:

- The structure during its operational life shall not develop cracks or damages requiring attention under the design loading spectrum and environmental conditions so that no specific scheduled preventive structural inspections for fatigue are necessary
- Scheduled structural inspections for purposes other than fatigue shall be by visual inspection only. It is a design aim that all parts of the structure shall be accessible for inspection and rectification
- New methods of construction shall not cause the need for extra scheduled inspections or contravene the safe life philosophy.

In order to fulfil the Inspection-free Concept of the structure the described procedure has to be applied by considering fatigue aspects from the beginning of the design phase of a new A/C.

2.3 Structural Health Monitoring System (SHMS)

Based on the Safe Life concept the occurrence of fatigue cracks within the specified A/C life is considered to be improbable. This concept undoubtedly yields reasonable overall results however incidental fatigue damages including cracks continues to occur.
One main cause for such unexpected fatigue problems is considered to be the difference between in-service load spectra and specified design assumptions over an usage life of 25 —35 years with increasing tendency for modern A/C.
Therefore Eurofighter/Typhoon will be equipped with a Structural Health Monitoring System (SHMS).

The SHMS performs real time fatigue calculations based on flight parameters and/or strain gauge responses and determines the life consumed by the airframe. Significant structural events and flight performance parameters (auxiliary data) are also monitored. Comparisons between fatigue design assumptions and in-service load spectra will be performed in the Ground Support System (GSS) on squadron level for each A/C. In addition the GSS supports engineering staff in the maintenance of the A/C.

2.4 Corrosion Prevention Plan

A permanently improved Corrosion Prevention Plan evolved from previous civil and military programmes has been applied for:

- material selection / combination
- design rules
- protective measures

Attention has been paid to the combination of aluminium alloys and composite structures.

3 Design features

Design features contributing to a significant reduction of operational costs are described below.

3.1 Maintainability / Accessibility on Aircraft/off Aircraft

Reliability. maintainability and testability were given the same priority as aircraft performance and cost.

Product support considerations have influenced the design of the Eurofighter Typoon from the beginning. Accessibility is the key feature to achieve excellent maintainability together with sufficient clearance for the standard hand tools.
The general structural concept takes into account, that the equipment bays are positioned in eye / chest level working height.
(see Fig. 3.1)

M, R + T consideration have been influenced permanently by the International Air Force Field Team. M, R + T improvements or non-compliances have been described in a maintainability observation sheets prior to their design incorporation.

3.2 Repairability of Aircraft

An analysis of in-service A/C-structures at DASA indicated following major damage modes:

- Corrosion
- Fasteners / latches (wear, locking device)
- Fatigue

The aircraft structure is designed using standard metal materials or composites materials to ensure availability along the whole life cycle.
For repairability high loaded structure prone to be damaged is designed in the following way:

- edge distance for connecting bolts is increased 2 times bolt diameter plus 1 mm
- machined parts which have reinforcements in web areas are designed with extra lands for repair solutions.

The aim is to design structures leading to reduced repair costs and consequently to reduced downtime.

3.3 Modular major components

The airframe structure consists of 6 major components:

- Forward fuselage	- Foreplane
- Centre fuselage	- Wing
- Rear fuselage	- Fin

These major components are designed to be completely equipped prior to final assembly operation. In addition most of the systems are already tested in the major component stage i.e. landing gear, fuel tank leakage tests, ...). This is to detect defects already in the major component stage of assembly. In case of severe damages replacement of major components with systems equipped is therefore possible.

3.4 Interchangeability and replaceability

Access panels and structural components exposed to potential damage are to be fully interchangeable (ICY) i. e. no trimming, drilling etc. is acceptable. A dedicated design as well as modern manufacturing techniques allowed a significantly higher percentage of fully interchangeable components.
The effects on operational cost are:

- Less spares required
- Reduced A/C-down time

3.5 Robust design solutions

- Extra landings in selected applications

- Anti wear provisions (bushings)
- No bonded joints for primary load pathes
- Conservative bolted joints
- Minimum bolt diameter 8 mm on removable panels
- Edge protections on composite structure for erosion

3.6 Integral fuel tanks

Integral fuel tanks, particularly in the fuselage, require extra attention in view of reliability of the sealing method, their testability and repair.

At least one barrier in the most critical areas can be resealed by reinjecting sealant-material.

(see fig. 3.6) Integral fuel tank sealing

3.7 Selection of material, semi-products and standard parts

For airframe structure only certified materials are used. The manufacturing processes are qualified and are of state of the art.

Advanced materials and processes are only used if the technology is qualified and risk is minimised.

The materials used in airframe structure are reduced to the minimum of types. Standard parts e. g. fasteners, latches and quick release fasteners are also reduced to a minimum of different types to improve supportability

Materials banned by the Montreal-Protocol are avoided. This is to reduce precaution efforts regarding health safety standards during the whole life cycle.

3.8 Digital Product Assembly

(see fig. 3.8)

With the start of designing the Eurofighter/Typhoon production aircraft, the participating companies decided to introduce the so called DPA (Digital Product Assembly) process.

DPA is the process/methodology which embodies the use of common CAD tools, common standards and procedures.

DPA ensures the simultaneous and controlled access to all engineering data both within the industry and the customers.

The inclusion of a „Product Data Manager" (PDM and the model technology provides the control mechanism needed to operate in a virtual A/C representation) (DMU = Digital Mock Up)

The main features of the DPA process are as follows:

- Part based design
- Solid modelling
- Company functions integrated
- Robust product configuration management
- Complete, nearly on line, visibility of the whole product to each user including the customers.

The selection of the tools plays an important role in order to work in a DPA environment.

3.8.1 Design Tools

The 4 participating companies have commonly decided to use

- CATIA for all geometric design tasks
- Mentor Graphics L-Cable for the electric design
- E3D for loom installation package

The selection of VPM (Virtual Product Model) as a local data manager with CATIA and 4D Navigator acts as an integrated system to provide to the customer a complete virtual training environment.

3.8.2 Product Data Manager (PDM)

Pending on the internal requirements each company have selected a PDM tool which fits their internal business.

However the main requirement for use in a DPA environment it has been ensured that the different PDM's have the following essential features for the necessary data exchange:

- Compatible capability in each tool
- STEP compatible
  - STEP tool will enable PDM's linked together electronically
- Common data model
  - Data requirements and formats
- Common integrated processes.

3.8.3 Implications

The process enables:

- On line near real time access to the weapon system data for all in service aircraft and pending deliverables.
- On line design support for repair incl. in service repair
- A configuration control system for each aircraft and networked between all operator locations and industry.
- Virtual training environment for ground crew

and aircrew.

- Step towards interactive technical manuals.
- Knowledge based fault diagnostic tools.
- Early identifications of spares for repairs.

This leads to the following benefits:

- Evolution from reactive support to proactive support.
- Significant increase in the final product quality.
- Common data
- Direct on line access to customer
- Improved customer support
- Reduced „Life Cycle Costs“

The DPA process is regarded as customer service orientated with the target of better response times and enhanced technical quality resulting in a higher aircraft availability.

4 Manufacturing Techniques

4.1 Manufacturing Techniques

The aim for affordable technology for improved products require an integrated approach of Engineering and Product Process Definition. The implementation of an integrated Quality Assurance Process, such as automated process control, on-line Non Destructive Testing, provides low-cost components at high quality. Available manufacturing techniques are showing significant improvements in terms of:

- Tolerances: Bolt pattern of mating interchangeable components can be NC-drilled separately
- Repeatability of processes
- Tolerances of steps and gaps
- Detectability of inherent failures/tolerances.

(see fig. 4.1) Foto YOMACH

4.2 Concurrent Engineering and Virtual Manufacturing Simulation

Emphasis in design has turned to concurrent engineering, design for maintainability, accessibility, and virtual manufacturing, producing verified manufacturable data based on the designed geometry.

4.3 Castings / Forgings

Castings provide great contribution to cost reduction since stereo-lithography became available consequently modular components can be provided in reduced lead time.

5 Qualification / Certification

The efficiency of the provisions incorporated in the design of the A/C structure to improve maintainability and to guarantee the required interchangeability of structural parts has to be demonstrated to the customer on a number of production A/C.

The qualification and verification of the "analytical" measures and methods applied to take care about the operational costs are part of the general qualification and verification process of the structure and is shown in Chapt. 5.1 and 5.2 respectively.

5.1 Damage Tolerance Verification

The shown flow chart gives an overview about the route to impact resistance verification or in other words the route to validate and qualify the applied damage tolerant design of the CFC structure.

(see fig. 5.1)

The applied process guaranties that the damage tolerance allowables used to design the structure, the development experience as well as the test results of the real CFC structure is considered and used in the design phase of the structural parts.

The verification is based on analytical and on qualification test results.

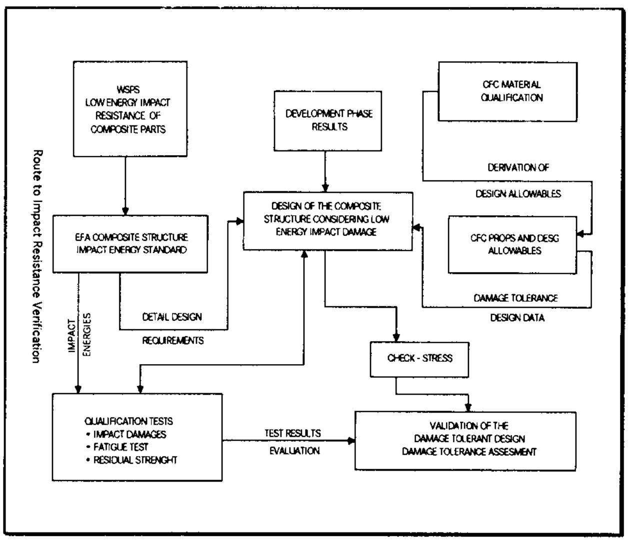

fig. 5.1

5.2 Fatigue Verification

The in *fig. 5.2* presented flow chart gives an overview about the route to fatigue verification of the airframe.
It is also guaranteed that in the early phase of the design process the fatigue allowables are available and are applied and that during the design phase the development experience, results from structural ground test programme (SGTP) as well as loads updates are considered.
The verification is based on the fatigue analysis supported by structural testing . The final qualification is performed by fatigue testing of a production standard airframe.

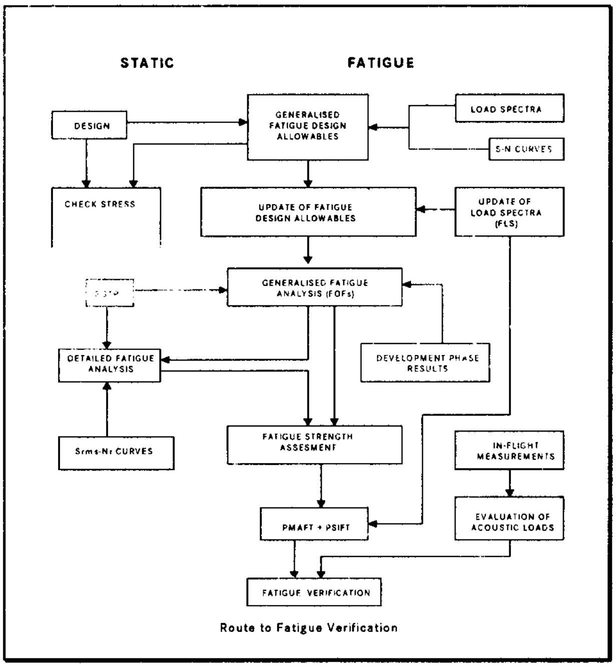

fig. 5.2

5.3 Interchangeability demonstration

For certification, interchangeability has to be demonstrated to the customer to verify full interchangeability between different aircraft after a defined minimum of flight hours. This is to ensure that flights in defined envelopes and normal wear will not result in structural deviations leading to a loss of interchangeability.

6 Summary

The impact upon life cycle cost become much more important and is affected by

- decreasing budgets available
- increasing energy cost expected
- increasing time between aircraft renewals

As a consequence any future product has to aim for:

- Nearly maintenance-free components
- Less expensive methods of inspection, preferably avoiding expensive tear-down
- Reduced repair costs as repair and replacement of components become more important affecting the requirements for replaceability and interchangeability
- Reduced down-time

DaimlerChrysler Aerospace

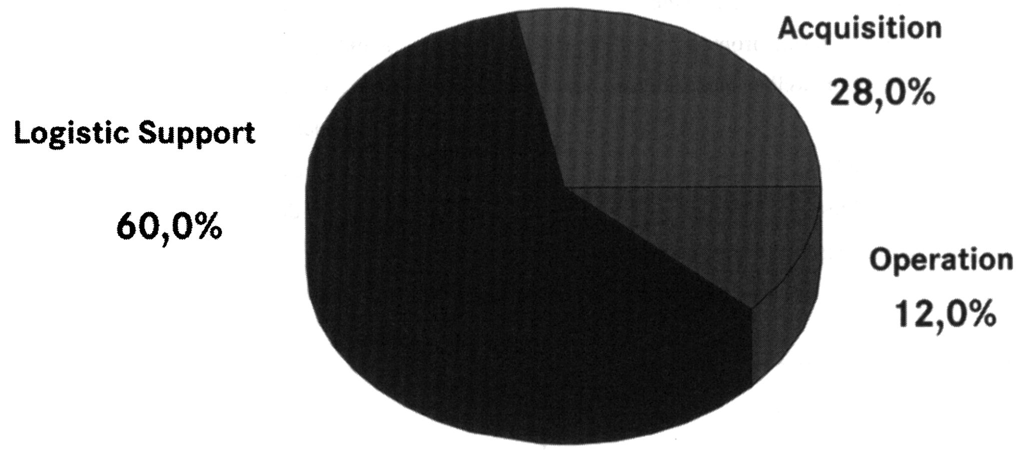

Fig. 1.1: Extrapolation of the Life Cycle Costs
(ass. 30 Years In-Service)

DaimlerChrysler Aerospace

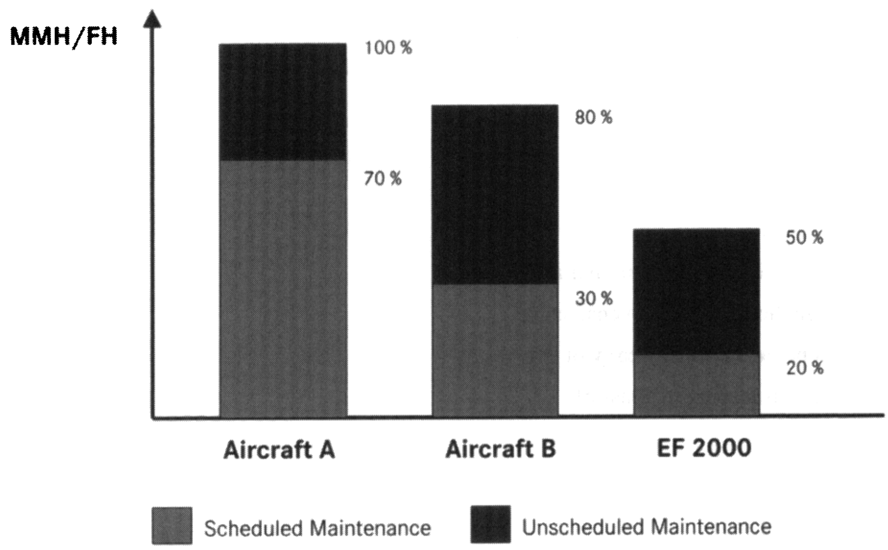

Fig. 1.2: Maintenance Effort

DaimlerChrysler Aerospace

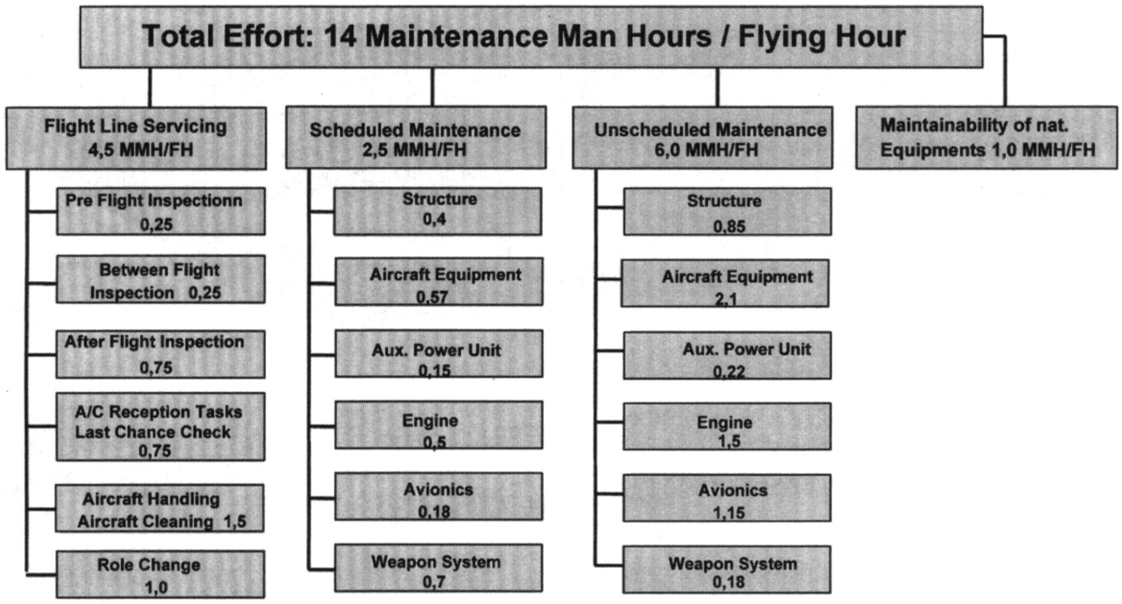

Fig. 1.3: M - Allocation

DaimlerChrysler Aerospace

SECTION	ZONE	ENERGY (JOULE)	IMPACT INCIDENTS COVERED
F/F	Sill	8	Normal servicing, Hail
	Bottom	8	Normal servicing
	Foreplane spigot region	20	Normal servicing, Installation
	Montage of Canopy region	20	Normal servicing, Hail
	Side skin	8	Normal servicing
	Radome	8	Normal servicing, Hail
C/F	CFC Skin Top	8	Hail
	CFC Skin remaining	20	Normal servicing
	Bottom panels	8	12,7 mm Dia Runwaystone
UPPER WING surface	Apex Region	8	Normal servicing, Falling tools, Hail
	Wing-Fuse Fairing	8	
	Skin (between Fairing and Y2100)	30	
	Flaperon (between Fairing and Y2100)	8	
	Skin (outboard of Y2100)	8	
	Flaperon (outboard of Y2100)	8	
LOWER WING surface	Apex Region	8	Normal servicing
	Wing Fuse Fairing	8	Runwaystone
	Main Wing Skin	17	Runwaystone
	Flaperon	8	Runwaystone
R/F	Top	8	Hail, Falling tools
FIN/RUDDER	Fin	20	Normal servicing
	Rudder	8	
	Precooler	8	
A/C	Internal Stucture	8 (minimum)	

Table 2.1: Potential Impact Damage Assessment

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Fig. 3.1: EF-Typhoon Maintenance

DaimlerChrysler Aerospace

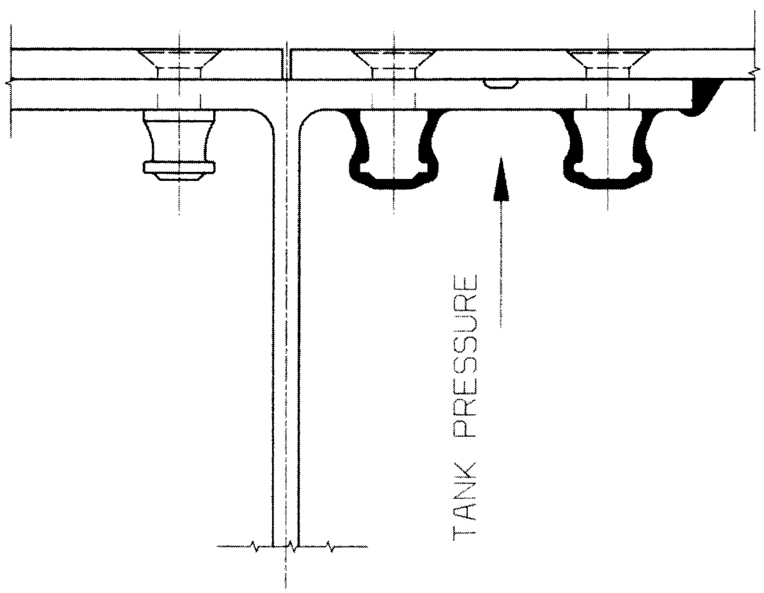

Fig. 3.6: Integral fuel tank sealing

DaimlerChrysler Aerospace

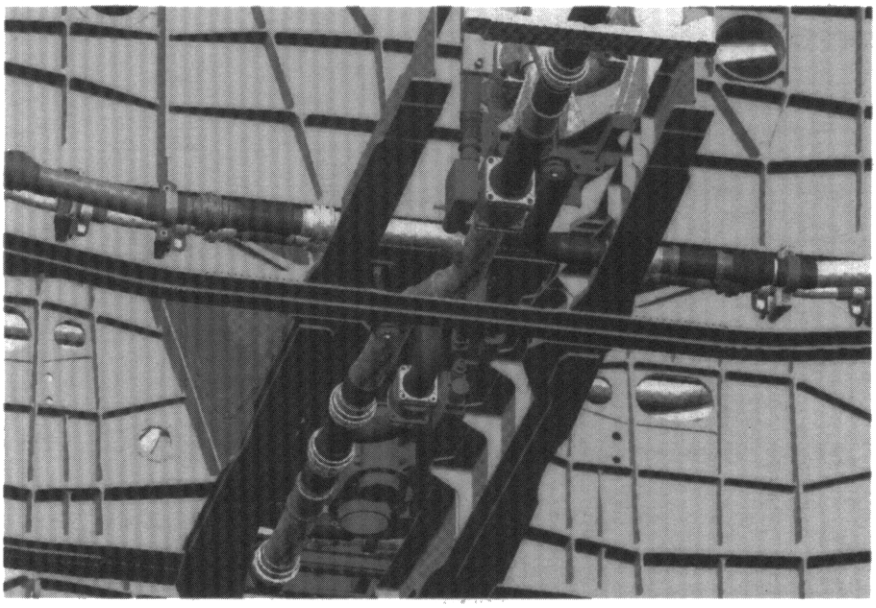

Fig. 3.8: Digital Product Assembly

DaimlerChrysler Aerospace

Technical Data:

X - axis 8300 mm
Y - axis 3200 mm
Z - axis 2000 mm
A - axis 200°
C - axis 400°
Spindle Capacity: 17 kW
Spindle Rotation: 9 000 rpm
Feed: 16 000 mm/min
Tool Capacity: 40 places

Application:

- Drilling of CFC-skin to CF structure
- milling interfaces to front and rear fuselage
- Drilling of ICY and non ICY substructure for Doors and Panels
- Drilling of Centre Fuselage Spine hole pattern

Fig. 4.1: Assembly Centre Fuselage

JSF F120 Engine Program Low Cost Operation and Support An Engine Manufacturer's Perspective

K. Murphy
GE Aircraft Engines
One Neumann Way MD G41
Cincinnati, OH 45215-6301
United States

J. Smith
GE Aircraft Engines
One Neumann Way MD G110
Cincinnati, OH 45215-6301
United States

D. Wensits
Allison Advanced Development Co.
P.O. Box 420, speed Code S-22B
Indianapolis, Indiana 46206-0420
United States

Abstract

The JSF F120 engine is being developed specifically to meet the overall affordability objectives of the JSF Program, addressing all elements of cost from development through operation and support. Uniquely different from current systems, the JSF affordability focus is driving fundamental changes in the engine configuration and development, acquisition, and support processes to facilitate meeting these overall affordability goals. Although these changes influence all aspects of the F120 engine design, one of the critical elements to meeting these objectives is improving the supportability characteristics of engine. Improved supportability, implemented through increased reliability, improved safety, reduced maintenance, and flexible support systems, will result in lower overall operation and support costs over the life of the weapon system. These improvements will facilitate the affordable operation of the F120-based propulsion system.

To meet the desired supportability improvements, the F120 engine is being designed as an inherently more robust, lower variation system based on the Team's Six Sigma initiatives to positively impact maintenance and support costs yielding lower total cost of ownership for our customers. The F120 engine design process is focused on configuration simplicity, full 3D simulation, advanced diagnostics, and support system flexibility to achieve the desired cost benefit. The F120 engine's simplicity, with significantly fewer parts than current engine systems, provides the basis for improved reliability and lower cost. Each of these parts is being designed in a full 3D visualization and modeling environment to permit full assessment of maintenance and support needs during the design process. Overall, the engine will utilize an advanced Prognostics and Health Management (PHM) system, combined with the weapon system's Integrated Flight Propulsion Control (IFPC), Vehicle Management System (VMS) and advanced information processing systems, to provide specific data on the health of the engine to facilitate "on-condition" maintenance and support.. Combined with the engine's PHM system is the ability to provide a flexible customer support system to facilitate the operation and support needs of the weapon system's various customers. This flexibility permits easy adaptability to both today's and future systems capitalizing on different partnerships between government and industry. Integrating these focused activities will permit the GE/AADC/RR Team to provide an F120 engine system that optimizes the balance between reliability, maintainability, and support resources to deliver a low cost, maintenance friendly system, ultimately meeting affordability objectives.

Introduction

A key objective of the F120 Program is to provide a fully supportable product that meets the overall affordability objectives of the Joint Strike Fighter Program. To accomplish this, an international team consisting of GE Aircraft Engines, Rolls-Royce plc, Allison Advanced Development Company, and Philips Machinfabrieken has been established to synergistically combine their collective capabilities to make the F120 the most advanced, supportable, and affordable fighter engine in the world. The specific JSF focus on supportability is driving fundamental changes in this team's processes to address all elements of cost from development through operation and support. These process changes provide the basis for the Team's ability to achieve the overall affordability goals of the program.

The F120 engine is being developed through a four-phase, risk-based program fully integrated with the JSF Preferred Weapon System Concept (PWSC) Engineering and Manufacturing Development (EMD) program. Phase I completed the necessary propulsion system conceptual design and weapon system assessment necessary to select the F120 engine as the preferred engine for the JSF program. This phase included a comprehensive technology evaluation process to select the right combination of technologies to meet the JSF program's affordability goals. Phase II, currently in progress, is focused on core engine technology maturation and risk reduction, providing the basis for either of the two Weapon System Contractors (WSCs) PWSC propulsion systems. This phase demonstrates the inherent capability of the F120 core to meet the needs of a Short-Take-Off-Vertical-Land (STOVL) capable propulsion system. Phase II is proceeding on cost and within schedule requirements towards a core engine test in July 2000. The Phase III, or Pre-EMD phase, is structured similar to the Phase II effort, but focused on the turbofan engine system. This phase provides the necessary risk reduction to prepare for a low-risk EMD program in Phase IV. The Phase III contract was recently awarded to the F120 Team, permitting the fan and low pressure system development to proceed. The Phase IV program completes development of the remaining propulsion system components and fully qualifies the F120 engine for production. The Phase IV effort includes the necessary flight test and operational evaluation of the engine. In February 1998, the US DOD certified that the F120 program is fully funded and detailed planning of the complete program is in process.

The JSF F120 engine is a dual-spool, fixed cycle, and multi-mode turbofan propulsion system, designed to specifically meet the JSF multi-service, multi-national weapon system

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

requirements. The engine is derived from the successful YF120-GE-100 engine developed in the Advanced Tactical Fighter Engine (ATFE) Program. This engine, with its inherent core capability, provides an excellent basis for meeting the JSF propulsion system requirements for either of the two PWSCs under consideration. For each concept, a tailored, derivative engine configuration has been defined to meet unique needs of each WSC. In either case, the F120 operates in a separated flow mode for STOVL, with core and fan airflow streams separately used for propulsive lift components. For Conventional Take-Off and Landing (CTOL) and Carrier Version (CV) variants, the F120's mode of operation is as a conventional mixed-flow, augmented turbofan engine system.

Although all aspects of the life cycle are important to cost operation and support costs, at approximately 40% of today's life cycle cost, are key contributors and must be dealt with differently than in traditional development processes if the affordability goals of JSF are to be met. For the F120, fundamental changes to these processes are being made to achieve the desired results.

Process Improvement

To achieve the objectives of JSF, a new approach to development, acquisition, and operation and support is necessary. Process improvements are being implemented across all functional areas for all phases of the F120 program. Of primary importance, operation and support must be included as a fundamental requirement at the very beginning of the development process and treated as an independent design variable, just like thrust, specific fuel consumption, and/or cost. The F120 Team program has been structured to provide the required focus on operation and support from the beginning of the development process.

With the launch of the Phase II core demonstration effort, the F120 Team has focused its attention in the following key activities to ensure life cycle affordability for the JSF engine, implementing necessary process changes to provide a fully integrated result:

- Formulating specific, allocated requirements derived from the WSC Tier III specifications provided to each component design team to drive suppportability assessments from the beginning;

- Applying GE Aircraft Engines New Product Introduction/Engine Development Cycle (NPI/EDC) and Six Sigma initiatives to the F120 program, including specific application of Design For Six Sigma (DFSS) and Design For Reliability (DFR) processes to provide the desired quality and reliability capability;

- Establishing a comprehensive Reliability, Maintainability and System Safety (RM&S) Program where RM&S engineers are active participants in the individual component development Integrated Product Teams (IPTs);

- Including a comprehensive Prognostics and Health Management (PHM) capability into the engine control system to meet the underlying supportability objectives of autonomic logistics and enhanced failure detection capabilities; and,

- Initiating advanced logistics support planning early in the program to assess innovative support concepts and ways to minimize the logistics costs while achieving maximum sortie generation.

Implementing these activities as an integral part of the overall development program will permit the F120 Team to successfully meet JSF's operation and support cost objectives.

Design Process Improvement

The design of the F120 engine is being executed based on the use of GEAE's NPI/EDC and similar processes at each of the other Team member organizations to provide a higher quality, more reliable, lower cost product that meets the full affordability objective of the JSF Program. The design of the F120 is being conducted through the use of Design for Six Sigma and Design for Reliability processes being implemented across the F120 Team. These process improvements provide a statistical method of evaluating process capability against requirements, provide component and system level product scorecards for tracking, and define a means of trading capability to meet the desired requirements.

The NPI/EDC process addresses the entire product life cycle from idea inception to product retirement. It defines the series of milestones, or "tollgates", that must be achieved at specific points in the program for it to successfully proceed to completion. The tollgates describe the type of business, project, and technical data necessary to make sure sufficient information is available for proper decisions to be made. Each of these tollgates has a specific set of criteria that ensure all aspects of the program are properly considered. Through the use of this process, the right data is generated in a timely manner, avoiding unnecessary effort.

Within the JSF F120 program, there are a significant number of new analytic tools and processes being used that are providing the team the ability to meet the program's affordability objectives. Three examples can be used to highlight the types of changes being made to improve operation and support costs: target costing, smart, simple design, and master model simulation. The first of these processes, target costing, is one of several cost-focused process improvements being made across the Team. It provides a cost target for every part in the engine based on the requirement provided by the WSC for their PWSC configuration.

This process uses GEAE's advanced COMPEAT$^{TM} cost model, which permits a feature-based cost assessment of each component's design. The second type of process, Smart, Simple Design (SSD), is one of several techniques focused on reducing the number and complexity of the engine components, along with reducing manufacturing, maintenance, and repair processes and costs. These techniques provide focus on simplifying and/or combining functions to produce more affordable components, along with the use of standard parts. The third type of process, master modeling, is a package of software that provides a single database for use by the Team. The F120 Team is utilizing master models of all component hardware in a common data base to permit all disciplines, from design to manufacturing, to utilize the same analytic representation for all design, including supportability and manufacturing analyses. These master models are all full 3D solid simulations of the hardware, permitting a full assessment of the part prior to manufacture. These tools, along with a host of others, are providing the Team with the basis of producing a supportable, affordable design.

Supportability Process Improvements

Traditionally, RM&S has not been treated as an independent design variable, but only as a measure of the overall system capability after the design has evolved sufficiently in the development process. The F120 Team has undertaken three key activities to consider RM&S as an independent variable and overcome this historic limitation:

- Evaluating legacy system capability to assess what reasonable RM&S goals should be set for the F120 engine system;
- Interpreting the specific WSC requirements, flowing them down to the individual engine component Integrated Product Teams (IPTs); and,
- Establishing a system evaluation process to trade capability with each independent variable, including cost, between individual components within the engine.

The Team is integrating the results of these three steps, balancing the needs of all elements of the propulsion system while providing a comprehensive process for achieving the desired goals. The F120 Team is working with JPO, both WSCs, and P&W to thoroughly understand all the weapon system and propulsion requirements.

Improved reliability is the corner stone to reducing maintenance cost and improving support over the life of a weapon system. Today's engines typically require some sort of corrective maintenance action approximately every 50 flight-hours to repair inherent, induced, and/or no-defect failures. Of these three types, inherent failures occur as a direct result of deficiencies in the inherent design characteristics of the system and this is where we, as an engine manufacturer, have the greatest ability to help reduce operation and support costs. It is in this area that the F120 Team is focusing its DFSS and DFR quality initiatives to design an inherently more reliable system. Using specific customer requirements, legacy system lessons-learned and aggressive goals, detailed Failure Modes, Effects and Criticality Analyses (FMECA) are being performed to ensure inherent reliability is designed into the F120 system. Overall, inherent failures will be effectively minimized through implementation of the F120 reliability program.

In addition to the focus on inherent reliability, the F120 Team is also aggressively pursuing design features that will minimize the possibility of induced failures later in service. Current experience suggests that 30% of air and ground aborts are directly attributable to maintenance induced failures. Induced failures typically occur as a result of performing maintenance to correct one problem and inadvertently introducing another fault in the process. This can occur directly while performing an appropriate maintenance action, but also frequently occurs during part cannibalization from other engines due to inadequate spare part availability. Control of induced failures has been traditionally managed by the user, through careful maintenance practices and attention to spare parts availability. Beyond these traditional approaches, however, the F120 Team is aggressively pursuing support concepts that will minimize parts shortage problems and design features that will minimize the possibility of mishandling and/or miss-assembly. These efforts will ultimately minimize the occurrence of induced failures. Maintainability and human factors engineers are part of the IPTs, working with the component designers to implement a comprehensive list of maintainability and human engineering features created specifically for the F120 engine.

To help address the induced failure issue, an advanced 3-dimensional solid modeling capability is being implemented to assess maintainability characteristics before engine hardware designs are completed. Instead of physical mock-ups, the F120 Team is using a combination of commercial 3D CAD and GE developed software to provide a full, electronic simulation of the engine, built from the individual part level. This simulation, or Digital Pre-Assembly (DPA), in concert with advanced visualization tools, is being used to simulate component and engine assembly, providing an early assessment of fits, clearances, and assembly procedures. These tools help identify and assess design changes that are necessary to meet supportability considerations early in the design process when they can be implemented most cost effectively. This early attention to detail will minimize overall development costs through the reduction of downstream re-design and will minimize exposure to maintenance induced failures in the future. Upon completion of the design process, this full engine simulation will become the basis for user maintenance and support training.

For the F120, the no-defect failure category will be minimized through implementation of a comprehensive, integrated Prognostics and Health Management (PHM) system. No-defect failures can occur because of inadequate troubleshooting practices and procedures, which lead to unnecessary removal of perfectly good parts. The inability to isolate faults to a single component results in multiple parts replacement and ultimately contributes to the cost of ownership. Through the use of the F120 PHM system, fully integrated with the engine and vehicle control systems, the operation of the engine will be monitored on a real-time basis, comparing its performance against a theoretical engine simulation. This comparison will be used to assess the health of the engine, providing data for use in life management and maintenance planning. The PHM system, using a suite of specialized sensors, will be able to provide specific data on component characteristics and permit significant improvements in fault isolation. Overall, the PHM system will be able to guide the user on what they will need to do to maintain the engine system in the field. This system will permit the focus to change from periodic inspections to "on-condition" maintenance, avoiding the cost for inspections that may not be necessary.

Concurrent with the efforts of F120 reliability and maintainability engineers, system safety engineers are active participants in the IPTs to ensure the maximum safety of personnel and equipment throughout design, test, operation and support phases of the program. A comprehensive safety program is in place and in-depth safety analyses are being performed to identify all potential safety hazards. The payback is real, but intangible, since there isn't a meaningful way of quantifying the benefit of aircraft losses that do not occur. Clearly, significant savings result for every catastrophic failure that does not occur.

Prognostics and Health Management

For the F120 engine system, the PHM system is an integral part of the logistics support system, with two primary objectives. First, it will facilitate implementation of the government's autonomic logistics concept, permitting the PWSC to achieve its sortie generation rate goals. Within the autonomic logistics system, the PHM system will provide the capability to determine operational status of the propulsion system within a returning aircraft prior to its arrival, without manual intervention. Second, it will enhance engine failure detection capabilities and life usage management. The PHM system will not only detect a degraded condition before it becomes an actual failure (prognostics), but will minimize the occurrence of no-defect failures through enhanced fault isolation capabilities. This enhanced fault isolation capability, along with life usage monitoring, will further benefit the management of spare parts supplies, thereby reducing the occurrence of maintenance and reducing operational support cost.

Logistics Support

In addition to delivering a safer, more reliable and maintainable engine, innovative approaches to customer support needs are also being investigated by the F120 Team to meet the specific needs of each of WSC. The F120 is being designed to be sufficiently flexible to operate within either a traditional support infrastructure or an original equipment manufacturer (OEM) "power-by-the-hour" concept, or some variation in between. As currently anticipated, traditional support concepts will necessarily be modified to address the rapid deployment environment of our future military. Partnerships between the F120 Team and government agencies will be developed to address the ever-increasing cost of support and asset management. Emphasis will be placed on reducing spare assets and utilizing "just-in-time" delivery of critical parts.

Engine Interchangeability

One of the key elements of improving the supportability of the weapon system is the use of two, fully interchangeable engines. Commonly referred to as "Plug and Play," the PWSC will be able to utilize either F119 or F120 engine alternative, in any variant, without changing or modifying the airplane. In today's systems, such as the F16, alternative engines are available, but they are not interchangeable. The JSF vision is to provide full engine interchangeability to meet supportability, fleet readiness, and cost objectives. This requirement has necessitated GE and P&W to cooperatively work together to provide this capability. For each WSCs PWSC propulsion system, GE and P&W are working to define the physical and functional interfaces that will enable either the F119 or F120 engine systems to work equivalently in the weapon system.

Summary

The JSF F120 Program is an international endeavor that is synergistically combining the capabilities of GE Aircraft Engines, Rolls-Royce plc, Allison Advanced Development Company, and Philips to produce the most supportable, affordable engine for JSF. The F120 engine effectively addresses reliability, maintainability, safety, and supportability needs integral with the design process to ensure affordability objectives can be met. The F120 design defined for each WSC balances reliability, maintainability, safety, and support objectives to deliver an engine that fulfills the need for low cost operation and support.

Implications of 'Power by the Hour' on Turbine Blade Lifing

SM Bagnall, DL Shaw and JC Mason-Flucke

Rolls-Royce plc
Filton, Bristol BS12 7QE
United Kingdom

Summary

'Power by the Hour'® engine sales contracts are becoming popular both amongst engine operators and engine manufacturers. This paper examines how accurate turbine blade life prediction is achieved and is combined with accurate measurement of damage in service for successful contract fulfilment.

Introduction

'Power by the Hour' engine sales contracts are becoming popular amongst engine operators and engine manufacturers, (1). This type of contract requires detailed assessment of the life cycle costs of the overall engine, and more specifically the individual modules and components therein. An example of a typical life cycle cost breakdown is shown in figure 1.

The turbine module, where blades are operating at high temperature under high load, is a critical area that can significantly influence the overall engine life cycle costs. The accurate prediction of turbine blade life at the design stage is therefore necessary to allow the life cycle costs to be estimated, and thus to influence the contractual discussions at the earliest possible stage. The life cycle cost estimates are used to judge the balance between life, cost and technical specification (e.g. performance and weight) of the blade. On release of engines into service, monitoring of engine usage is necessary to ensure that the blades are performing well with respect to the damage usage rate per hour and that the initial assumptions of aircraft operation were correct.

This paper reviews how 'Power by the Hour' contracts require accurate turbine blade life prediction, combined with accurate measurement of damage in service for successful contract fulfilment.

What is 'Power by the Hour'?

A 'Power by the Hour' contract implies that the engine operator will buy a fleet of engines, but will not purchase spare engines. The engine manufacturer then agrees to supply spare engines, accessories or modules when required, and to perform all the maintenance work required on the fleet of engines. The rate paid by the customer is charged per flying hour, and the manufacturer would then be expected to carry out all the required maintenance of these engines. This transfers much of the technical risk onto the engine manufacturer, and although providing the opportunity for profits from spares and overhaul operations, clearly requires careful setting of the appropriate hourly rate. This in turn requires accurate life cycle cost estimates that rely heavily on accurate life prediction. From a customer point of view it offers a way of budgeting for the operation of the fleet of aircraft, whilst providing guaranteed availability of engines and a continuous warranty.

The manufacturer is really selling component damage accumulation at an agreed rate over the life of the component. The customer gains an advantage if he exceeds the operating conditions, by opening the throttle more or longer than agreed in order to reduce his mission time. Or perhaps the throttle movement may be a genuine attempt to obtain a given guaranteed level of thrust at a condition. It is only by measuring the damage accumulation that sensible conclusions can be reached. This requires accurate prediction of modes of damage or failure for the blade, and accurate measurement of damage accumulation in each of these modes.

Modes of Blade Failure

Before discussing the methods used for the assessment of blade life it is necessary to briefly review the prime modes of failure for both substrate and coating, see figure 2. Modes of failure that lead to wear out rather than loss of integrity of the blade are considered. For this reason blade failure from high cycle fatigue or integrity cracking of coatings, which are assumed to be designed out prior to entry into service, are not considered.

Blades have a finite life due to the arduous conditions in which they operate. They will require replacement before their mechanical condition deteriorates to the point of failure or has a severe impact on the performance of the engine. Deterioration can result from the separate or combined application of mechanical and thermal loads or the effects of environmental degradation. Turbine blades, particularly those from the high pressure turbine, are subjected to a combination of high mechanical loading due to the high speed of rotation and the transfer of gas loads through the blade into the disc, and high thermal loading caused by high temperatures and steep thermal gradients in the blade (2). The high temperatures and temperature gradients are initially the result of radial variations in the gas stream temperature leaving the combustion system that produces a peak of gas temperature around the mid-height of the blade, combined with the pressures and flows that result in high heat transfer to the blade. However the magnitude of the gradients is often made worse by the internal cooling system of a cooled blade, which is primarily introduced to reduce the mean metal temperatures, and then tuned to minimise the peak temperatures. Uncooled blades have significantly lower thermal gradients, reducing the degree of thermal strain contribution.

The prime failure modes are as follows:

1. Creep - permanent deformation that occurs as a result of the application of mechanical and thermal loads that are held over a period of time at high temperature (3). In uncooled and lightly cooled blades this can result in a blade length increase combined with a reduction in cross sectional area due to build up of dislocation mechanisms. If allowed to progress, this ultimately leads to rupture across the whole aerofoil

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section. In cooled blades creep tends to be more localised and leads to crack initiation and propagation.

2. Low cycle fatigue - occurs due to the repeated application of thermal and mechanical loads resulting in stress and temperature cycles that can be of high magnitude but are at low frequency. This cycling leads to the initiation and propagation of cracks. In the blade aerofoil, where the prime driver is thermal strain, cracks may initiate in any one of many locations, figure 3. These locations are mostly associated with local hotspots or strain concentration features such as film cooling holes. These cracks may propagate under the mechanical loads, or in some cases remain benign for a significant proportion of the blade life. In other areas of the blade such as the shroud, shank or root, cracks may initiate and propagate due to the load controlled mechanical stresses that are not relieved as the crack grows.

Any of these aforementioned cracks may reach a critical length, and then propagate rapidly under the influence of dynamic strains or reach a point where ultimate failure occurs and a portion of blade is lost.

3. Surface attack - takes the form of oxidation or hot corrosion, and results in the progressive loss of material with time exposure to the environment. In the case of oxidation or accelerated hot corrosion the rate of material loss increases rapidly at temperatures above 1050°C. Oxidation produces a thin layer of oxide on the surface, which under thermal-mechanical cycling undergoes microscale rupture, leading to spallation (4), figure 4. This process is repeated, with progressive loss of material until a predefined limit is reached whereupon the blade would be rejected at the next overhaul. There are lower temperature forms of corrosion which, together with accelerated oxidation, are to some degree dependent on the presence of salts or sulphur in the gas stream. These are referred to as Type I and Type II hot corrosion (5).

   An additional means of surface degradation is through erosion. This is usually a result of particulate impact on the blade leading edge, but is not a common failure mode, although it may become so as the times to failure under other failure modes are improved. An example of the cause of erosion would be shedding of carbon particles from the combustion system.

4. Coating Failures - most hot gas washed surfaces are coated to protect against oxidation and hot corrosion. The presence of a coating results in additional failure modes specific to the coating. The process of failure due to oxidation and hot corrosion of the coating is similar to that outlined in the previous section for the bare material, figure 6, but an additional failure can occur through usage of the thermal mechanical fatigue life of the coating. This results in the initiation of small cracks in the coating, which may propagate along the interface, resulting in loss of coating material, or more commonly, propagate into the substrate material. Early failure due to exceedence of the coating fracture strain is deemed to be an integrity issue.

5. Thermal Barrier Coatings (TBC's) - introduce further potential failure modes (6). In most cases the ceramic coating will have a bondcoat, an oxidation resistant coating. After a period of time the bondcoat can oxidise and result in a lack of adhesion due to the build up of oxide layer, which is the most likely reason for spallation in a mature coating during cycling. The development of bondcoat cracks which propagate along the interface during cycling can also result in spallation of the ceramic topcoat. Similar to basic coatings, the ceramic topcoat will have integrity issues that can lead to cracking.

6. Combined Modes - individual modes of failure can in some cases combine to reduce the life to below that of either of the individual modes (7). In this case an understanding of the interaction between these modes is required. An example is the interaction between creep and fatigue which can result in a significant reduction in life of cast materials. Other examples would be loss of coating leading to substrate oxidation and cracking, or stress corrosion fatigue where the fatigue life is reduced by the presence of corrosion.

Methods used for Life Prediction

Life estimation for turbine blades involves the use of an integrated system that employs Rolls Royce 'Turbine Blade Lifing Methodology' (TBLM) to assess life in the principal modes of failure. The integrated system provides a slick system with many automatic features, which sits within the Turbine Key System, a computing environment across all functional disciplines. This enables a significant reduction in the time taken to perform a life assessment, an improved user interface, an increased quality in life assessment through harmonisation of methods across the company, and most importantly an environment receptive to improvement and update of lifing methods. The lifing methodology has been verified by material characterisation on specimens and blades, by programmes of life assessment on demonstrator engines and by thorough validation against development and in-service experience.

The integrated system performs the following:

1. imports the geometric definition of the blade
2. automatically meshes the geometry using finite elements for thermal and mechanical analysis
3. allows application of the thermal and mechanical boundary conditions
4. solves the thermal problem to provide the temperature distribution
5. automatically accesses physical property data required for the solution of the mechanical problem to obtain the mechanical stresses and strains
6. post-processes these results to obtain the average blade life using a database of lifing algorithms for each failure modes
7. produces graphical and tabular output of lifing data
8. performs a statistical estimate of the whole set life

This method can be applied to both 2-dimensional (2D) models that represent cross sections of the turbine blade, figure 7, and to 3-dimensional (3D) models that represent the full blade geometry. When lifing the aerofoil it is common practice to perform analyses for each failure mode separately and then to combine the failure mode assessment where appropriate. The following sections describe how each failure mode is treated.

2D Life Assessment

A fatigue assessment employs an elastic 2D generalised plane strain method that is essentially an in-plane model with out-of-plane loads applied. The finite element model yields the cyclic variation in stress and strain at each node from the cyclic variation of thermal and mechanical boundary conditions. These results are then automatically post-processed to extract the major and minor cycles. In each cycle the maximum strain range and peak temperature is determined and the life is predicted using low cycle fatigue behaviour algorithms based on strain controlled data. The strain range may be modified to include a dynamic strain due to vibration, and to account for the influence of any localised stress concentration such as film cooling holes, internal cooling ribs or pedestals. Further correction of the strain cycle is made by taking account of the location of the minimum and maximum strains of the cycle, and is done automatically by an R-ratio correction. This variation has been established from a database of material specimen tests at different R-ratios, to which an algorithm has been fitted to define the equivalent zero to maximum strain cycle. Miner's rule is then used to calculate the total life at each nodal point by accumulating the damage from each of the individual cycles. This is repeated for as many 2D sections as are required to adequately define the aerofoil, normally at five sections. From this analysis the fatigue life-limiting region can be identified.

A creep assessment uses the same mechanical mesh as for the fatigue analysis, but is for either a single steady state condition or a series of steady-state conditions from a flight cycle or mission. A constant rating creep life is calculated for each of these damaging conditions, and Robinson's rule used to sum the individual rating times as a proportion of the constant rating creep life to obtain the damage fraction (Dc) i.e.

$$Dc = Dc1 + Dc2 + \ldots\ldots + Dcn$$

where Dcn is the damage incurred during time at condition n.

A damage fraction of less than one is required to give an adequate service creep life for creep alone, although with the effect of fatigue interaction a value much less than one could be required.

There is a great deal of evidence to show that creep and fatigue interact to reduce the combined life of cast materials to less than the life obtained through linear summation of both the creep and fatigue damage, figure 8. A database of combined creep and fatigue test results has been developed across the full range of operating temperatures to establish the interaction curve constants. This combined life is calculated automatically using an iterative process to establish the position on the interaction curve, allowing calculation of the average blade life for the given operating mission. Weibull statistics using shape parameters for the distribution of failures from past experience in these failure modes are applied to calculate the blade set life for assessment against the Project Requirements.

Oxidation and hot corrosion assessment is performed by consideration of the operating surface temperatures around the blade. Bare and coated material behaviour has been modelled in terms of time at temperature to produce a given amount of material loss or degree of coating penetration. Using these algorithms the coating and any subsequent allowed substrate penetration life could be predicted for a given metal temperature.

3D Lifing Method

The application of 2D analysis allows the life of the aerofoil to be calculated in most cases. However there are some cases where a full 3D analysis is required. Firstly when very high surface thermal gradients exist and cause high thermal strains. Secondly for 3D blade features e.g. shroud fillets, shroud acute corners, platform to shank fillet and shank features when the elastic peak stresses and strains at these locations are required. The postprocessing to obtain the fatigue life of the 3D features is the same as for the 2D models, allowing a complex assessment of the 3-dimensional strain vector through the cycle to determine the direction and value of the maximum strain. Life assessment takes account of the 3D vector of strain around the flight cycle and will identify the worst strain cycle and consequently the minimum life for that location.

Where the features are driven primarily by mechanical loads, then consideration will be given to load controlled specimen testing material data as well as strain controlled specimen testing. Otherwise many of the other aspects remain the same as for the 2D-lifing method.

Power by the Hour Requirements

The development of a sound contract between engine manufacturer and engine operator requires not only the accurate prediction of the blade life but an efficient and timely prediction for Stage 1 of the design process, the business concept and preliminary design concept phase (7), figure 9.

During Stage 1 the market opportunities are identified for a particular engine size, the concept options are established, and from initial design analysis against a defined mission or cycle, options are downselected for preliminary design in Stage 2. This requires the use of the TBLM in the integrated system to obtain preliminary life estimates of the blade lives, where fast analysis enables the optimum cooling concept to be identified. Full 2D temperatures may not be available and therefore scaling from previous thermal solutions may be necessary. The limiting failure modes are identified for each blade and the life predicted. This information, accompanied by the cost estimates for manufacture of the blade, is used in the life cycle cost estimate. Each concept can then be reviewed with respect to the initial unit cost and the life cycle cost of the individual blades, and summated to determine the module life cycle costs against the Project Requirement. Further design iterations and life estimates must be made where these costs are unsatisfactory. The prime concept is selected and the design moves into Stage 2, the 'Full Concept Definition' phase.

In Stage 2, more detailed aerodynamic definition, cooling analysis and geometry definition is carried out. Steady state and transient thermal behaviour is predicted and more detailed life estimates made, again requiring fast and accurate life estimates. The rapidity with which life estimates can be made is clearly demonstrated by the fact that with the input information available (e.g. temperatures, material properties etc.) for a 25 point transient cycle, a creep analysis, fatigue analysis and full life assessment can be made in less than one hour for a single 2D section. This includes creep-fatigue interaction life prediction at each node of the model.

The design proceeds into Stage 3, which is the 'Propulsion System Realisation' stage. Blades are validated in rig and engine tests, not only to demonstrate the performance characteristics but also to demonstrate the blade life capability through accelerated endurance tests. The TBLM is applied to assess the component damage that will occur during the test, and to make revisions to the test programme. The life is predicted prior to the test, and then recalculated by a back analysis at the end of the test when the actual engine performance has been measured. In this way an accurate picture of the life capability of the blade is built up.

Stage 4 is reached when the engine enters service. Throughout the assessment of life made so far the accuracy of the predictions has been dependent on the assumed engine operating conditions in service. Therefore, from an engine manufacturer's point of view, the essential element for confirmation of blade life is verification of not only the blade damage accumulation, but also the engine operating behaviour. This can be achieved by monitoring of engines as far across the fleet as possible. The results of the life assessment will be compared with service experience on these components to show how the blade is meeting its design requirement. Engine operators will also benefit significantly from monitoring of engine behaviour because this will enable them to understand how the damage usage is accumulating for individual missions, and how planned maintenance will effect their fleet operation.

Measurement of Life Usage

It is essential that the life usage computation should mirror the design computational method to achieve life usage measurement to an acceptable degree of accuracy. This section describes the processes undertaken within a damage counter system and applies equally to an airborne or ground based system. The general procedure is as follows:

At each time point,

1. Sample performance data signals
2. Derive additional performance parameters
3. Calculate blade stresses, strains and temperatures for the predicted failure positions
4. Isolate stress and strain extremes
5. Extract cycles by modified TREND method
6. For critical components, convert cycles to 0-max equivalent damage cycles
7. Ascertain if cycles are damaging
8. Accumulate damage

The actual measured performance data signals will vary from one engine type to another and with different operations, but will generally include those parameters identified in figure 10.

Performance algorithms are used to derive parameters that cannot easily be measured directly. These can take the form of equations or look up tables.

Analysis models used during the design phase to calculate transient temperatures and stresses require substantial computational power and storage and can only be effectively used on a workstation installation. The major restraint on service monitoring operation however, is the requirement to operate on a mini-computer at a maintenance base, or on-board microprocessor. It is therefore necessary to construct a simplified transient heat transfer/stress analysis model that represents an acceptable compromise between computational power limitations and accuracy. The model is then scaled based on datum temperatures and stresses to temperatures and stresses for each condition. A description of the failure mode damage assessment follows.

<u>Creep Damage</u>

Creep damage is computed from an algorithm that describes the creep strain behaviour with time. Graham and Walles is used to relate creep damage (Dc) to temperature (T) and stress (σ) through the relationship:

$$Dc = k4 * (\sigma^{k5}) * \Delta\theta / (k6 - T)^{20}$$

where k4, k5, and k6 are material dependent constants

$\Delta\theta$ is the time spent at condition.

This creep damage is then summated during the mission in accordance with Robinson's rule.

Creep damage calculation requires knowledge of the stress (σn) at every steady state condition n. This stress is scaled as being proportional to the square of the measured HP shaft speed (NH^2), and is related to the datum speed and the stress obtained from the detailed design calculation.

The blade temperature (Tn) is scaled from the design value using a non-dimensional relationship involving the local gas temperature (Tg) and cooling air temperature (Tc). Cooling air temperature (Tc) is linearly related to the compressor delivery temperature (T3), and the local gas temperature is linearly related to the stator outlet temperature (SOT) at exit from the combustor. T3 is a function of the two measured parameters, NH and intake temperature (T1). SOT is a function of the measured jet pipe temperature (T5) and the intake temperature (T1), or may be derived directly from a pyrometer measurement of the blade aerofoil temperature (TBT) and knowledge of the cooling effectiveness at the measurement point.

Thus from the measured parameters NH, T1, and T5, a knowledge of their interrelationship, and a detailed design estimate of the creep life usage, the turbine rotor blade creep life usage can be computed at any condition encountered in service.

<u>Low Cycle Fatigue</u>

Traditionally, low cycle fatigue on a blade has been referred to in engine monitoring circles as thermal fatigue in order to distinguish it from LCF of Critical group A parts. Thermal fatigue life usage is derived from a knowledge of the strain range ($\Delta\varepsilon$) experienced by the elements of the turbine rotor blade when cycled from one condition to another.

Notionally, the thermal fatigue damage (Df) is a function of the strain range and temperature (T) at the maximum temperature in the cycle. They are related by an algorithm of the form:

$$Df = 1 / Nf \quad \text{and}$$
$$\text{Log } Nf = \text{Log } Nf_{datum} - (\text{Log } (\Delta\varepsilon_{datum}/\Delta\varepsilon) / k7)$$

where Log $\Delta\varepsilon_{datum}$ and k7 are material constants, each of which has a temperature dependency, and Nf is the number of cycles to failure.

The thermal fatigue damage can be linearly summated in accordance with Miner's rule. The method of cyclic extraction is the same TREND method as used in LCF cycle extraction. Nf is then dependent upon local element metal temperature, and the strain range through which the element is cycled. The strain range is computed by separating out the strains due to each type loading. Each of these constituent strains is then scaled from the datum design cycle by the use of the appropriate parameters, after which they are re-summated at the new cyclic condition.

The calculation of each cyclic strain range requires the parameters HP shaft speed (NH), HP compressor delivery pressure (P3) and compressor inlet temperature (T1). Whereas the creep damage summation could be achieved by using steady state temperatures, thermal fatigue damage summation requires transient temperature variation around the cycle to be determined. This is determined by a relationship between local response rate of the element to changes in temperature, and the interval between sampling. The turbine rotor blade metal temperature response rate at any condition is calculated from knowledge of the turbine gas mass flow rate, which can be calculated from the measured parameters. Thus, using the additional measured parameter (P3), and knowledge of the interrelationship with the parameters measured to compute creep life damage, the thermal fatigue life usage can also be monitored.

Oxidation

Oxidation life usage monitoring is similar to creep damage assessment. The local temperature is computed in the same way as for creep life usage computation, without the need for additional parameter measurement. The rate of oxide penetration into the material or coating with time uses the oxidation life algorithm used during the analytical phase. The oxidation life usage is summated during the service life assuming a linear damage relationship.

Power by the Hour Requirements

Relatively simple programmable algorithms allow the prediction of the life usage of turbine blades from a few aircraft and engine parameters. This operational life usage has been calibrated to reproduce the life usage that would be predicted by the more precise, but computationally more demanding design methodology. Algorithms specific to a particular application are validated against engine bench programmes of accelerated simulated mission endurance tests or type tests, formulated to validate the engine against its operational design requirements. There is also the capability to modify the algorithm constants in the unlikely event of a service- demonstrated anomaly.

Simultaneous development of the engine monitoring hardware and electronics has provided a sophisticated means of operational life monitoring of turbine blades and allowed more precise prediction of life usage. This, in turn, has allowed life extension of these blades without jeopardising safety requirements. The precise prediction of life usage has led to a reduction in cost of ownership by providing a tool for more accurately planning maintenance and inspection intervals whilst at the same time reducing the probability of premature failures thus optimising power by the hour requirements.

It has also provided the engine manufacturers with a more accurate means of determining actual mission and service loads, which in turn has allowed more realistic power by the hour evaluations, and allowed cost savings through more realistic parts provisioning programmes.

Conclusion

This paper has reviewed how 'Power by the Hour' contracts require accurate turbine blade life prediction to establish meaningful and sound contracts. The advanced system employed by Rolls Royce for the assessment of turbine blade life has been described and its merits outlined. The requirement for engine monitoring in these contracts has been described and the benefits for both the engine operator and engine manufacturer described. 'Power by the Hour' contract fulfilment requires both the analytical tools and monitoring methods to be part of a fully integrated lifing system, which has been demonstrated. The future holds the increasing application of smart computer technology - someday the engine measurement system will tell the operator when a part needs to be changed!

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Life Cycle Cost Breakdown

- **Research, Development, Test and Evaluation (7%)**
  - Conceptual studies 1.2%
  - Full scale development 5.8%
- **Investment (33%)**
  - Production investment 4%
  - Engine investment 23%
  - Spares/Support 6%
- **Operating and Support (60%)**
  - Fuel, oil and lubrication 31%
  - Maintenance - labour 4%
  - Maintenance - material 18%

  - Sustained engine support 5%
  - Component improvement 2%

Rolls-Royce

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Figure 1

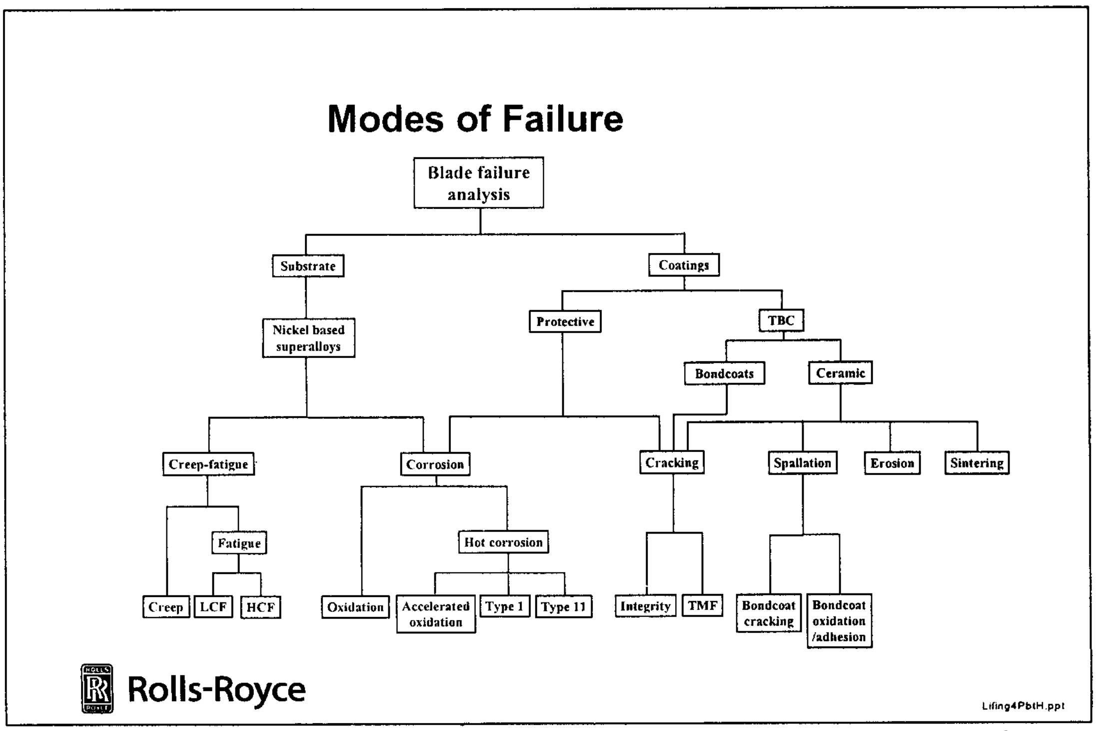

Figure 2

Potential Low cycle Fatigue Failure Locations

1. Leading edge holes, chordal cracking
2. Trailing edge holes chordal cracking
3. Hotspots, any location
4. Pressure surface film cooling holes, chordal cracking
5. Pressure surface film cooling holes, radial cracking
6. Cold web cracking

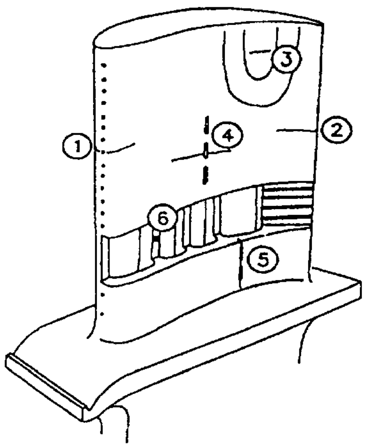

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Figure 3

Surface Attack - Oxidation

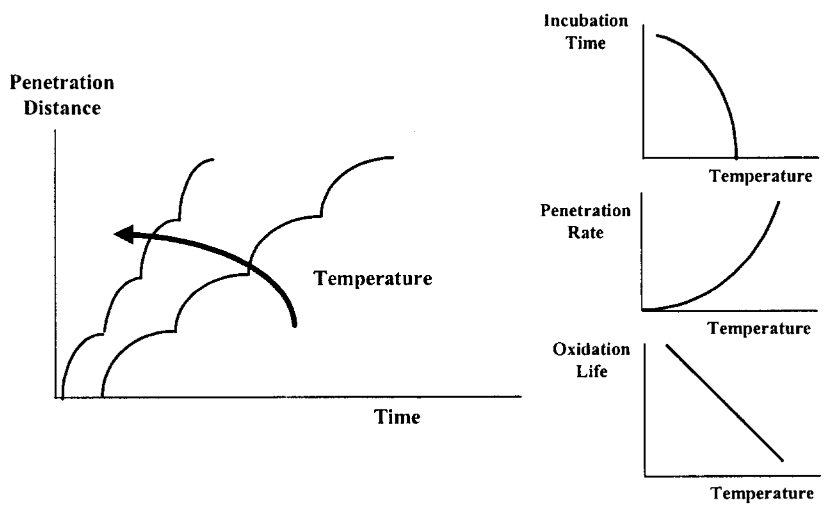

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Figure 4

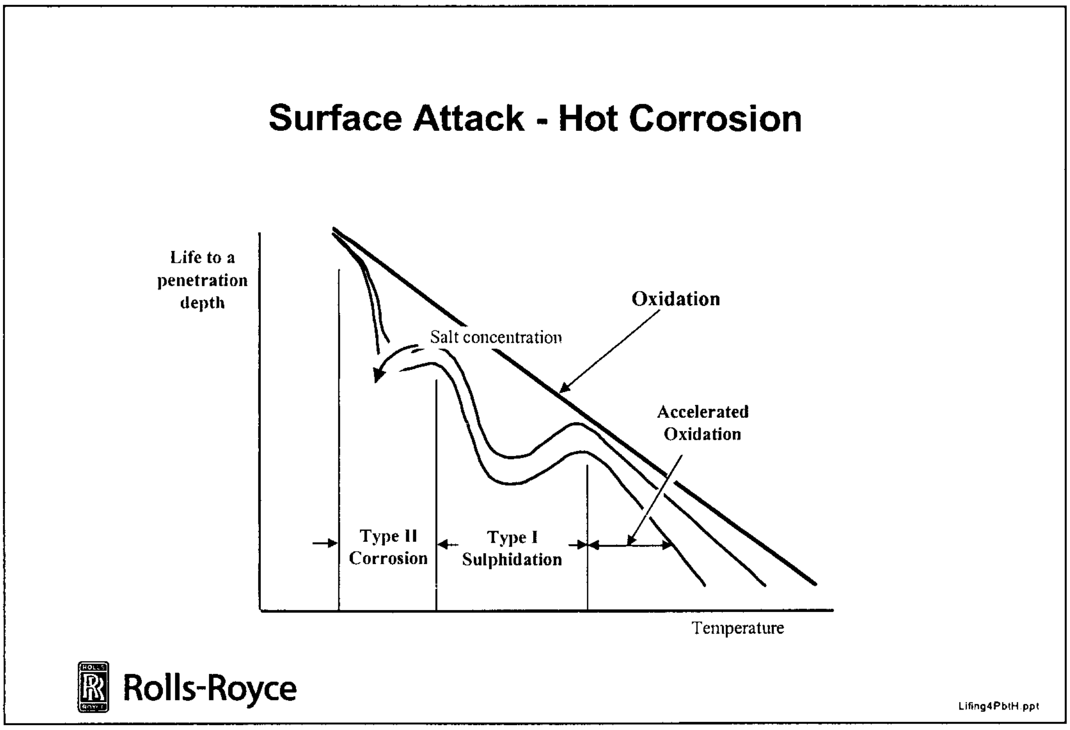

Figure 5

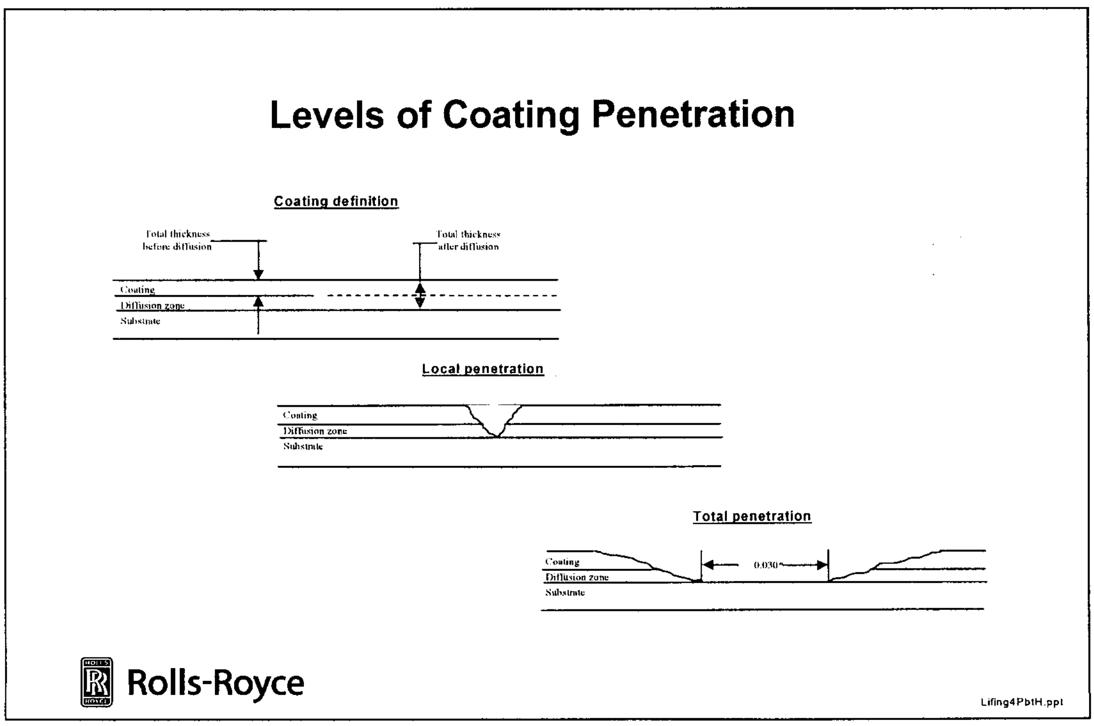

Figure 6

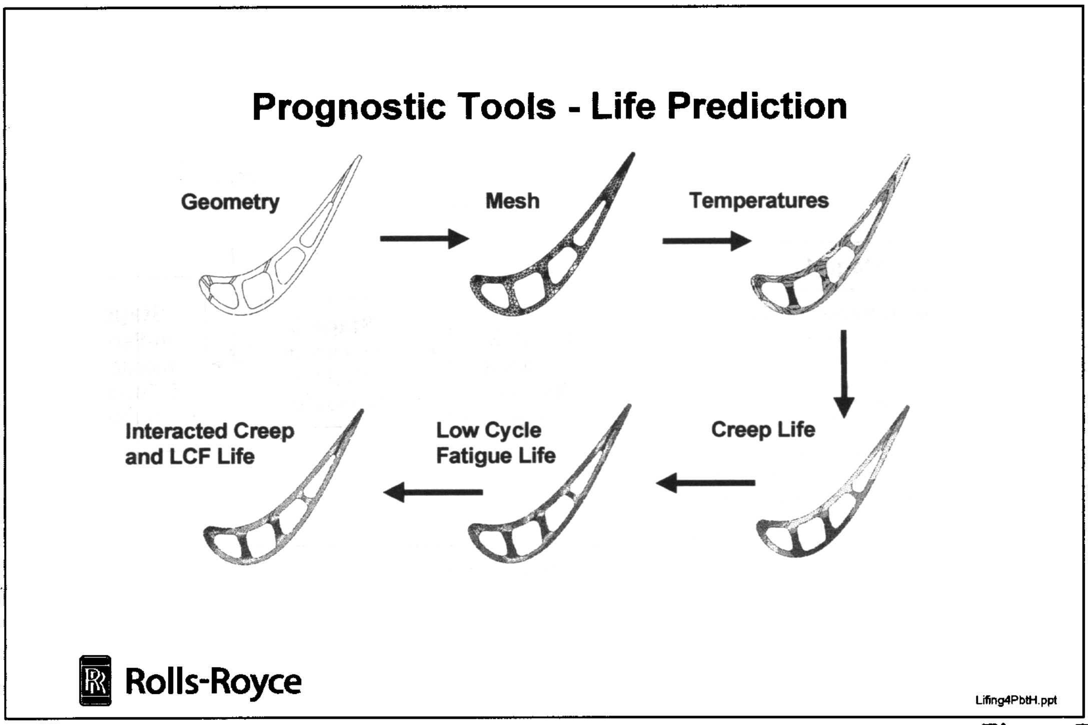

Figure 7

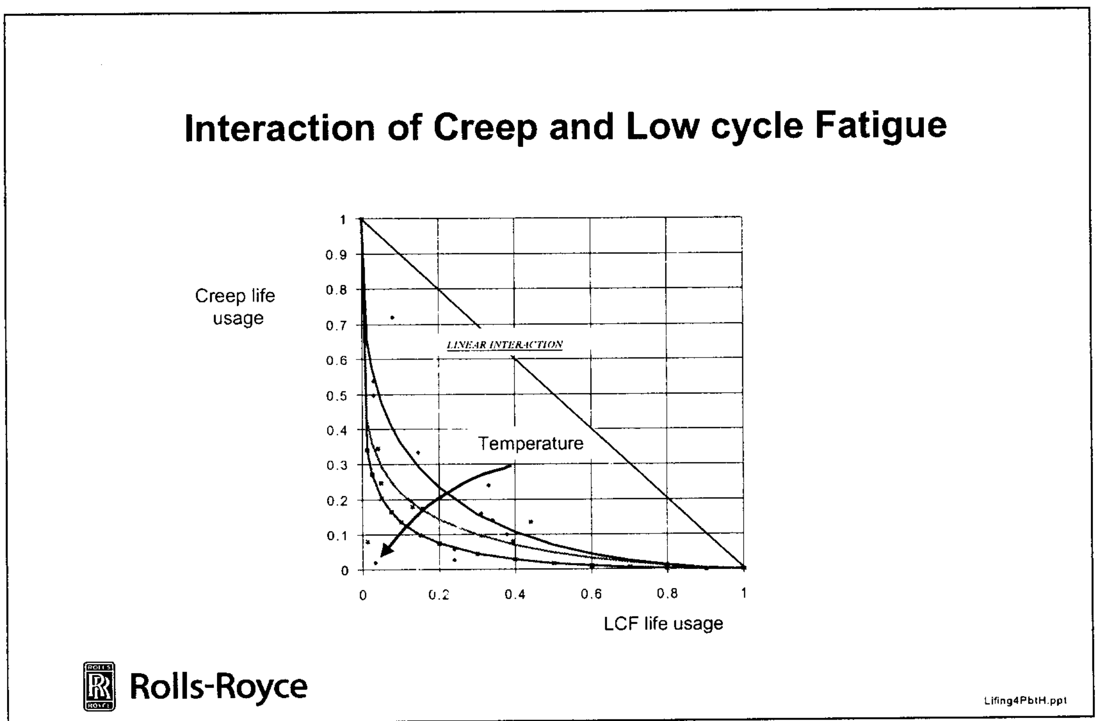

Figure 8

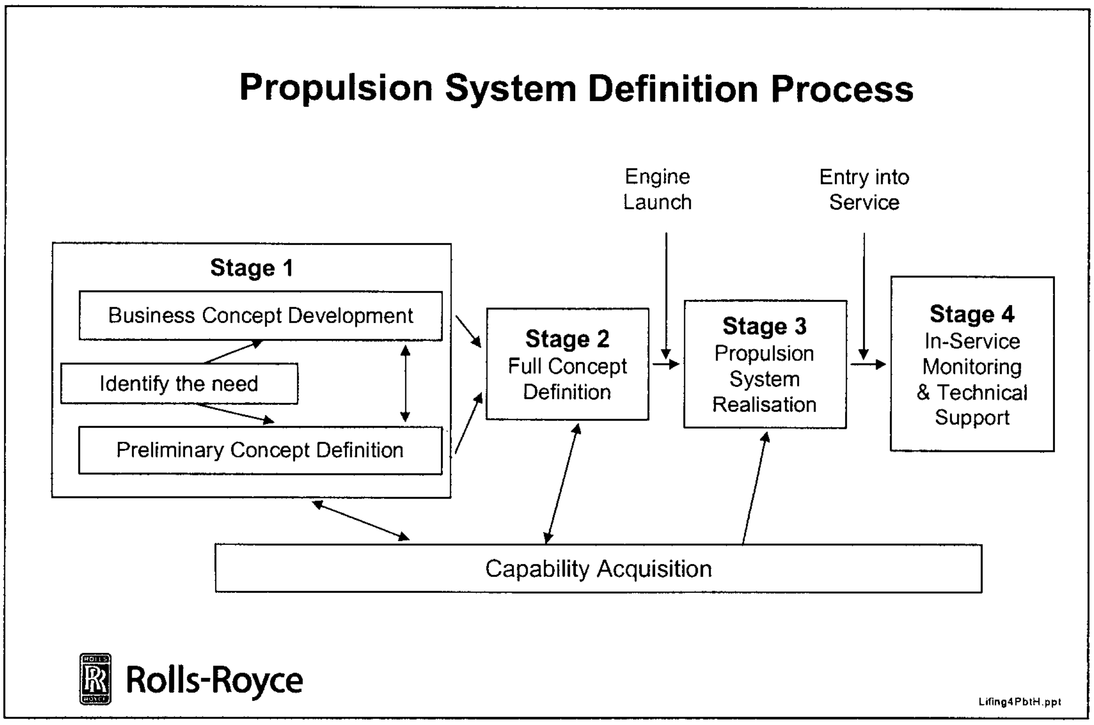

Figure 9

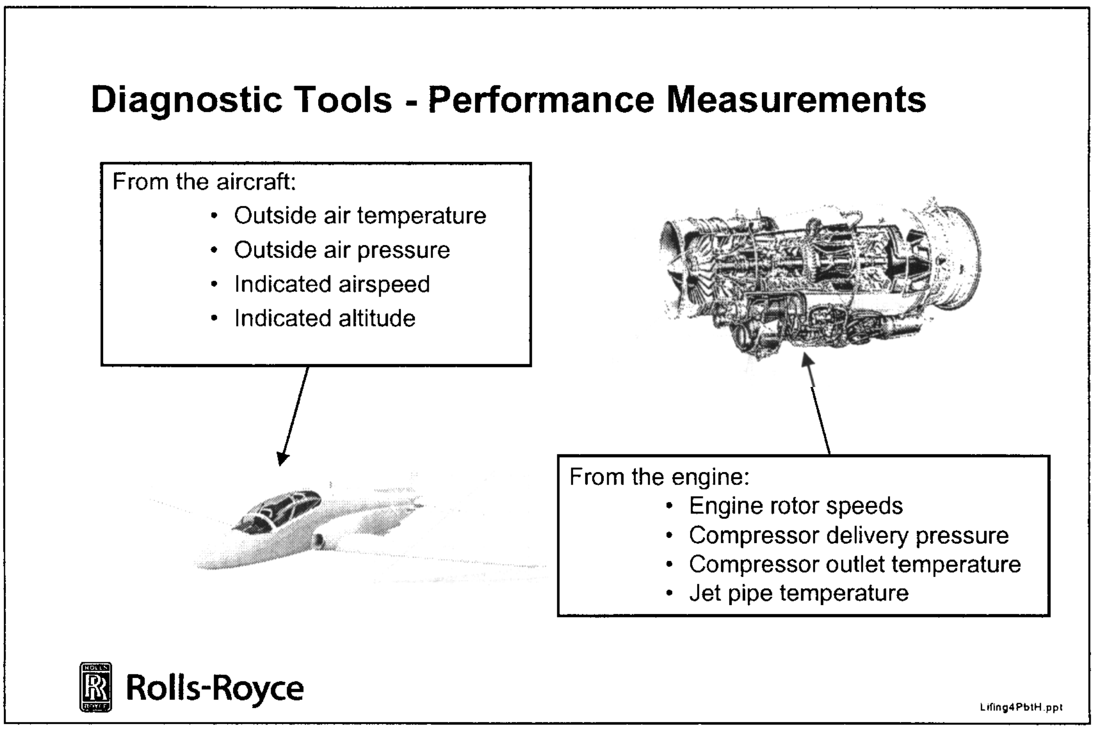

Figure 10

AMPLIFICATION OF THE BENEFITS OF A RELIABLE AND MAINTAINABLE DESIGN BY ADEQUATE MAINTENANCE AND SUPPORT CONCEPTS

Detlef Reiss

DaimlerChrysler Aerospace AG
Military Aircraft Division
P.O. Box 801160
81663 München
Germany

0. Scope

A reliable and maintainable design has obvious benefits with respect to Life Cycle Cost. However, in order to make full use of these design features, adequate alternative maintenance & support concepts - which are only viable in case of excellent Reliability and Maintainability of the Weapon System - must be considered.

The traditional 4-level maintenance concept does not satisfy the requirement for low Life Cycle Cost if a Weapon System featuring a reliable and maintainable design is to be supported. This requirement is fulfilled if the more advanced 2-level maintenance concept which is characterised by the limitation of base level maintenance to on A/C tasks and transfer of the remaining activities to a single source supplier, i.e. industry.

In order to make the 2-level maintenance concept a viable solution, aircraft availability and Airforce self-sufficiency need special attention but can be ensured via an adequate support concept and integration of military personnel in industry maintenance.

The 2-level maintenance concept was analysed for the Eurofighter/Typhoon to be operated by the German Airforce. A thorough comparison with traditional maintenance concepts revealed that the 2-level maintenance concept is much more cost-effective, therefore this advanced concept is now applied by the German Airforce.

1. Reduction Of Life Cycle Cost

1.1 Ways For Reduction Of Life Cycle Cost

In the last decades tremendous effort has been spent in reducing the Life Cycle Cost of Weapon Systems. Considering the increasing complexity of the Weapon Systems the Life Cycle Cost were reduced dramatically by improved design.
A number of different areas contributed to these reductions, however, they all can be allocated to one of the following groups:

- Design improvements affecting the production investment, e.g. design allowing more simple tooling
- Design improvements affecting production, e.g. design for easier assembly
- Design improvements affecting operation, e.g. engines consuming less fuel
- Design improvements affecting support, e.g. design for better reliability and maintainability

Naturally the above areas, as well as the design and development process itself, contribute to the Life Cycle Cost - and their reduction - through their inherent features.
Examples of the improvements of the processes are:

- Design and Development: use of Computer Aided Design (CAD)
- Production Investment:: use of tooling allowing rapid change of the item to be produced
- Production: pre-assembly of groups prior to installation
- Operation: optimised planning of inspection intervals
- Support: use of optimised maintenance and support concepts

However, the highest reductions in Life Cycle Cost can be achieved if the design issues and the processes are not looked at in isolation. An integrated approach is used today to ensure that possible improvements e.g. in the production are supported by an adequate design.

With respect to the support of a Weapon System, the first step towards low Life Cycle Cost is a design featuring good Reliability and Maintainability. For the Eurofighter/Typhoon Weapon System this lead to the requirement that equal priority was given to

- Performance,
- Cost,
- Reliability, Maintainability and Testability (RM&T)

of the aircraft.

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1.2 The Role Of Integrated Logistic Support In The Optimisation Of Life Cycle Cost

The overall aim of Integrated Logistic Support (ILS) is the cost-effective support of a Weapon System through integration of design and logistic disciplines. In order to achieve this, ILS ensures on the one hand, that the requirements leading to cost effective operation and support are considered in the design phase. This is achieved in particular by monitoring and controlling the Reliability and Maintainability features of the design.

On the other hand, ILS develops the optimised maintenance and support concepts and associated products, e.g. technical publications, for the resulting design and ensures their timely availability.

The following considerations have been made based on the ILS principle, thus ensuring the integration of design and support which ultimately leads to an overall reduction in Life Cycle Cost.

2. Improved Reliability and Maintainability

2.1 Improvements Achieved In Reliability And Maintainability And Their Limited Direct Positive Effect On Life Cycle Cost

When considering the Life Cycle Cost of a Weapon System, Reliability and Maintainability are of paramount importance because these features are determined very early in the design process. In order to allow an early assessment of these features, convincing characteristics for Reliability and Maintainability are taken into consideration.

Reliability is normally expressed by the Mean Time Between Failures (MTBF) while a good measure for Maintainability is the Mean Time To Repair (MTTR). Since the MTTR is measured in elapsed time, it provides a good measure for the availability of a Weapon System. However, when considering the cost of operation and support, the Maintenance Manhours (MMH) per flying hour for scheduled and unscheduled maintenance are of greater importance.

These features have been improved a lot in the recent. As an example, the Reliability and Maintainability characteristics of various aircraft over the last decades are shown in Table 1 below.

	First Flight	MTBF	MMH/FH
Aircraft 1	1958	0,6	57
Aircraft 2	1974	0,7	53
Aircraft 3	1977	1,2	55
Aircraft 3	1994	1,5	24

Table 1: Improvement of Reliability and Maintainability in the recent years

These improvements in Reliability and Maintainability result in decrease of effort required for the maintenance of the aircraft. Unfortunately, when considering the Life Cycle Cost of an aircraft, only a relative small portion is directly influenced by Reliability and Maintainability. An overview of the composition of the cost of operation and support for a traditional 4-level maintenance concept is provided in Table 2. The table also shows to what extent the individual cost elements are directly influenced by Reliability and Maintainability.

	Percentage of O&S Cost	Percentage influenced by R&M	Combined Percentage
Initial Investment	13 %	25 %	3 %
Operation	24 %	5 %	1 %
Military Support	42 %	70 %	29 %
Industry Support	4 %	100 %	4 %
In-Service Modifications	17 %	0 %	0 %
Total	100 %		37 %

Table 2: Distribution of Operation and Support Cost for a traditional 4-level maintenance concept and how they can be influenced by Reliability and Maintainability

Table 2 suggest that the influence of Reliability and Maintainability on the cost of operation and support is limited to only 37%. It can be seen that most cost contributors are not directly linked to the Reliability and Maintainability performance of the Weapon System, e.g. the cost for operation and modification are in principle not affected and also the cost for initial investment are only influence by 25%, mainly through a reduced number of spares. With respect to operation and modifications it is obvious that they are not influenced by Reliability and Maintainability, the reason for the limited influence on initial investment is due to the fact that the majority of investment is related to the maintenance concept, e.g. the facilities, support equipment, technical publications and training.

However, the maintenance concept is also driven by the Reliability and Maintainability performance of the Weapon System. Therefore, improvement in the Reliability and Maintainability features of a Weapon System offers further potential for reducing the Life Cycle Cost.

2.2 Further Potential For Reduction Of Life Cycle Cost Based On Improved Reliability and Maintainability

Excellent Reliability and Maintainability features of a Weapon System are a prerequisite for low Life Cycle Cost. The positive effects and their limitations with respect to Life Cycle Cost reduction have been explained before. The following concentrates on the further possibilities of LCC reduction.

It needs to be pointed out that the potential of further reduction of Life Cycle Cost is extremely subject to a very reliable and maintainable design. The further potential for Life Cycle Cost reduction lies in the development of maintenance and support concepts which take full advantage of these design features.

Traditional maintenance and support concepts are optimised to ensure maximum availability of the Weapon System based on a high effort for scheduled and unscheduled maintenance. In order to satisfy this high demand of maintenance, the traditional maintenance concepts employ large resources which are expensive in acquisition as well as in operation and maintenance.

Since newly developed Weapon Systems do not require – through improved Reliability and Maintainability - as much maintenance, the amount of resources can be reduced. However, a simple reduction does not meet the requirements of the complex environment a Weapon System is operated in. Mainly the target of a high availability is contradicting the simple reduction in resources. Therefore, new concepts, e.g.. the 2-level maintenance concept needed to be developed in order to ensure high availability and reduced cost.

3. The Traditional 4-Level Maintenance Concept

The maintenance concepts to be used for a particular aircraft need to serve several aspects. The most important are:

- cost-effective operation & support
- aircraft availability
- adequate self-sufficiency of the Airforce

In the past these criteria have been fulfilled by the traditional 4-Level Maintenance Concept described in the following.

3.1 General Layout Of The 4-Level Maintenance Concept

The 4-level maintenance concept relies mainly on the capabilities of the Airforces which performs the following levels of maintenance:

- Organisational Level (O-Level)
- Intermediate Level (I-Level)
- Depot Level (D-Level)

The 4th level of maintenance is performed at industry. Sometimes this 4th level is not counted individually. In these cases, the D-Level and industry are considered one level implying a 3-level maintenance concept.

Although the levels of maintenance are tailored to the individual needs of the Airforce and Weapon System in general the following tasks and locations are associated with the respective level:

<u>O-Level</u>
This level of maintenance is performed on aircraft at the flight-line. It includes mainly servicing of the aircraft and maintenance by exchange of Line Replaceable Units (LRIs)

<u>I-Level</u>
This level of maintenance is performed at the shop located at the base. In general, the defective LRIs are restored by exchange of Shop Replaceable Units (SRIs) and minor scheduled inspections as well as minor repairs of the structure are performed here.

<u>D-Level</u>
This level is performed at a central depot operated by the Airforce. Depending on the skills and capacity available at the depot, repair of SRIs, major (depot) inspections and major repair of the structure are performed here.

<u>Industry</u>
At industry the repair of SRI beyond the skills and/or capacity at the military operated depot is performed. Furthermore, the following large-scale tasks are performed:

- overhaul of equipments
- major repair of the structure
- major (depot) inspections
- modification of equipments
- modification of structure

A generic overview of the 4-level maintenance concept is provided in Figure 3.

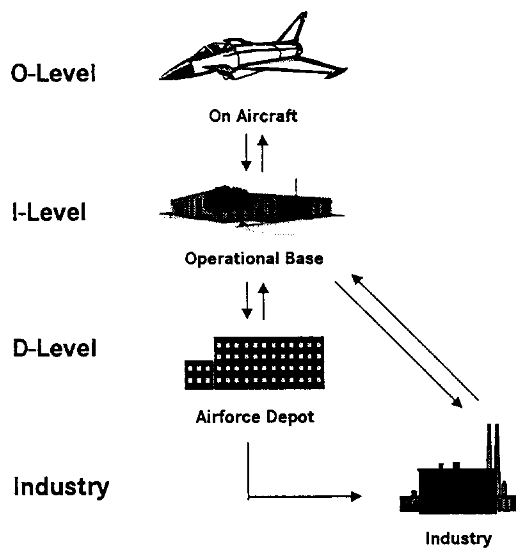

Figure 3: Generic overview of the 4-level maintenance concept

3.2 Main Advantages And Disadvantages Of The 4-Level Maintenance Concept

As already mentioned, the tasks performed at the individual levels may vary for certain applications, however, the principle of de-centralisation of O- and I-Level and sharing of tasks between the military operated D-Level and industry remains.

These two features are also the key areas for the advantages and disadvantages of the 4-level maintenance concept:

On the one hand, the de-centralisation of O- and I-Level allows a fast response to defects by repair of the defective LRI at the base ensuring a high availability of the Weapon System for a given number of LRI spares. On the other hand the resources required for repair, e.g. test equipment, must be available at every base.

With respect to the sharing of tasks, the advantages are the flexibility of the system by using industry resources in case the capacity at the military facilities is exceeded and the build up of knowledge at military facilities ensuring self-sufficiency of the Airforce in times of crises. Again the disadvantage is the duplication of resources at military and industry facilities.

Obviously, the disadvantages of the 4-level maintenance concept are mainly the high number of resources required resulting in high Life Cycle Cost associated with the acquisition and operation/maintenance of these resources.

With the increasing pressure to reduce Life Cycle Cost investigations for more cost-effective maintenance concepts were initiated. At this point in time it came in handy that the requirement for low Life Cycle Cost has already had a very positive influence on the Reliability and Maintainability of the newly developed Weapon Systems. These improved features opened the possibility for a more advanced maintenance concept.

4. Cost-Effective Support For Modern Weapon Systems: The 2-Level Maintenance Concept

With the increasing pressure on military budgets, the requirement for cost effective support is of utmost importance. However, the other important factors aircraft availability and self-sufficiency of the Airforce need also to be considered. Therefore, a maintenance concept needed to be developed which considered all these aspects. Since the main disadvantage of the traditional 4-level maintenance concept are the high Life Cycle Cost, this aspect was addressed first.

4.1 Centralisation Of Maintenance Due To Improved Reliability And Maintainability

The 4-level maintenance concept features widely spread logistic resources at the de-centralised base level maintenance facilities (O-Level and I-Level). This is necessary because of the high effort for scheduled and unscheduled maintenance required to operate and maintain the Weapon Systems to be supported. Under these circumstances it is cost effective to have all logistic resources available close to the place were the Weapon System is operated because their utilisation at these de-centralised facilities is ensured.

Because of the dramatic improvement of Reliability and Maintainability, the latest generation of aircraft do not create enough maintenance to ensure a constant utilisation of the logistic resources at the de-centralised maintenance facilities. Analyses showed that the cost associated with additional spares required to guarantee the same operational availability compared to the traditional 4-level maintenance concept are less than the additional Life Cycle Cost of logistic resources at decentralised facilities.

4.2 Maintenance At Single Source Supplier

Next to the de-centralised maintenance, the availability of full depth maintenance at the military facilities is the most outstanding peculiarity of the 4-level maintenance concept. The reason for maintaining the capability for the performance of major inspections and full depth repair at the military depot was the requirement of self-sufficiency of the Airforce. However, the budgetary restrictions and other factors put this requirement on the touchstone. One of these additional factors is the long-term production of current and future Weapon Systems, dictated by restricted budgets. This ensures the availability of production tooling and test equipment over a very long time without additional cost involved if used in parallel for production and repair of airborne equipment and aircraft itself. Therefore, performance of in depth maintenance of equipments and structure of a Weapon System at the manufacturer is more cost effective because the investment in support and test equipment is already funded by the production.

Additional to this obvious effect, two further considerations need to be made. First of all, current Weapon Systems are normally operated by a number of Airforces. Therefore it is much more efficient to return all defective equipments to a single source supplier for repair rather than building up a maintenance facility at each individual Airforce. With the improved Reliability of the equipments this centralisation is even more effective. Additionally, the knowledge gained from the maintenance of equipments and structure can be used by the supplier for modifying the equipments with the target of improved Reliability and Maintainability.

Of course, the idea of performing a significant amount of maintenance at industry contradicts the requirement of self-sufficiency of the Airforce. In order to mitigate this shortfall, ways of involvement of military personnel have been established. One of these ways is the involvement of military personnel in the maintenance of the Weapon System at industry facilities. This so-called co-operative concept is explained in para 6.2.

4.3 Layout Of The 2-Level Maintenance Concept

Based on the above considerations a maintenance concept based on limitation of the tasks performed at the de-centralised facilities at base level and the usage of single source suppliers for maintenance has been generated. This maintenance concept, called the 2-level maintenance concept, features the following levels:

<u>Base-Level</u>
At base level all the tasks necessary for the daily operation of the Weapon System are performed. This includes:

- Flight line servicing
- Stores loading and Role changes
- Rectification of defects by exchange of Line Replaceable Items or major components such as engines and ejection seats
- Software loading on- and off-aircraft
- Aircraft battle damage repair
- Routine daily maintenance actions like wheel/tyre
- Remedy of simple sealing problems and malfunctions for hydraulics, environmental control, oxygen supply, fuel supply and electric systems
- Minor repair of airframe parts.

<u>Industry-Level</u>
All activities beyond on-base maintenance are performed by industry, following the single source repair principle by using the manufacturer's facilities and assets from production. These activities include:

- Periodic aircraft inspections
- Structural repairs

- Engine repair and overhaul by module exchange
- Full depth equipment and engine accessories repair
- Module repair and overhaul including component repair

This procedure eliminates the build-up and the duplication of maintenance facilities. Instead, most of the facilities which in case of the 4-level maintenance concept are required at the de-centralised I-Levels are eliminated. Together with the D-Level maintenance facilities these facilities are now located at industry level. For the equipments this means that full depth repair is performed at a Single Source Supplier. The same applies for the engine, while with respect to the airframe all major repairs and inspections are performed at the manufacturers facilities.

Additional to the higher cost effectiveness of the 2-level maintenance concept it offers the advantage that the Airforce can concentrate on its main task: flying missions. Supporting effort is limited to on-base activities thus providing more flexibility with less personnel resources.

A generic overview of the 2-level maintenance concept is provided in figure 4.

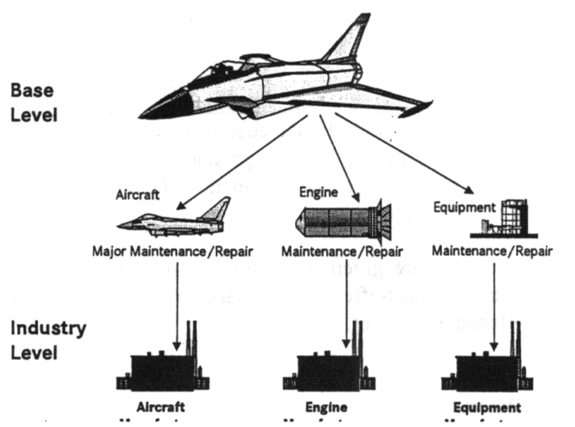

Figure 4: Generic overview of the 2-level maintenance concept

5. Safeguarding Aircraft Availability: The Associated Support Concept

5.1 Drivers Of The Operational Availability

In order to ultimately judge the effectiveness of a maintenance concept, not only the cost of maintenance facilities need to be taken into consideration. An important factor is the operational availability of the Weapon System. This operational availability is to a large extent driven by the maintenance concept and the associated support concept.

When considering aircraft availability it is necessary to know what factors are driving the operational availability. These are in general the frequency and duration of maintenance. While the frequency of maintenance is mainly driven by the design-feature "Reliability", the duration is driven by the design-feature "Maintainability" and the logistic system in which the aircraft is operated in.

5.2 Requirements For The Logistic System

In order to achieve a high operational availability, the logistic system must feature fast repair response times. Given a certain number of spares, these response times have been kept low in the 4-level maintenance concept via the de-centralised maintenance which is characterised by short waiting times for repaired items. In case of the 2-level maintenance concept, the centralisation has an adverse effect on the operational availability of the Weapon System. However, this problem can be solved by a very responsive transportation process and fast repair of the defective item at the Single Source Supplier.

In order to establish this responsive support environment, the following criteria must be met:

- progressive control of the movement of spares
- avoidance of intermediate storage times of spares
- fast transport of the LRIs to and from the repair facility
- short repair turn around times at the Single Source Supplier

5.3 The Support Concept Associated With The 2-Level Maintenance Concept

Of course all the requirements stated above can be fulfilled by the Airforce. However, due to the high management effort the required staff is quite high and the current structures and processes at the Airforces are not really predestined to perform these tasks. Moreover, this is a domain of industry which can be tasked via appropriate contracts. In this case industry can use commercial procedures e.g. for transportation to ensure the responsiveness of the support system. Within these contracts the required response times must be guaranteed.

An example of a support system in conjunction with the 2-level maintenance concept can be found in figure 5.

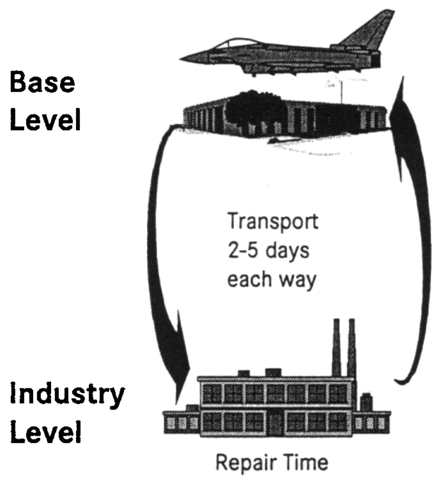

Figure 5: Support concept associated with the 2-level maintenance concept

6. Adequate Self-Sufficiency Of The Airforce

6.1 Requirement For Self-Sufficiency

With the 2-level maintenance and support concept two main criteria for the maintenance concept are fulfilled: cost-effective support and high operational availability of the Weapon System. However, the third requirement of adequate self-sufficiency has not been addressed so far.

With the transfer of most of the activities to industry, the self-sufficiency of the Airforce is naturally decreased. However, today the Airforce requirement of getting involved in the maintenance of a Weapon System is not only driven by the desire to be in position to ensure the operation without the support of industry. Of increasing importance is the requirement to have a certain degree of knowledge of the Weapon System available at the Airforce. This knowledge is needed to ensure optimum operation of the Weapon System as well as the ability to decide on modifications required to improve the operation and support.

6.2 Co-operative Model

In order to ensure the building up and preservation of knowledge at the Airforce, the Airforce needs to be involved in the maintenance of the Weapon System. This can be ensured by establishing so-called co-operative models in which military personnel is located at industry facilities and works together with industry personnel in the maintenance of the Weapon System.

This proceeding has on the one hand the advantage of avoiding additional logistic resources to be procured by the Airforce with all its disadvantages discussed before. On the other hand Airforce personnel can be involved in all levels of maintenance from full depth equipment repair to airframe maintenance and major scheduled inspections.

The co-operative model ensures that:

- The Air Forces are involved in intermediate and depot level maintenance although under industry control
- Airforce personnel with the required know-how for maintenance is immediately available in times of tension, crises and war.
- In depth knowledge of the equipments is gained by military personnel due to their close co-operation with industry personnel.

6.3 Deployed Operations

In case of deployment the Airforce capabilities are limited to the tasks normally performed at base level. For the 2-level maintenance concept this implies that mainly on A/C tasks, e.g. exchange of defective LRIs, are performed. Further repair of these LRIs cannot be done at the deployed location due to the limitation of Support Equipment available at the Airforce.

However, even in the case of a traditional maintenance concept, in-depth maintenance of defective LRIs is not always performed at the deployed location because major support equipment is in often not available in enough quantity to allow it to be shipped to the deployed location. Moreover, the defective LRIs are sent back to home-base for further repair. This proceeding can also be used in case of the 2-level maintenance concept with the difference that the defective LRIs are then forwarded to industry for repair. In summary there is no real difference in case of deployment between the 2-level and traditional maintenance concept.

7. Summary Of The 2-Level Maintenance And Support Concept

7.1 Prerequisites

Based on the following trends for airborne Weapon Systems the 2-level maintenance concept offers more cost-effective support compared to a traditional 4-level maintenance concept:

- Improved Reliability leading to a low number of defects which can be dealt with at a centralised maintenance facility, making the costly requirement for de-centralised maintenance facilities obsolete.
- Low Maintenance Manhours per FH achieved by high Reliability and long scheduled maintenance intervals again leading to centralised maintenance facilities.
- Availability of Production Facilities For Maintenance Purposes without additional cost is ensured because of the long overlapping between production and in-service phases, making the procurement of resources for maintenance unnecessary.

If the above facts are given the 2-level maintenance concept proves to be more cost-effective compared to the traditional 4-level maintenance concept.

7.2 Characteristics

In summary the 2-level maintenance and support concept consists is characterised by the following:

- On Base Maintenance limited to those tasks absolutely necessary for the immediate logistic support of missions, i.e. the main scheduled and unscheduled on-aircraft work and some limited off-aircraft work.
- Off Base Maintenance where all activities beyond on-base maintenance are performed by industry, following the single source repair principle by using the manufacturer's facilities and assets from production.
- Responsive Support Concept ensuring a fast transportation and repair turn around in order to safeguard a high operational availability of the Weapon System.
- Co-operative Models in order to build-up and maintain the required level of knowledge at the Airforce.

7.3 Benefits

The benefit of the 2-level maintenance concept opposed to the 4-level maintenance concept is in the Life Cycle Cost.

The investment cost are dramatically reduced because a number of logistic resources normally necessary at I- and D-

Level must not be procured. This applies to the following disciplines:

- Support and Test Equipment: not required because production facilities at single source supplier can be used
- Documentation: industry documentation can be used for maintenance
- Training: industry personnel is already trained as part of the production process

But not only the investment cost are positively affected. Since the logistic resources which need not be procured do not create cost for their maintenance and modification, additional savings are made.

Although there are minor disadvantages like the increased requirement for pipeline spares (which can be reduced by a responsive support concept) and the sometimes higher cost for the repair of a defect at industry compared to the military organisation, the positive effect on Life Cycle Cost is outstanding. This can best be shown by a worked example.

8. Example For The Application Of The 2-Level Maintenance Concept

8.1 Eurofighter/Typhoon for the German Airforce

As successor for the F-4 Phantom currently operated by the German Airforce (GAF) the German government decided to procure Eurofighter aircraft. The Eurofighter/Typhoon is developed for the Airforces of the United Kingdom, Germany, Italy and Spain. The development and production is contracted to the major aerospace industry of the participating Nations: British Aerospace plc, DaimlerChrysler Aerospace AG, Alenia S.p.A. and Construcciones Aeronauticas S.A.

Due to military budget restrictions there is a high pressure on the German Airforce and industry to explore all possibilities for minimum Life Cycle Cost of the Weapon System. Further to the stringent requirements of the aircraft design this resulted in a detailed assessment of the maintenance and support concept to be adopted for the GAF.

8.2 Analysis Of Different Maintenance Concepts For The German Airforce

In order to have a sound basis for the decision on the maintenance concept of the Eurofighter/Typhoon for GAF, a detailed study conducted by DaimlerChrysler Aerospace AG (DASA) was performed. The following maintenance concepts have been assessed in this analysis:

Traditional Maintenance Concept
The traditional maintenance concept considered by the GAF employed the 4-level maintenance concept as described above. The only peculiarity is that the tasks performed at D-Level and industry is generally allocated as follows: 30% of the tasks to be performed at D-Level, the remaining 70% to be performed at industry.

Modified Traditional Maintenance Concept
This maintenance concept is based on the traditional maintenance concept described above with the exception that the I-Level tasks for avionic equipments are not performed at de-centralised avionic shops at base-level. Instead the repair of avionic LRIs is performed at a central depot.

2-Level Maintenance Concept
As an alternative, the 2-level maintenance concept as described above has been considered. As an exception to the straight forward application of this concept, some maintenance on systems like Crew Escape, Environmental Control, Battery, Gun and Role Equipment is performed at base-level.

The analysis is based on the following parameters:

- 175 A/C operated in 5 Wings
- 167 flying hours per A/C per year
- The A/C are put into service over a period of 12 years
- Each A/C is operated for a period of 25 years

The study analysed the Life Cycle Cost of the Weapon System, however, the difference for the individual maintenance concepts was of course limited to the cost of operation and support including their initial investment (e.g. initial spares, ground support equipment, publications etc.).

8.3 Study Results

A comparison of the cost of operation and support including initial investment as calculated in the analysis is provided in Table 6 below.

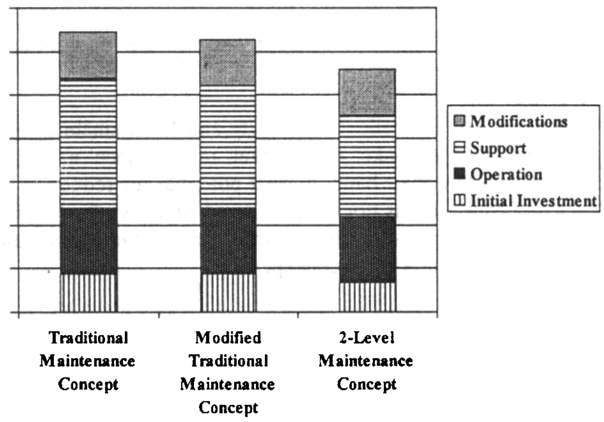

Table 6: Comparison of cost of operation and support for the 2-level maintenance concept versus the 4-level maintenance concept

It can be seen that there is an large advantage for the 2-level maintenance concept for both, initial investment and support cost. In terms of total cost for operation and support of the Weapon System this advantage is around 15% for the 2-level maintenance concept compared to the traditional concept. Bearing in mind that roughly 40% of these cost are associated with the operation and modification of the Weapon System, e.g. fuel, pilot manuals and training, role equipment, operational ground crew, facilities etc., and are therefore not influenced by the maintenance concept, the advantage of the 2-level maintenance concept increases to 23%. This equals some Billion DM.

In order to judge if the result of the analysis changes when important parameters are changed, a sensitivity analysis against a number of these parameters has been conducted including:

- Number of flying hours
- Number of defects

- Repair Turn Around Time

In all cases the 2-level maintenance concept proved to be the most cost-effective alternative.

Therefore, the German Airforce decided to apply the 2-level maintenance concept for their fleet of Eurofighter/Typhoon aircraft.

9. Summary And Conclusion

The 2-level maintenance concept is characterised by

- A reduction of the maintenance tasks to be performed at base-level, mainly on A/C and very limited off A/C tasks
- Transfer of the majority of off A/C maintenance and major scheduled maintenance to a single source supplier (industry)

The 2-level maintenance concept offers significantly reduced Life Cycle Cost compared to the traditional 4-level maintenance concept if certain prerequisites are fulfilled. These prerequisites are:

- A reliable and maintainable design featuring low defect rates and long scheduled maintenance intervals
- Availability of assets and tools required for maintenance at industry without additional cost
- An efficient support concept keeping the turn around times short

On the one hand, excellent Reliability and Maintainability are a prerequisite to make the 2-level maintenance a viable solution. On the other hand, a great potential for reduction of the Life Cycle Cost is not used if the advantages of a reliable and maintainable design are not amplified by the application of the 2-level maintenance concept.

WHAT THE CUSTOMER WANTS

MAINTENANCE-FREE AND FAILURE-FREE OPERATING PERIODS TO IMPROVE OVERALL SYSTEM AVAILABILITY AND RELIABILITY

SQUADRON LEADER P MITCHELL
MSC BEng CEng MRAeS RAF
Logistics (OR) 5D Room F30
HQLC, RAF Brampton
Huntingdon, Cambs. PE18 8QL, UK

INTRODUCTION

BACKGROUND

1. Military commanders require high levels of mission effectiveness and supportability to ensure success in an inherently hostile environment. The emphasis must be on safe equipment operation under a variety of adverse environmental conditions and with a minimal logistics support footprint. In-service experience shows that unreliability of defence equipment remains a dominant factor during operations and training and that there are deficiencies in the traditional specification of military reliability requirements. Consequently, an alternative method for specifying reliability is required, one which is not subject to the uncertainties of characterising product reliability with a single failure-rate number or Mean Time Between Failure (MTBF). The traditional approach to reliability specification has been based on often unrealistic reliability predictions followed by potentially endless product testing to provide assurance, without the recognition that many failures can be prevented by attention to basic design details. Manufacturers need to develop a better understanding of materials and process conditions, and their effects on product reliability, in order to provide the customer with defence equipment that works when needed and continues operating for a defined period of time.

2. High mission effectiveness in future defence equipment is achieved by accurate predictions of in-service reliability and minimum system functionality. Thus, new reliability techniques are required that foster fault prevention and control and, most importantly, focus on user operational requirements. The ultimate goal is to reduce the dependence on characterising reliability by a single failure-rate number, ie MTBF, and to look for new methodologies which focus on causes of failure and their control or elimination, rather than measuring and responding to their effects. This leads to the twin concepts of Maintenance-Free and Failure-Free Operating Periods which are alternative, more practical, approaches to specifying, measuring and assuring product reliability. The implementation of this new approach would involve an evolutionary progression from the current system.

AIM

3. The aim of this paper is to promote the philosophy of Maintenance/Failure-Free Operating Periods (M/F-FOP) as an additional methodology for the specification and assurance of defence equipment reliability.

DEFINITIONS

4. Failure-Free Operating Period (F-FOP) is a period, measured in appropriate units, when the system is meeting its minimum operating capability.

5. Maintenance-Free Operating Period (M-FOP) is a period of operation during which the system must be able to carry out all its assigned missions without any maintenance action and without the operator being restricted in any way due to system faults or limitations.

PRODUCT RELIABILITY REQUIREMENTS

6. We, the customer, have allowed the current approach to reliability specification to prevail, in that we expect a MTBF or its reciprocal, a failure rate, to form part of a proposal from an equipment supplier. Vendors may then typically estimate the product's reliability by using commercial reliability models, such as Mil-Hdbk-217 in the specific case of electronics equipment. On other occasions an internal proprietary reliability model may have been developed and maintained, based on historical or test data and an assumed failure-rate. Often, the prediction methodology used assumes an exponential failure-rate, meaning that random failures and faults are inevitable. The use of MTBF has thus bred and sustained a culture of inevitable and acceptable failure, a tacit acceptance that equipment will fail randomly with little incentive to understand the mechanisms of when and why failures occur. Once an equipment has been allocated a particular reliability level, it has been traditional for most activities to then concentrate on nourishing this belief in random failure, using predictions and other statistical tools, based on the application of exponential theory, without addressing the underlying mechanistic reasons for failure.

7. The majority of random failure modes can be removed by study into the mechanics of failure followed by interactive design influence. In particular, most

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avionics failures have been attributed to associated mechanical problems such as packing densities, quality assurance shortfalls, and heavy exposure to vibration, dust and moisture. Taking steps to remove these causes of failure reduces the number of random failures such that many of the remaining failure modes exhibit certain mechanics of failure that have non-random failure distributions. These failure distribution curves can then be plotted and used to determine overall product durability or a minimum required time to failure, eventually creating better generic design tools. . It is generally accepted that as equipment operating time increases, then the probability of failure increases: extending the durability of an element increases its probability of failure. Reliability requirements will need to be optimised in terms of durability and its associated probability of failure.

8. The nuclear and space industries aim to eradicate random failures from the outset and the car and rail sectors are following suit. In many defence related industries, the continuing acceptance of the random failure approach inhibits the most effective use of limited in-service support resources and will be a continuing factor impeding the effectiveness of future operations.

PRODUCT RELIABILITY ASSURANCE

9. Traditionally, reliability levels have been monitored through product development and testing. As technology approaches the boundaries of material and process capabilities, as ever greater levels of reliability are predicted, and as the demonstration of such levels is expected in shorter timescales, practical limits to the traditional approach of reliability demonstration are being reached. It is currently a reactive process, characterised by the use of sample tests as a means of monitoring product reliability levels and subsequent reaction to any signs of degradation. In contrast to this scenario the M/F-FOP approach is a new method of reliability specification, based on the identification and control of the causes of unreliability. It is intended to anticipate failure and design it out, rather than reacting to developmental failures. The aim is to provide greater assurance of enhancing equipment reliability and its predictability in service. This is achieved by understanding and controlling those elements in product design, manufacture and use which affect system and component reliability.

10. Military contracts often require suppliers to implement a prescribed reliability programme and to perform tests aimed at achieving specified contractual reliability requirements in terms of allowable failure rates. Many of these tasks are reactive in nature, in that they represent fault detection rather than prevention. Other activities, which are designed to be proactive, frequently turn out to be reactive because contractors pay lip-service to them, perhaps by conducting them far too late to be able to influence the design process. One such example is a Failure, Modes, Effects and Criticality Analysis which, when conducted at the relevant stage, can influence design and provide designers with an understanding of the consequences of failure, thus allowing effective alterations to be incorporated as necessary. However, it is often applied too late to have any meaningful impact on the design and is often regarded as a deliverable to the MOD rather than an aid to design

11. During testing, sample sizes required to resolve low failure rates become impracticably large and economically untenable. To present large numbers of components for confidence testing, either for qualification or monitoring purposes, is unrealistic. During such testing and initial production, few products are available at a time when manufacturers wish to maximise the number of parts for delivery to the customer. Even during full production, there is reluctance to divert large numbers of components for testing and suffer the consequent financial loss. Also, with small order quantities, there is every chance that the number of parts needed for testing would exceed the total number produced. Consequently, the return on investment in conducting tests to provide evidence of product reliability needs to be carefully evaluated as component reliability estimates increase. Testing for high MTBF potentially requires massive investment in parts and test time which manufacturers are understandably reluctant to do. This again leads to the 2 linked concepts of M/F-FOP, aimed at overcoming this dilemma whilst also providing the military commander with greater operational availability and mission reliability. M/F-FOP confidence would be obtained by a combination of progressive assurance during development and production supported by a tailored in-service demonstration.

FAILURE-FREE OPERATING PERIOD

12. A Failure-Free Operating Period (F-FOP) means that the equipment is able to operate to its full mission requirement for the period required or specified. There may well be faults which occur, however, the required system operation is unaffected and thereby no functional failure is recorded. Clearer comprehension of the mechanics of failure and ruggedness of components, together with better understanding of the operational environment can lead to a probability of time in-service before the occurrence of a failure. The ability to plan for known periods of high operational availability remains a key feature in the effective use of expensive assets. To achieve this, specifying reliability in terms of a F-FOP is a realistic option. The reliability requirements of some minor RAF equipment have already been specified in terms of a F-FOP. This does not mean that faults cannot occur, but rather that any faults which do arise are absorbed by the inherent fault tolerant architecture of the system. The application of a F-FOP maintains system functional capability whilst not necessarily restricting maintenance activity to certain periods, and as such is more applicable to CE systemsOne example of the application of a F-FOP is a ground-based radar installation, where the maintenance timing is not necessarily constrained.

MAINTENANCE-FREE OPERATING PERIOD

13. A Maintenance-Free Operating Period (M-FOP) for a weapon system is a period of operation during which a number of assigned back-to-back missions would be carried out, without any mission losses due to system faults and with no unscheduled maintenance activity. As with the F-FOP, this does not necessarily mean that the system must be fault free, rather that any fault which does occur must be absorbed by the system and not lead to system, and potentially mission, failure. Even if a fault occurs on the first sortie, the system must be able to continue to the end of the M-FOP with that fault still present. The only maintenance envisaged during the M-FOP would, for a military aircraft, be that typically carried out during flight servicings. This would include re-arming, refuelling and routine inspections. The M-FOP concept is currently being addressed within ST(A)425 Future Offensive Air System (FOAS) feasibility studies to demonstrate that in theory M-FOP is technically achievable and to reduce project risk from poor reliability.

MAINTENANCE RECOVERY PERIOD

14. When the equipment requires maintenance this would be carried out during a Maintenance Recovery Period (MRP). After each designated M-FOP there would be a MRP which would include all maintenance actions necessary to recover the weapon system to a state whereby it can complete the next M-FOP. The length and content of the MRP would be directly related to the length of the previous M-FOP and the required length of the subsequent M-FOP.

15. Within the MRP there would be different maintenance policies for different systems and equipment, but at this stage there should not be any pre-conceived solutions. This responsibility would fall to the Design Authority, who may need to make trade-off decisions about improving the reliability of one part of the design to achieve a more practical system or overall M-FOP. Generally, the aim would be for all maintenance to occur on a planned basis which would mean that the designer would have a much greater appreciation of how and when items fail.

ENABLING TECHNOLOGY

ACHIEVING A MAINTENANCE-FREE OR FAILURE-FREE OPERATING PERIOD

16. Fundamental to the achievement of a M/F-FOP will be a bottom-up approach to reliability with a clear understanding of why items fail and an ability to predict accurately when they will fail in use. Gathering relevant environmental data such as aircraft localised vibration, temperature and humidity, as well as indicative failure characteristics at the earliest stage in the development programme, will offer designers much better opportunities to design for durability and reliability. An early indication of design weaknesses will also allow precious resources to be focused in the appropriate development areas to maximise return on investment. Specifying reliability in terms of M/F-FOPs would motivate the designer to devise a fault tolerant architecture. Naturally, the reversionary configurations would need to meet relevant airworthiness requirements. An essential factor in such fault tolerance is detection using BIT and HUMS, together with an ability to override item failure. The following techniques and methods are relevant:

a. Condition Monitoring. Measurement and interpretation of data, condition indication, determination of maintenance requirement.

b. Redundancy. To achieve fault tolerance, using either hardware, software or data duplication in various forms. Can achieve significant reliability gains but at cost of potential increased complexity, weight, volume and power consumption.

c. Re-configuration. Recovery, automatic or otherwise, of a system after a failure without the need for the system to go off-line.

d. Advanced Diagnostics. To enable timely, accurate failure diagnostics to support minimum repair times during the MRP.

e. Prognostics. The capability to detect early warning of impending failure, enabling pre-emptive maintenance action to be carried out or to trigger re-configuration or redundancy processes.

f. Reversionary Modes. Allowing the software to back-up when a failure occurs and take a different path, thus bypassing failure causes.

g. N-version Programming. A software form of redundancy, involving voting between differently, often independently, developed software units.

h. Recovery Blocks and Self Healing. Backwards error recovery carried out by periodically saving the system state and reverting to it when necessary.

j. Exception Handling. Giving the software the ability to deal actively with failures, so avoiding system crashes or erroneous results.

CHANGING DURATION OF A MAINTENANCE-FREE OR FAILURE-FREE OPERATING PERIOD

17. Statistical analysis should substantiate the reliability of the proposed architecture and identify faults likely to occur during the operating period. Once equipment has reached a mature in-service phase, the

periods of maintenance-free operation may be amended in the light of further analysis of user experience. However, these changes would not be appropriate for immature equipment without the requisite field experience and supporting data.

CURRENT RESEARCH

18. Under the auspices of The Committee for Defence Equipment Reliability and Maintainability (CODERM), some practical aspects of specifying reliability using the M/F-FOP approach have been examined. Whilst much work remains to be conducted, desk level agreement has been reached that M/F-FOP is an acceptable alternative for the specification of reliability, provided that evolving results from continued conceptual development substantiate its future effective use. In addition, under the Society of British Aerospace Companies (SBAC) Foresight Action initiative, which aims to provide a national programme for aerospace growth through capability demonstration, the Ultra Reliable Aircraft programme is developing the application of M/F-FOP through modelling activities in particular. The current Future Offensive Air System (FOAS) feasibility study phase requires the contractor to examine M/F-FOPs with respect to FOAS. This is creating additional research in itself. Work in the United States, partly MOD funded and with active MOD participation, is investigating physics of failure mechanisms, the results of which will benefit designers working to M/F-FOP criteria. Through the presentation of papers and formal and informal contacts with defence industry representatives, the concept of M/F-FOP is becoming better understood and acknowledged as a potential significant contributor to enhanced weapon system reliability.

CONSEQUENCES

IMPACT OF A MAINTENANCE-FREE OR FAILURE-FREE OPERATING PERIOD

19. M/F-FOP approaches reliability from a different standpoint, focusing on determining and understanding causes of unreliability or failure and eliminating or controlling them. Not only does this allow potentially a new way of ensuring product reliability, but it also provides a methodology for improving it.

20. M/F-FOP involves a continuing search for, and implementation of, reliability-driven designs. Characteristics of such designs mean that a product should be more resistant to failure mechanisms, defects, and the degradation of materials and components. This obviously requires effective, informed communication between all disciplines involved in the design, development, manufacture and use of the system. Assuring and improving reliability requires an integrated effort between suppliers and customers, a responsibility which implies the removal of some organisational walls. In addition, current customer expectations of failure-rate predictions based on test data will have to be re-directed to be consistent with an emerging M/F-FOP methodology. To modify such expectations and promote the role of the customer in the M/F-FOP process, the degree of trust and communication between customers and suppliers must be increased substantially from current levels. This is precisely the message emanating from both MOD and the Defence Industry in the wake of SDR and Smart Procurement : there must be greater openness and trust to underpin mutually beneficial partnering arrangements.

BENEFITS

21. The fact that a weapon system will only need particular levels of maintenance at pre-determined intervals would greatly enhance the mission operational effectiveness. Systems would be available when needed and mission failures would be significantly reduced. Maintenance downtime would be programmed around operational commitments, with concomitant simplified supply chain management. Being able to make dramatic reductions in unscheduled maintenance arising rates would be a major advance. It would minimise logistics support and the costs to repair. To realise this objective will, however, require a significant culture change amongst many key defence contractors. Other potential benefits include:

a. M/F-FOP is simpler than MTBF. It therefore offers an improved basis upon which to contract for reliability.

b. Familiar and comfortable design practices would be abandoned and contractors would gain a deeper insight into their product. There would be greater research effort into failure mechanisms and development of the necessary design tools.

c. Reduced random component failures.

d. A physics of failure approach would be more likely to identify the true causes of failure than a statistical analysis involving MTBF.

e. The assumption of a constant failure rate would be challenged because system predictions would be built-up from the sum of the individual component failure distributions, rather than as a population, giving a more realistic bottom-up rather than top-down approach.

f. Using the principle of a failure-free period rather than failures randomly occurring would alter the basis of logistics planning. Compared with using reliability predictions based on constant failure models, more realistic spares provisioning should be possible, and expensive, inconvenient unscheduled maintenance should be minimised.

g. The approach would deliver a simple and more confident prediction of fleet costs and lease pricing details. Although contracting mechanisms for M/F-FOP need to be developed, they do lend themselves to alternative methods of logistics support.

RISKS AND COSTS

22. There are potential risks and costs in moving from MTBF to a M/F-FOP. The new approach may increase the frequency of inspection or refurbishment requirements for some parts. Other components may be scrapped before the end of their previously used life. Each component, LRU and system will require design analysis to establish its optimum M/F-FOP and associated cost. Some items will need little change, however, others may require design changes or an appraisal of whether inspection, refurbishment or scrapping would be more cost-effective. Modelling this scenario to determine potential manpower savings has proved difficult. In addition, there is the possible increase in acquisition cost as a result of the more rigorous design process. It will be essential that further work is undertaken to understand the trade-off between the investment in design/manufacture for M/F-FOP and the cost/operational consequences of today's poor equipment reliability.

23. There is the additional problem of aggregation of a large number of individual LRUs, sub-systems and system M/F-FOP into an overall weapon system M/F-FOP which needs skilled techniques and analysis to considerable depth. A clearer understanding of the M/F-FOP concept will require an integrated knowledge of engineering process design, an appreciation of practical in-use problems and an understanding of statistics. If the potential benefits are not to be negated at the systems integration stage, prime contractors will need to introduce process improvements and pay greater attention to detail during this phase. Partnership between sub-contractors, suppliers, prime contractors and customers will be essential. The greatest risks lie with system integration and participant motivation, yet the potential rewards are huge, both for producers and customer alike.

FUTURE AREAS OF STUDY

24. Further work is required to establish the main inter-relationships with operational effectiveness and logistics support when using M/F-FOP. This would include: application to different types of projects, for example, COTS; statistical inferences of M/F-FOP and associated confidence levels; contracting issues; methods for the assurance or demonstration of M/F-FOP; and how the use of M/F-FOP would interact with the ILS process. These are significant pieces of work, which have been brought to the attention of CODERM and which must be taken forward in partnership with industry. Moreover, experience to date suggests that reliability requirements for certain new projects should be specified in terms of a M/F-FOP whenever appropriate. Understanding, experience and knowledge will thus be enhanced. Furthermore, discussions and research through CODERM show the applicability of M/F-FOP across all defence environments. It is therefore essential that the approach is matured on a pan-PAO basis.

CONCLUSIONS

25. Current reliability specification methods do not take account of the understanding of fundamental failure processes. An alternative , M/F-FOP, embraces a logical, integrated approach to reliability, targeted at achieving greater accuracy in weapon system reliability predictions and hence, increased operational availability and reductions in life cycle costs. Product reliability assurance for items with high predicted MTBF and hence low failure rates becomes a costly, inaccurate process. Design to M/F-FOPs focuses on causes of failure, and their control or elimination, rather than on measuring and responding to their effects. The success of M/F-FOPs lies in the designer's clear understanding of failure mechanisms in the appropriate environment, a comprehensive, integrated design approach and the further maturity of key enabling techniques. Current limited work, supported by CODERM, is developing M/F-FOPs.

26. Progression of M/F-FOPswill require specific partnering between customers and suppliers at all levels. Additional potential benefits of such partnering would include a stronger basis on which to contract for reliability, greater insight into product design, enhanced realism in spares predictions and reduced logistics costs. Risks lie with enabling technologies not being sufficiently mature, particularly modelling techniques and the need to demonstrate clear cost reductions over a product's life cycle. Factors such as premature item replacement before useable life is consumed, the successful integration of a large number of items with different failure rate distributions and the need for additional up-front design will all have an impact on cost. It is, therefore essential that future areas of study are identified, prioritised and funded with MOD, through CODERM and in partnership with industry, playing a leading role.

Maintenance and Failure-Free Operating Periods

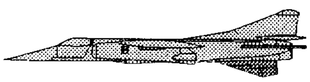
M/F-FOPs

Sqn Ldr P Mitchell RAF
LOGS(OR)5d
01480 52151 ext 6213
pm@logs4raf.demon.co.uk

WHAT DOES THE FUTURE HOLD?

- Pressure on Defence Budget
- Smaller RAF
- Less Manpower, more efficiency
- More deployments, more flexibility
- More complexity and more expense
- Global competition

THE KEY TO FUTURE AIR POWER



MISSION RELIABILITY

MISSION EFFECTIVENESS

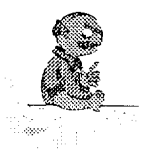
Weapons that Work
Whenever Required
and keep on
Working

W^4

WHAT THE CUSTOMER ACTUALLY NEEDS

Guaranteed Periods of Availability

result



Mission Effectiveness
Planning Certainty
Minimum Logistic Footprint

DEFINITIONS

- *Reliability* is: the ability of an item to perform a required function under stated conditions for a specified period of time. *Defence Standard 00-40 Part 1.*
- *OR:* the duration of failure free performance under stated conditions. *US Mil Std 785.*

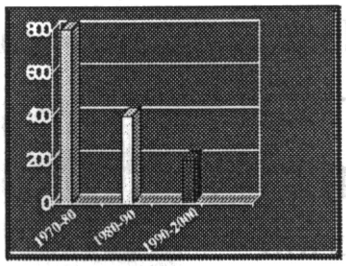
So Why Do We Use

The allowable number of faults in a given time

eg. 800 faults per 1000fg hrs

?

So What Next?



Predicting Failure Rates

VENDOR	Mil-Hdbk 217 prediction	MTBF observed
A	7247	1160
B	5765	74
C	3500	624
...E	2500	51
...G	1600	3612

Traditional R

MTBFs

- Failures are Inevitable
- Failures Occur Randomly
- Data is Aggregated
- Top-down Approach
- Accounts for Reliability

but

fails to Engineer a Solution

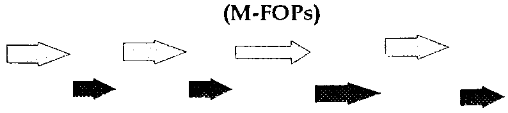
Traditional Approach to R

RAF specific problems with MTBFs:

- RAF ignores failure distribution and assumes constant failure rate.
  - Exponential Dist over 63% fail before MTBF
- Need to test all equipments to failure in order to substantiate a MTBF
- Large MTBFs mean long test times.
- Small sample sizes mean tests are statistically insignificant

The Way Forward

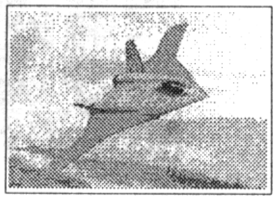
Maintenance-Free Operating Periods (M-FOPs)



Maintenance Recovery Periods

Twin Concept M/F-FOP

- Maintenance & Failure
- Free
- Operating
- Period



Definition of F-FOP

A period (measured in appropriate units) when the system is meeting its minimum required mission capability.

F-FOP APPLIED

- SR(A)1305 - UKADGE Command & Control System
- SR(A)0931 - Harrier GR7 ZEUS Upgrade

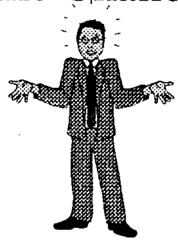
Definition of M-FOP

A period of operation during which the system must be able to carry out all its assigned missions without any significant maintenance action and without the operator being restricted in any way due to system faults or limitations.

M-FOP APPLICATION

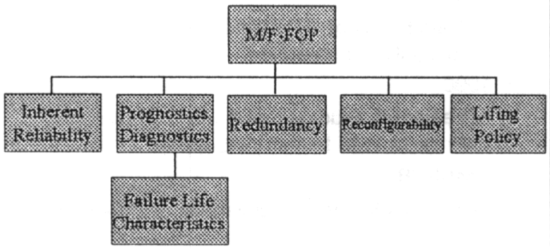
- MER 06/98 Satellite Communications System
- MMER(OE)(A) ALARP
- FOAS ST
- FLA
- INTERPRET
- Joint Strike Fighter
- FASM
- CV(F)

Platform M-FOP is the Challenge

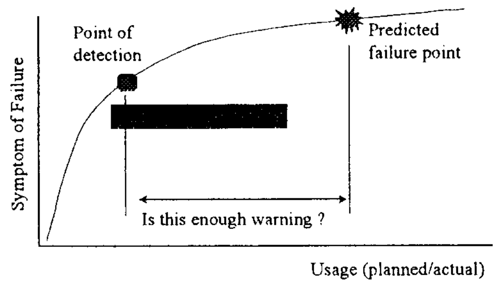


....how do we achieve it ?

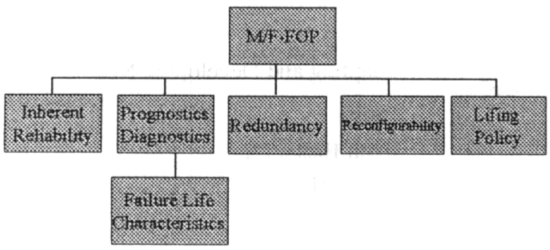
The M/F-FOP Options



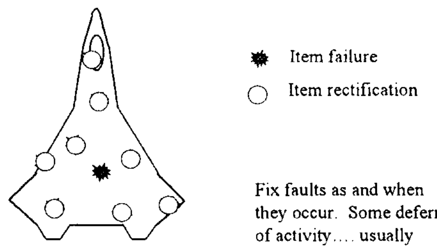
Failure Life Characteristics



The M/F-FOP Options

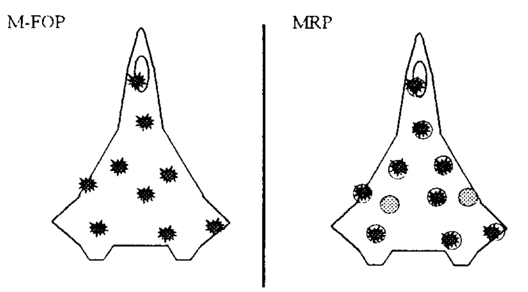


Current working practices



Fix faults as and when they occur. Some deferment of activity.... usually spares driven.

So what is different ?



Design Solutions

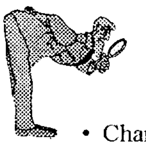
- SMART STRUCTURES
- SELF-DIAGNOSIS & CONDITION MONITORING
- EARLY INDICATION OF IMPENDING FAULTS
- FAULT TOLERANCE
- RE-CONFIGURABILITY
- SYSTEM REDUNDANCY

Design Solutions cont.

- DESIGN for LIFE
- GRACEFUL DEGRADATION WITHOUT MISSION LOSS
- NEW EMERGING TECHNOLOGY
- IMPROVED PROCESSES (IMPROVED RELIABILITY)

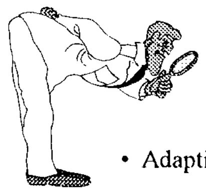
STRATEGY

- 1997
  - Main Focus on Problems of Current Reliability Approaches.
- 1998
  - Feasibility Studies and Apply to Minor Projects With Industry's Support.
- Post-PPB
  - Benefits & Cost Effectiveness of M/F-FOP.



The Risks

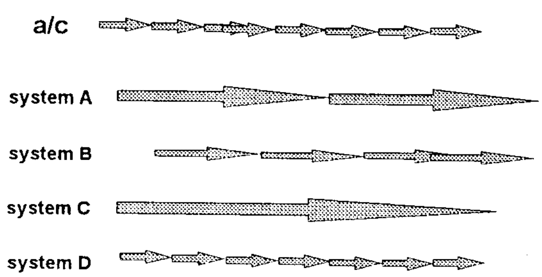
- Changing the Culture Throughout Industry
  - Including All Sub-contractors
- Perceived - or Real - Increase in Initial Costs
- Making the Partnership Work
  - So All Parties Benefit



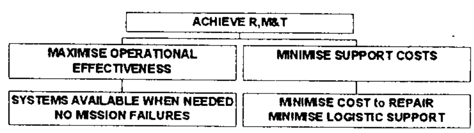
Continued.....

- Adapting and Developing New Tools
  - Mil-Hdbk 217F
  - LCC Models
- Contracting

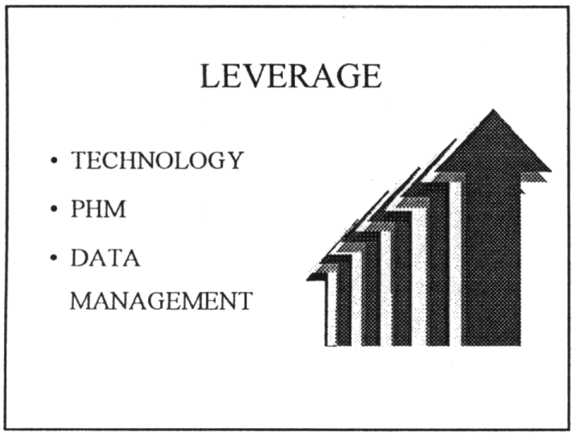
M-FOPs

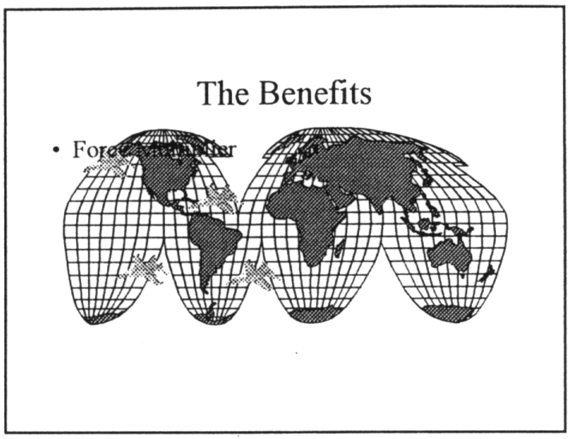


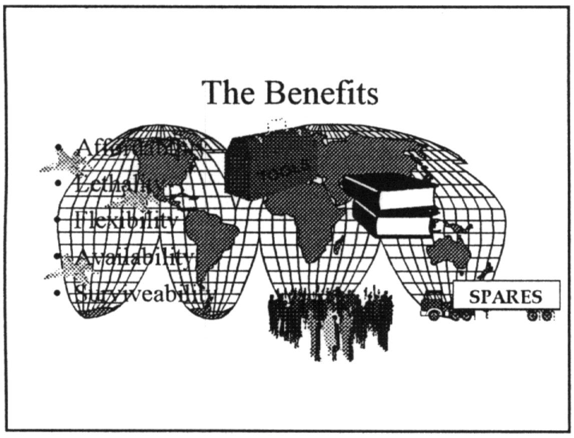
MOTIVATORS



Reduced Downtime
Reduced Logistic Footprint
= M-FOPs


LEVERAGE
• TECHNOLOGY
• PHM
• DATA MANAGEMENT


The Benefits


The Benefits
• Flexibility
• Availability
SPARES

The Ultra Reliable Aircraft

Ted Bottomley
British Aerospace Military Aircraft and Aerostructures
Research and Technology (W392C)
Warton, Preston
Lancashire, PR4 1AX, UK

Abstract
Rather than a flying aircraft, the Ultra Reliable Aircraft (URA) is a research project which aims to enable substantial increases in aircraft operational availability and reliability. Customers, both civil and military, now expect reduced costs with improved satisfaction and UK industry must take action to meet these new challenges. In response, the Society of British Aerospace Companies (SBAC) through their Foresight Action programme, initiated the Ultra Reliable Aircraft programme. This programme has, as its ultimate objective, the elimination of all unscheduled aircraft maintenance. However, at the current rate of design and development effort, and in terms of reliability, attempts to dramatically increase the in-service reliability of systems and equipment are providing diminishing returns. Even when new technology and increased complexity are taken into account, what is needed is a step change in reliability performance to break the trend and realise the levels of reliability required to respond to the new challenges.

1. Introduction

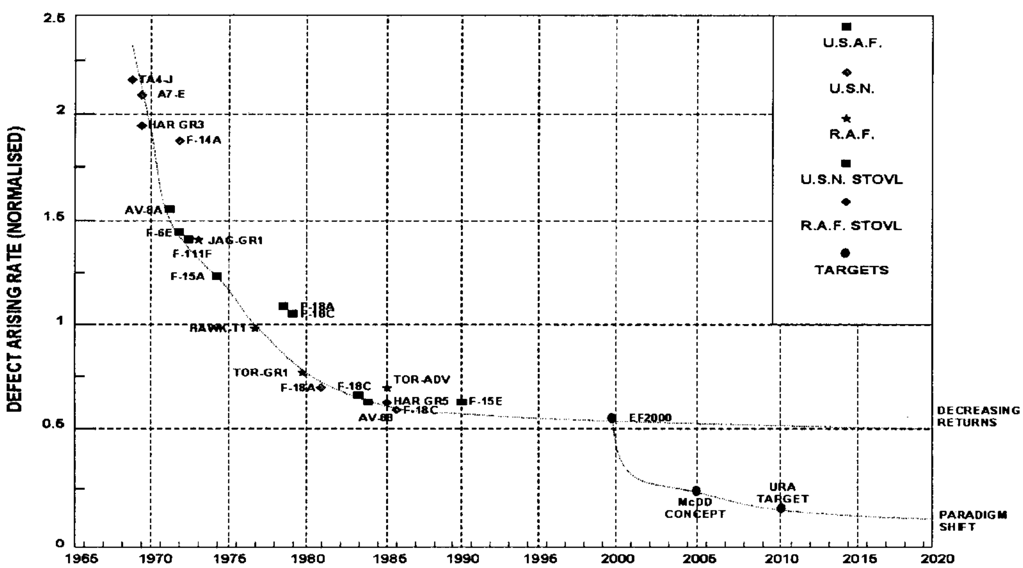
In the last ten years, the UK share of the world market for aerospace products has reduced from 13% to 9%. In the same period, competition has intensified with new entrants and existing competitors presenting new challenges. Customers expect both reduced costs and improved satisfaction and UK industry must respond to this environment and meet these new challenges. For the UK aerospace industry to maintain or increase its share of the highly competitive global market place, it must aspire to become the global benchmark for affordable Life Cycle Costs (LCC).

It is a well known fact that unscheduled maintenance disrupts the availability of aircraft and equipment, as well as producing uncertainty in the cost-effective use of assets; this has the overall effect of increasing LCC. Analysis has shown that investment in developing the processes and technologies relating to aircraft reliability will provide the greatest pay-back in terms of reducing LCC.

To a civil operator, the consequence of unscheduled delays and their rectification typically exceed £1M per aircraft per annum.
The MoD maintenance bill for its fleet is some £1B per annum.

With each new aircraft, there has been a trend towards improved reliability; this improvement has been most marked over the last 20 years. However, an extrapolation of the improvement curve shows that the gains in reliability are slowing and, if the future life cycle costs and availability targets are to be met, industry must seek ways of breaking free from the curve.

The step change required from the existing curve to a new and more aggressive curve has been called the 'paradigm shift'. The reducing returns and the paradigm shift are shown diagrammatically below:



Within the framework of the Foresight Action programme, the Society of British Aerospace Companies (SBAC) provided the focus for such an effort through the establishment of the Ultra Reliable Aircraft (URA) industrial collaboration programme. The overall aim of the Project is the elimination of unscheduled maintenance by achieving significant improvement in the current levels of reliability. The intention is to create a market differentiator for UK companies, through the reputation of their aerospace products, in terms of dependability and reliability.

2. The Ultra Reliable Aircraft Project

The URA Project is a consortium comprising customers and platform/major systems companies representing rotorcraft, military and civil aerospace interests. The major companies are members of the SBAC; however, the Project intends to include the involvement of suppliers at all tiers of the industry to enable reliability to be addressed at all levels of the supply chain. Membership currently includes:

> British Aerospace Airbus and Military Aircraft and Aerostructures; GKN Westland Helicopters Limited; GEC Avionics; GEC Aerospace; GEC Marconi Electronic Systems; Lucas Aerospace; Messier Dowty Limited; Dowty Aerospace; Normalair Garrett; Rolls-Royce Military and Civil; BMT Reliability Consultants; The Royal Air Force; The Defence Evaluation and Research Agency and Warwick Manufacturing Group (University of Warwick).

A collaboration agreement has been signed by the partners which indicates their willingness to recognise the need to break down protectionist barriers, even between competitors; especially when each partner stands to gain from a more capable UK aerospace industry base. It was also recognised that any new processes and techniques which may be the result of work done by the partners, should be protected in terms of Intellectual Property Rights (IPR). The resultant confidentiality agreement covering IPR, and protecting information of a more sensitive nature provided by the partners, has also been signed by all participants.

3. Method of Approach

The URA has three phases: a Pilot study (which is now complete), the main Project work and a follow-on demonstration. The main Project work is about 50% complete at the time of writing this paper whilst the demonstration phase(s) are currently under discussion.

4. Pilot Phase

A partnership of companies, sufficiently concerned about their competitiveness, agreed to collaborate using £0.5M of their own funding in a one-year pilot study. This commenced in April 1996, with the objectives of:

- Demonstrating that the URA aims are sound and achievable
- Demonstrating that the disparate companies can collaborate in an open and effective manner
- Planning for the URA Project main phase
- Preparing proposals to potential funding sources
- Publicising the potential of the Project
- Recruiting further members from industry and academia.

The URA Pilot study also aimed to identify the key processes that influence reliability. In order to achieve a significant improvement, it will be necessary to adopt new processes, develop new technologies and change the cultural attitude to reliability engineering.

5. URA Main Phase

Following the Pilot study, the main Project phase commenced in April 1997 and is being funded jointly by industry, the MoD and the DTI. The aim is to further develop the modelling, best practice and technology themes to a point where they can be applied to existing or emerging technology demonstrator programmes. A key aim is to identify the areas that will produce the greatest dividend in improved reliability.

5.1 Work Programme and Breakdown

The URA aims to achieve its challenging target through a programme of six Work Packages. Each work package has a lead partner and contains several sub-tasks. The first five packages have the following aims:

> **Work Package 1** - Identify the feasibility of achieving the complete removal of unscheduled maintenance and the provision of "guaranteed" Maintenance Free Operating Periods (MFOPs)

> **Work Package 2** - Identify and develop the world best practice 'Design for Reliability' and producing a 'Best Practice Handbook'

Work Package 3 - Demonstrate the benefits to aircraft operators through simulation of LCC reductions and the commercial benefit to industry through new operating procedures

Work Package 4 - Network existing technology programmes and identifying and developing technologies to support the target goals

Work Package 5 - Benchmark the URA partners against their competitors.

The sixth work package (Work Package 6) provides the overall co-ordination of the Project.

Each work package is more fully explained below and Appendix A details the objectives and task descriptions, along with the partners leading and/or participating in each.

1.1.1. WP1 Paradigm Development

This work package consists of studies into various support and procurement policies for aerospace products. It is evaluating alternative strategies and will determine the consequences, both technical and commercial, for suppliers and the operators. It involves the consideration of novel approaches to failure forecasting, condition monitoring and fault tolerance provision, as well as the contractual terms that might be invoked for performance warranties. The aim of the work is to identify a paradigm capable of the elimination of unscheduled maintenance and the provision of "guaranteed" MFOPs. In addition, this work package will include academic contributions to the other work packages below.

1.1.2. WP2 Process Group

The guiding principle for the process group is the perception that business engineering and manufacturing processes are the key factors in facilitating the production of reliable products. The URA Pilot activities led to identification of the sensitive processes and to their ranking, according to their impact on reliability.

The Process Group is developing a set of recommended processes, taking the best elements from any relevant sources, to produce a compendium of best practice guidelines for incorporation into the business procedures of the URA partner companies. The best practice guidelines are being developed from the practices in use in aerospace and from other industry sectors world wide. The task will involve literature searches, working parties and visits to partner companies, to review current practices and document the findings. The approach is using case studies taken from the partners and the study of how other companies improve their processes. Within Work Package 3 described below, the reliability impact of applying best practice is being assessed and compared with current performance. In addition, a set of selected processes for design, development, qualification and manufacture are being simulated in a synthetic environment model.

There is recognition that a more cross company participative culture is needed to address reliability, involving all levels of the supply chain. For example, involvement of participants from all levels of the supply chain will lead to improved project communication, design specifications and the more effective co-ordination of production quality. The relationships between suppliers at different levels in the supply chain, and between those at a similar level, whose products must integrate together are being studied. Recommendations will be made for preferred supplier arrangements and concurrent engineering practices, as they relate to the achievement of dependable and reliable products.

Tools and methods are being identified that will assist in the business, engineering and manufacturing process, including the collection of failure reports (both for products and processes), root cause analysis, collation of information on reliability databases, the best ways of assessing reliability, the best practice use of reliability procedures and lessons learned databases.

1.1.3. WP3 Modelling Group

In the URA Pilot Phase, the root causes of unreliability were investigated, using a causal tree model, populated with data from the records of existing projects covering each main sector of aerospace products. This was used to rank the drivers for the process and technology assessment main phase work. The impact of reliability on LCC was evaluated for some simple cases and this is being extended to a full study in the URA Main Phase. In order to work with contracts stipulating MFOP warranties, it will be essential to have a capability to credibly forecast the reliability performance of systems and aircraft in MFOP terms. This will require simulations designed to track a large number of individual lifed items for each aircraft and its systems, and to add in the effects of functional redundancy and carried faults. The failure statistics and characteristics of lifed items are being explored, to see if the variability between individual examples of components, and their usage, is small enough to allow meaningful predictions to be made. Reliability data for input to LCC models has been traditionally derived from "random failure" Mean Time Between Failure (MTBF) handbooks and company databases, which reflect existing products. A new style database will be needed for the assessment of future products based on the above MFOP principles. This database format is being generated together with the Technology Assessment group, to form an industry generic tool for reliability assessment.

A synthetic environment modelling exercise is being used to assess the impact of process improvements and novel technologies on the operational capabilities, costs and support levels needed, from the operators' viewpoint. This addresses operational readiness, availability, flexibility of deployment, attrition rate due to failures, mission success rates etc., for the military, and will review despatch reliability, Aircraft On Ground (AOG) provisions and support logistics for civil users.

1.1.4. WP4 Technology Assessment

Technological improvements can make substantial contributions to the reliability and dependability of aerospace products, not only in the fields of components, processes and materials, but also in the disciplines of systems architectures, diagnostics and fault tolerance. A major concern of all aerospace operators is the very high level of No-Fault-Found (NFF) removals, which greatly detracts from availability and adds to costs. The self diagnostic capabilities of equipment need to be greatly enhanced, by improvements in detection, location and false alarm rates. Available NFF data is being reviewed to identify root causes, both technically and organisationally. Current advances in diagnostics are being researched and recommendations made for reinforcement where shortfalls are identified. Operators and maintainers are being interviewed to further establish the underlying problems and their causes. Health and condition monitoring provides another avenue for improved dependability and the present capabilities will be established as the basis for recommendations for further developments. The current status of vibration spectral analysis, performance trend tracking, temperature profiles etc., is being reviewed and suggestions made for further improvement.

In order to assess the improvements likely to made by the introduction of specific elements of technology, a "tool" is being developed for use within the group, capable of:

- Co-ordinating the outputs of case studies, technology investigations and databases
- Collating information from existing reliability databases
- Listing relevant bibliographical references
- Running case studies into the consequences of technology insertion.

Within the participating companies, research institutions and academia, there are technology improvement programmes that will bring benefit to the reliability of aerospace products. The Technology Assessment group is considering how these can be networked to provide overall aircraft reliability improvements. From the Process and Modelling groups, the most significant and effective areas for realising improvements will have been identified. Where these are already being addressed within identified technology programmes, the URA will seek to establish links and monitor progress. Where there are technology gaps, not being addressed in such programmes, the Technology Assessment group are making recommendations for additional activities to complete the technology coverage.

1.1.5. WP5 Competitive Analysis

In order to track the benefit of the URA to the UK aerospace industries, a benchmarking exercise is being carried out, researching the capabilities of overseas infrastructures, their improvement status and rate of uptake of novel processes and technologies. The URA recommended practices will be compared with the international trends and any potential UK advantage(s) derived. Individual participating companies, within the URA, will be encouraged to align themselves to the benchmarks and then to evaluate their level of uptake of the potential URA benefits.

1.1.6. WP6 Project Management

The definition, process, modelling, technology assessment and simulation Work Packages are programme managed through a formal project management team, agreed by the consortium.

6. URA Demonstration

On completion of the technology assessment (WP4), a report will be produced recommending the process and technology demonstrations that would be required to progress towards the overall aim of eliminating unscheduled maintenance. These recommendations will place identified existing programmes in their reliability context and will advise where new programmes are desirable. Where a need to develop innovative technologies or processes is identified, recommendations for supportive projects will be formulated.

A LOW COST APPROACH TO OSS&E ASSURANCE THROUGHOUT A SYSTEM'S LIFE

Ajmel S. Dulai
Technical Advisor, Systems Engineering
ASC/EN
2530 Loop Road West
Wright-Patterson Air Force Base, Ohio 45433-7101

ABSTRACT

In periods of declining budgets and downsizing, it becomes increasingly important to select the best possible design and development approaches that provide the desired life cycle cost benefits while sustaining system capability. Aging of the United States Air Force (USAF) systems, factored with efforts to extend their operational longevity, has an impact on the systems' safety and operational capabilities.

On 3 December 1997, the commander of the Air Force Materiel Command (AFMC) chartered an integrated product team (IPT) to develop a cost-effective Air Force policy for assurance of operational safety, suitability, and effectiveness (OSS&E) of USAF systems. The team developed this new policy based on proven commercial and U.S. Government practices, processes, and methodologies in place today. A key element of this policy is the certification process that ensures airworthiness is established and maintained throughout the life of the system. The highlights of the policy and the selected processes, best practices, and methodologies are presented.

1. INTRODUCTION

The commander of the Air Force Materiel Command (AFMC), General George T. Babbitt, has long been concerned about the configuration control of Air Force systems. In 1997, he saw an alarming trend in the mishap rates in fielded systems and end items, which led him to question his technical staff as to how airworthiness is managed within the USAF.

To address this question, Aeronautical Systems Center (ASC) provided a comprehensive briefing in December 1997. It pointed out that the USAF did not have clearly documented airworthiness policies similar to those that the Federal Aviation Administration (FAA) imposes on commercial aircraft. The briefing emphasized that, as a regulatory body, the FAA is empowered by the FAA Reauthorization Act of 1996, as amended. The Act very clearly applies to civil aircraft and air commerce, but it does not apply to purely military aircraft. If the FAA were to address military aircraft, legislation would be required. Further, the FAA would have to expand its capabilities to address military-unique equipment and operations.

The briefing also points out that airworthiness is only one element of overall flight safety. Airworthiness is concerned with system design, the quality of the parts and their integration, operational flight limits, and the maintenance and repair of the aircraft and its equipment throughout its service life. The second element is the capability of the aircrew, which necessitates proper qualification and training requirements.

The safety of aircrew members is extremely important to the USAF. Equally important is the successful conduct of USAF military operations. Thousands of military and civilian lives are at stake if the outcome of a military operation cannot be controlled. Recent experiences indicate that air dominance plays the major role in controlling outcomes. Therefore, the Air Force's ability to accomplish its missions at will and in a timely manner is of the utmost importance. Thus, the suitability of the aircraft and its effectiveness also become key considerations along with safety of flight. For this reason, it was only logical for General Babbitt to expand the USAF airworthiness effort to include the operational safety, suitability, & effectiveness (OSS&E) required for successful military operations.

The current high rate of mishaps, decreasing trends in the mission capability rates, and the effectiveness of USAF systems have a profound effect on the ability of the Air Force to fight wars safely and effectively. These factors, combined with the realities of a shrinking DoD budget and workforce, demand that our resource utilization be improved considerably to sustain our air dominance in the world. Furthermore, for the past decade, workforce downsizing has constantly eroded our technical foundation in both experience and corporate knowledge.

The USAF aircraft mishap rate per 100,000 flying hours continues to climb. Mishaps may be caused by a variety of factors, including human performance, weather, design, technical orders/ manuals, operation, training, maintenance, aging of systems, dwindling resources, and infrastructure. For many USAF systems, aircraft mishaps are largely caused by human error. Yet, some of these human error mishaps are attributable to inadequacy of technical orders or manuals, or training of pilots or maintenance personnel. The USAF has the ability to control the factors that contribute to aircraft mishaps, except purely human errors, by improving technical rigor and applying disciplined engineering design techniques governed by appropriate policies and priorities. Therefore, AFMC has set an objective by the year 2005 to reduce by half the mishap rate resulting from controllable factors.

Concerned about the mishap trends and their potential impact on national security, General Babbitt tasked the commander of the Aeronautical Systems Center in December 1997 to take the lead for the USAF in establishing a new policy to assure operational safety, suitability, and effectiveness. The IPT chartered to develop this policy faced several challenges that are discussed in this paper. The specific objectives of the IPT and the philosophy adopted to overcome those challenges are also briefly discussed. The highlights of the policy are summarized. The major portion of the discussion, however, is devoted to those technical aspects that create the bedrock for this proposed policy. This paper further describes how those technical aspects could contribute to reducing the mishap rate. Additionally, it explores the costs for applying the disciplined systems engineering rigor and supporting processes, best practices, and methodologies.

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2. DISCUSSION

IPT Effort and Challenges

A highly cohesive, cross "Center of Excellence" OSS&E Integrated Product Team (IPT) was formed to address operational safety, suitability, and effectiveness issues and develop options for resolution. This effort affects USAF Product Centers, Logistic Centers, the Air Force Research Laboratory, Air Force Major Commands, the Air Reserve component, and Defense Logistics Agency. Stakeholders in addition to the Air Force include the FAA, Army, and Navy. A tremendous amount of information was collected from the various services and the FAA. As a basis for developing the policy, the team conducted a comprehensive review of existing policies, mishaps, airworthiness certifications, best practices, and processes. From these, the team selected information that could support a disciplined systems engineering process for OSS&E. In order to avoid duplication on joint programs and commercial procurements, one of the team's major objectives was to harmonize with the other services and FAA the USAF's proposed approach.

Mishap rate is a serious challenge for the USAF. The number of fiscal year 1999 (FY99) mishaps has already exceeded the number of FY98 mishaps." As of February 18, the rate of major F-16 accidents for FY99 was 5.83 per 100,000 flying hours. The rate in FY98 was 3.89, which was a 30 percent increase over the FY97 rate of 3.0 and an 81 percent increase over the FY96 record-low rate of 2.14 [1]. Engine failures and human errors continue to be the primary causes. However, most of the aircraft are designed for a 20-year design life and are flying today beyond their service life [2]. To a varying degree, all these airplanes can be expected to experience such aging problems as cracking and corrosion [3].

Furthermore, the aging aircraft inventory impacts safety and creates economic burdens. "Corrosion and fatigue separately have led to serious safety as well as economic problems" [4]. These problems are common to both military and commercial aircraft and have resulted in several mutual efforts to resolve those issues. For example, in 1989, the failure of the maintenance program to detect the presence of fatigue damage was cited as the probable cause for the commercial airline accident [2] [5] that led to military and commercial aircraft policies and priorities that benefited both. The FAA and NASA are developing a host of advanced, highly accurate, nondestructive evaluation systems that will significantly improve the accuracy of inspections while reducing airframe disassembly and associated costs [6].

The aircraft aging problem has been well recognized by the USAF and is being tackled on several fronts, such as structural integrity and corrosion control programs. The USAF has the experience in inspection and repair techniques to extend airframe lives beyond the 20-year design life [7]. The USAF structural integrity program and other services' efforts, in combination with industry initiatives, have kept aging issues in check to date. However, continued focus is needed in this area. The Air Force expects to mitigate the adverse trend in mishap rate through the development and application of the OSS&E policy and an emphasis on the use of disciplined engineering and risk management processes.

Mishap investigation reports provide much insight on the prevention of mishaps and possible safety improvements. The analysis of the information received reveals a clear breakdown in the Air Force technical processes. The technical processes are inconsistently applied across systems during acquisition and are seldom applied during the sustainment phases of their life. Because unauthorized changes have been made to systems in the field without the application of a disciplined engineering process, it is not clear who is accountable or responsible for some mishaps. Thus, the second objective of the team was to require the application of a disciplined engineering process throughout the life of the system. And a third objective was to delineate clearly the roles and responsibilities of the organizations and individuals (that is, the chief engineer and the single manager) in the policy documents.

The IPT faced many challenges in creating the OSS&E policy. Two major challenges are especially difficult to overcome in today's austere environment. The first one is that policies are generally viewed as adding to the product's cost unnecessarily. The issuance of a policy requires coordination with a multitude of organizations with varying interests. Valid concerns of everyone should be carefully considered and appropriate adjustments made to accommodate those concerns.

The second major challenge is that the acquisition reform advocates view imposition of policy as contrary to their initiatives. Most of the acquisition reform initiatives enjoy high visibility within the DoD and are resulting in significant cost savings. Therefore, it is extremely important to ensure that the new OSS&E policy continues to embrace acquisition reform initiatives. Open communications and stakeholder involvement are key in facing both of these challenges and gaining support.

Weighing these factors, and recognizing our dwindling resources, the team adopted a philosophy to develop a policy that fosters the combined use of industry and Government resources as a single team in fielding and sustaining capabilities required for our national defense. The team was cautious to avoid any policy content that may result in duplication of effort (e.g., obtain FAA certification where possible) or that may be in conflict with other initiatives. For example, the policy should not restrict the use of the clear-accountability-in-design (CAID) approach. Under this approach, the contractor is given control of the design and technical documentation, while the Government retains the responsibility for defining the required performance capability. While this eliminates duplication of responsibilities, it also affords a contractor opportunities to cut the development cost of products and parts. Given this authority to control the detailed design, technical data, manufacturing, and quality assurance, in essence, contractors are provided the flexibility to take advantage of nondevelopmental items (NDI), commercial-off-the-shelf (COTS) products, and the best practices & processes they deem necessary.

The IPT developed a common technical management process and created a draft guidance document, a draft Air Force policy directive, and a draft Air Force instruction in the short period of one year for the Headquarters AFMC to sponsor at the Air Staff level. In December 1998, the USAF Chief of Staff directed the cognizant organizations to expedite formal coordination of this policy.

USAF Policy Highlights

This section provides the synopsis of the new USAF policy for OSS&E assurance that is delineated in several hierarchical policies and related documents. The policy applies to Air Force systems and end items. The main focus of the policy is on improving the technical disciplines for effectively fielding Air Force systems. It requires the Air Force to assure the OSS&E of systems currently in, or entering the operational inventory and to employ a disciplined engineering process and effective operational, training, supply, and maintenance procedures to preserve its OSS&E throughout the operational life.

This policy mandates:

1) Systems and end items must be delivered with a baseline that enables continuing assurance of OSS&E.
2) Preservation of baseline OSS&E characteristics of systems and end items over their operational life.

Certifications, such as airworthiness and nuclear surety, are referenced in this policy as important, supporting processes, central to baseline establishment and preservation. These focused activities remain stand-alone Air Force policies. A separate Air Force Airworthiness Certification policy has also been drafted and staffed. Airworthiness certification responsibility resides with the single manager (SM) for the program.

The single managers and chief engineers are responsible for preservation of operational baselines and are required to utilize a disciplined engineering process toward that end. AFMC further assigns technical responsibility to its four Product Centers. Each Product Center is responsible for providing supporting policy, guidelines, processes, and technical standards tailored to their unique product lines. These tools will assist the single managers and their chief engineers in accomplishing their responsibilities and provide AFMC with necessary insight into the health of the fielded systems and end-items. The Air Force Operating Command will coordinate any changes to configuration or usage with the single manager/chief engineer.

While the single managers have the ultimate responsibility for OSS&E, they are expected to delegate authority to competent technical entities, as appropriate. The new policy requires that a chief engineer or lead engineer be assigned to each program. It allows the single manager to delegate authority for OSS&E technical aspects of the SM responsibilities to the chief system engineer. As an example, the chief engineer is responsible and accountable to the SM for assessing the airworthiness and formulating certification recommendations throughout the system's operational life. He/she will be responsible for preserving the baseline for fielded systems. The chief engineer will continue to provide technical risk assessments so the single manager, in conjunction with the users, can make informed cost and performance tradeoffs.

Selected Processes

The OSS&E Process Overview

The OSS&E process consists of two parts: 1) establishing the OSS&E baseline and 2) preserving OSS&E baseline characteristics throughout the life of a system. To establish the baseline, air systems are assessed for operational safety, suitability, and effectiveness. To preserve the baseline, this OSS&E assessment is updated throughout the operational life as missions and system use change, or as modifications are incorporated. Correspondingly, the airworthiness certification process also consists of two parts: 1) certifying airworthiness and 2) maintaining airworthiness certification throughout the life of a system. Aerospace vehicles are initially certified for airworthiness. To maintain airworthiness, the certification is updated to account for configuration changes throughout the operational life of the system.

Disciplined Systems Engineering Process

A disciplined systems engineering process is a comprehensive, orderly, iterative, problem-solving process that transforms validated user needs into a cost effective product for the customer to use reliably throughout its defined life. Many supporting processes are involved in transforming customer's requirements into a description of a balanced life-cycle solution, including people, products, and subprocesses. The systems engineering process and its subprocesses apply to new system product and process upgrades and modifications, as well as to engineering efforts conducted to resolve problems in the field or on the manufacturing floor.

The following subsections address a few of the key systems engineering subprocesses. These are described at a very top level and are not meant to be all encompassing. Some of the generic subprocesses such as definition of requirements, incremental milestones (that is, design reviews, etc.), and test and integration are commonly applied across Air Force systems with varying degrees of success. They are necessary but are not addressed in this paper. Refer to MIL-HDBK-500, "Key Supplier Processes for Aeronautical Sector Acquisition and Sustainment Programs" [8] for further detailed information on those processes. The subprocesses discussed below, system integrity, risk management, and configuration management, occasionally lack discipline in their application during the development and sustainment of systems.

System Integrity Subprocess

The system-level integrity program is crucial to the engineering and management process used to ensure the design/modification, manufacture, quality, and maintenance of a system is consistent and compatible with both its intended and actual use. This is necessary to ensure the required levels of safety and reliability are achieved while meeting other performance requirements. When technological capabilities are incapable of maintaining sufficient safety margins while meeting required performance levels, safety margins shall be maintained via the modification of inspection, repair, and/or replacement intervals based on the life used and margin remaining. This necessitates a feedback or tracking mechanism to ensure adaptability to changes in usage. Additional feedback should also be provided to ensure the correctness and completeness of technical orders and training. Strong ties are required between configuration management and the system level integrity program to allow determination of the item's life remaining based upon how the system is used and maintained versus its expected usage at the beginning of the program.

Throughout the development (or modification) process, several integrity program functions should be performed. Figure 1 depicts key elements of the system integrity process. Each element, and its function or related activity necessary for ensuring integrity of the system, is discussed briefly.

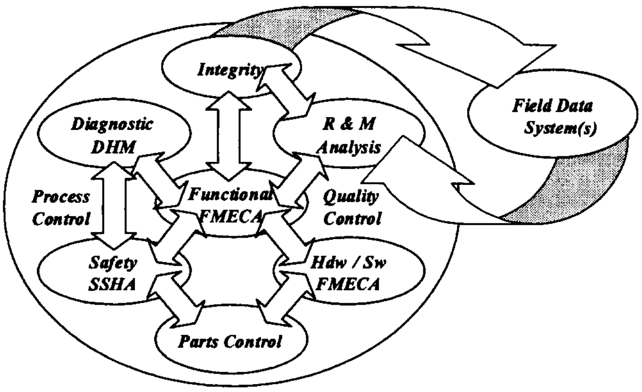

Figure 1
Key Elements

Field data system(s): Field data systems should provide serial number, part number, manufacturer number, tail number, accumulated stress, or hours as needed to be able to determine life used and indicate when maintenance, replacement, or inspections are called for to maintain appropriate design margins. Field data systems should accurately reflect the impact of functional failures and maintenance activities on meeting operational capabilities. Systems should minimize the need for input by maintainers and pilots. Notes from maintainers and pilots should be available for review. Databases containing maintenance information should provide direct links to manufacturing databases (failure reporting, analysis, and corrective action systems) and to warranty tracking systems to ensure manufacturers have the latest field information. Information should also be available for the chief engineer to review current fielded status and prioritization of fixes, etc.

Reliability & maintainability (R&M) analysis: Provides system level design considerations to ensure mission and hardware reliabilities are achievable and consistent with the user's needs. Integrity program tasks ensure a sound understanding of the environment and usage as well as the consistency and level of product quality to be accounted for in design.

Failure modes effects criticality analysis (functional): Functional failure modes effects criticality analysis (FMECA) is accomplished at the system level and should include functional failures of lower-level subsystems (both internal failures and loss of input). The functional FMECA describes, through the database, how functional failures propagate through the system as well as the eventual effects of said functional failures. These are expressed in terms of safety in addition to the diagnostic indicators that should appear and the actions the pilot or maintainer should take to mitigate the problem.

Subsystem safety hazard analysis: Safety draws initial information from FMECAs. Unlike FMECAs the subsystem safety hazard analysis (SSHA) evaluates multiple failure scenarios. The SSHA can result in designating items as safety critical and safety significant. A safety significant item or system is one that requires multiple failures to cause the loss of a function. For example, loss of flight controls on the new systems usually requires loss of three independent channels: in such a case each channel is considered safety significant.

Diagnostics & health management (DHM): DHM information is included in functional FMECA(s). Since both information pointing at the loss of a function and the cause of the problem are in the FMECA, it is a good source for DHM analysis. DHM can further use the FMECA(s) to develop fault-filtering algorithms to provide better isolation and to reduce false alarms. Where the loss of function is significant, it may also be presented to the pilot as an integrated caution and warning (ICAW). These, too, are usually part of FMECA(s).

FMECA (hardware or software): Hardware or software (Hdw/Sw) level FMECAs are generally done by subcontractors and are based on a piece-part (for software it means computer software unit) analysis of the subsystem in question. Hdw/Sw level FMECAs relate individual piece-part failure modes to losses of functions. The functional losses expressed in Hdw/Sw level FMECAs should be the same as those functional losses examined in the functional FMECA. Standardized database structures would help relate these level FMECAs to functional FMECAs and reduce the manpower needed to accomplish FMECAs in general. Hdw/Sw level FMECAs, when tied to functional FMECAs, reveal which part failures result in the loss of a safety critical and/or mission critical function.

Parts control: Parts control provides control for safety-critical parts through a serial number tracking system. Parts identified as safety critical through the FMECA, and those also identified as safety significant (needs multiple failures) via the subsystem safety hazard analysis (SSHA), may require special checks during manufacturing as well as in field usage. The parts control system should be capable of ensuring that the parts purchased are consistent with the intended usage and environment and have quality levels as good as or better than the parts they replace. Necessary part functional tolerances should be evaluated when considering a replacement part. Authority should reside under parts control engineering as opposed to being relinquished to a purchasing agent who is not under engineering control.

Quality control: The assurance of quality for production articles is critical to assurance and preservation of OSS&E. Quality, for the purpose of this discussion, refers to the engineering of the product to meet user's needs reliably (design quality) and the manufacturing of production units repeatedly in complete agreement with the design (production quality). To assure the quality of design, and to assure that the as-built configuration matches the as-designed configuration, an effective quality system should be in place.

Process control: In order to assure OSS&E of a product, the capability and stability of the manufacturing processes are extremely important. Therefore, the processes need to be qualified and controlled by the manufacturers throughout the life of a system. It would be possible to test fully each unit of product, including comprehensive testing necessary for the intrinsic manufacturing processes subsequent to the first production unit delivery. However, a more economical approach is to assure that follow-on units are functionally identical to the one that is tested. This should address the product characteristics that exert some influence over the product's OSS&E. Manufacturers should consider the minimum set of criteria listed below to assure OSS&E of a system (for noncomplex or COTS items, verification inspection and testing may be sufficient). A prime contractor for the system is responsible for the flow down of these criteria to appropriate suppliers.

1) Identify product's key characteristics (at the form, fit, and function level) that are related to OSS&E.
2) Identify appropriate product appraisal methods (inspection/test) for key characteristics and report results of those appraisals.
3) Identify key manufacturing process parameters that determine integrity of the product.
4) Identify the required key manufacturing process capabilities (e.g., process capability index, such as Cpk) and match them to the design requirements.
5) Implement controls over the key manufacturing processes.

Risk Management

Risk Management is a key element in the disciplined engineering process required to assure OSS&E and is an essential component in the Department of Defense's strategy for acquiring and sustaining mission-capable weapon systems in an environment of diminishing resources. A disciplined, comprehensive risk management structure involves the early and continuous identification of critical program risks, and the establishment and monitoring of risk handling plans. When properly implemented, an effective risk management program facilitates identification of areas that require special attention and supports setting realistic and executable technical, schedule, and cost objectives. Integrated Risk Management is the practice of controlling risks (those things that are in conflict with achieving program objectives). ASC uses the integrated risk management (IRM) process, which consists of four essential elements: planning, assessing, handling, and monitoring risk. It is implemented by IPTs, throughout the life of a program, to focus resources on the areas of the program that are most critical to delivering weapon systems that meet the user's mission needs. To be effective, risk management should be a continuous, daily activity employed from cradle to grave.

Configuration Management

An effective configuration management (CM) program is imperative in order to maintain operational safety, suitability, and effectiveness of Air Force weapon systems. CM provides the discipline, control, management of data, and access to accurate data that is necessary to implement the systems engineering process. CM principles are inherent in sound business practices to develop, integrate, test, acquire, operate, maintain, logistically support, and dispose of a weapon system. These practices apply across parts, assemblies, subsystems, hardware, software and firmware, and, indeed, all modifications to weapon systems.

Operational safety, suitability, and effectiveness are associated with a specific system or end-item configuration. The specific configuration and its characteristics should be defined by engineering data at all times. Therefore, a robust configuration management process should be used to establish and preserve operational safety, suitability, and effectiveness baselines. Permanent and temporary configuration changes, as well as the use of nonconforming material, will be reviewed and approved prior to implementation or installation. Delegation of specific configuration management authority between organizations should be formally documented. This authority includes configuration management responsibility for supply, maintenance, and user- and test-initiated changes.

Best Practices

In developing this policy, the IPT made a conscious effort not to limit any use of best practices currently reaping benefits in both the civil and the Government sectors. This approach lowers both acquisition and sustainment costs significantly and allows industry and Government to share benefits. Some of the best practices are briefly presented in this section.

Commercial Off the Shelf (COTS)/Nondevelopmental Items (NDI)

The DoD places enormous emphasis on the use of COTS and NDI for several reasons. COTS and NDI have many common attributes that reduce the total ownership cost of Government systems. All COTS are NDI, but not all NDI are COTS. The NDI could be a product or part that has been developed for another military application and may not have led to use in any commercial application. In contrast the COTS are products and items that are developed for the commercial market and are readily available for Government applications. In either case, there is no development effort involved. Both reduce acquisition cycle times for fielding a product, and the procurement costs are significantly reduced.

As a keynote speaker at a conference in 1998, Mr. Robert Spitzer, Vice President of Engineering at Boeing Commercial Airplane Group, remarked "Throughout years of air travel, safety has improved with the development of new technologies" [9]. He cited the development of jet engine technology as an example to support his point. Use of COTS items leverages the technology innovations of the commercial market that are outpacing DoD's ability to exploit them. This improves safety while increasing the availability of products from the commercial marketplace that satisfy military needs. The use of proven technologies further reduces another major portion of the cost; namely, that associated with an item's testing/qualification.

COTS items cover the entire spectrum ranging from systems down to piece parts. Where the Air Force mission is similar to the commercial sector, it affords a tremendous advantage to the Air Force to buy, in an expeditious manner, a commercial aircraft that has already been developed, tested, and certified by the FAA. Such acquisitions result in tremendous savings to the Air Force. The use of COTS at an equipment or part level improves the supply chain management posture for fielded systems. It increases the availability of equipment and systems for the war fighters. Additionally, utilizing commercial inventories provides the Air Force opportunities to reduce infrastructures that are required to support those weapon systems.

The use of COTS/NDI also allows our contractors to use their production, maintenance, and test facilities as well as associated staffs and processes for both commercial and Government use. Dual use of products, equipment, processes, and practices by the civil and military sectors, where it makes sense, is a "win-win" situation for the industry and Government. It not only cuts down the cycle time, but it also eliminates duplication. Further, COTS/NDI has a potential for minimizing inefficiencies and avoiding the waste of valuable national resources if the appropriate level of technical assessments and analyses are accomplished prior to their use.

There are two key elements of OSS&E that should be considered when using COTS/NDI. The first element is an understanding of the inherent capability of the COTS/NDI so as to form an initial OSS&E baseline. The second element is a thorough understanding of the operational requirements associated with its intended use as an end item or as an integrated part of a larger platform. Lack of, or incomplete knowledge of the inherent capability of the COTS/NDI does not exempt the chief engineer from OSS&E responsibility. It is the responsibility of the chief engineer, as part of the overall acquisition strategy, to acquire or develop the key product characteristics, including COTS/NDI, necessary to form the basis for an initial OSS&E assurance baseline.

Performance Based Specifications

Military specifications and standards reform initiated in 1995 was a key aspect of DoD acquisition reform. Any military specification or military standard which contained detailed levels specifying "how to design" systems/items was considered inappropriate for new development efforts. Most were cancelled and others needed to be rewritten.

Back in the 1970s, the Air Force had embarked on a standardization effort called MIL-PRIME to ensure that the Government provided requirements for acquiring aircraft products in terms of operational performance. Having used this approach to acquire many systems, the industry and other services within the DoD endorsed this idea.

The MIL-PRIME concept was generally acceptable, but the documents needed restructuring and editing. MIL-PRIME documents were not consistent in content, and their level of detail varied.

Under the purview of the Joint Aeronautical Commander's Group (JACG), therefore, this initiative to specify performance requirements was revived with industry participation under the name "Joint Service Specification Guides (JSSG)" [10]. The JSSGs are being developed by the JACG Aviation Engineering Board (membership includes Industry, Army, Navy, and Air Force). These Guides contain the current best available guidance for identifying general performance requirements for aeronautical systems and subsystems. These guides are fundamental for preparing specifications for performance-based systems and major subsystems and airworthiness certification criteria. This JSSG approach provides the contractors clear accountability in designing safe, effective systems in a most economical way.

Form Fit & Function (F3)

The concept of form fit & function has been applied selectively to military systems for at least the past three decades [11]. Its application has brought mixed success for many reasons. One of those reasons has been that, until recently, commercial technologies lagged the technologies needed by the Government by several years. Another major obstacle has been that commercial parts and equipment were not suitable for military use mainly due to their lower standards for reliability.

This trend has now reversed. A large, competitive, commercial marketplace exists with expanding domains of application. Competition is driving technology innovations and variety in functions and performance. The technology innovations, in turn, have vastly improved reliability of electronics equipment and parts; and the trend continues. At present, the commercial technology is outpacing DoD technological needs. Parts and equipment that provide the desired functionality and performance at competitive prices are readily available commercially. In addition, system architectural schemes allow replacement of older equipment with new-technology equipment using the F3 approach. This is especially attractive for the military applications in which system life spans several decades.

The OSS&E policy takes these considerations into account and encourages the exploitation of the F3 concept. As long as the usage spectrum and the environments are conducive to the use of F3 parts or equipment, the original equipment manufacturers are given the flexibility to make that determination without being hindered by the Government. The F3 concept is an integral part of several cost-cutting initiatives being pursued jointly by the industry and the Government. A few of these initiatives are total system performance responsibility (TSPR), flexible sustainment, and diminishing manufacturing resources.

FAA Certifications

The FAA certification methodology has been developed over 40 years and is accepted world wide as the premier method of certifying aircraft. The new Air Force policy takes full advantage of the FAA methodology, when practical. For systems with unique Government missions, the Air Force has created a methodology that parallels the FAA policy construct. Current USAF commercial-derivative aircraft with missions similar to commercial operators (e.g., C-20, VC-25, C-32, C-37) will be FAA certified. The USAF hybrid commercial-derivative aircraft (e.g., E-3, E-4) should comply with FAA standards to the extent possible. Use of commercial-derivative aircraft in meeting Air Force missions is a special case and usually requires adaptation of the Air Force airworthiness methodology. Obtaining and maintaining FAA certification for the above cases is both cost effective and the preferred method of assuring airworthiness.

Methodologies

System Safety

System safety is a vital part of the OSS&E for the life of a system. The objective of system safety is to achieve an acceptable level of mishap risk through a systematic approach of hazard analysis, risk assessment, and risk management. Current Air Force policy details responsibilities for program managers with regard to the US Air Force Mishap Prevention Program. Specifically, program managers responsible for the development or modification of a system are to establish and maintain a tailored system safety program in accordance with MIL-STD-882D [12]. MIL-STD-882D has recently been revised with industry participation under the guidelines of acquisition reform. The resulting document requires judicious imposition of MIL-STD-882D. Only section 4 of the standard is contractually binding. This section provides for (1) documentation of the system safety approach, (2) identification and tracking of hazards and (3) acceptance of residual risks by the appropriate authority.

In addition to establishing and maintaining a system safety program, the policy requires system safety groups (SSGs) to be established for aircraft programs unless waived by the appropriate Government office. The purpose of the SSG is to oversee the system safety program throughout the life cycle of the system and to document the mishap risk review process. The Chief Engineer is a key member of the SSG. The SSG is to be chaired by the program manager or the deputy program manager, and is to have a charter which includes representatives from the system user in the membership. The system safety policy also defines the appropriate levels of Government authority for acceptance of residual mishap risks. This methodology is extremely important for the Government to maintain the cost control by focusing on eliminating unacceptable risks.

Operational Clearances at Program Milestones

The operational clearance approach is an orderly, incremental, sequential activity that leads to aircraft certification. This incremental clearance approach establishes a framework of responsibility and accountability for establishing and maintaining the operational safety, suitability, and effectiveness of weapon systems throughout their life. The operational clearance approach can be applied to new acquisitions, to modifications to fielded systems, and to modified commercial items. This approach should be applied any time changes are made to the approved configuration of a system or end item. The configuration control board should not give approval for any temporary or permanent modification unless this approach has been followed. It is comprised of two parts. One part deals with clearance for individual equipment items, and the second part deals with the aircraft as a whole.

Equipment operational clearance (EOC): The EOC methodology described here (or one similar) is a disciplined engineering process for assuring OSS&E of aircraft. It should be recognized that products that are safe, suitable, and effective result from the disciplined application of multiple technical processes. Some of these key processes have been presented above. These processes embody a number of functional disciplines, each with its own unique, expert knowledge base. Criteria are extracted from the expert knowledge base of several functional disciplines that have a direct effect on the achievement of OSS&E. Adherence to these minimum criteria may not guarantee safety, suitability, and effectiveness; however, deviations from these criteria dramatically increase the likelihood of unfavorable results. Additionally, more detailed criteria may apply given particular programmatic details. A prime contractor may have a more detailed description of methodology to accomplish the equipment operational clearances. At the discretion of the prime contractor, suppliers and equipment developers may be required to follow that specific methodology.

The contractor accomplishes initial clearance of the equipment prior to approval for first flight by the Government's aircraft program manager. The update to the clearance is accomplished for the follow-on clearances throughout the development activities leading to the final airworthiness certification for operational use. Any modification to the equipment that received an EOC as part of original aircraft certification effort will require an EOC and, depending on the magnitude of the modification, most likely recertification of aircraft.

Figure 2 is a notional representation of the equipment operational clearance methodology. It depicts progressive levels of design maturity as equipment moves to higher levels of clearances. This methodology would be applied to hardware, software, and removable/replaceable items comprising the various component items of the total system.

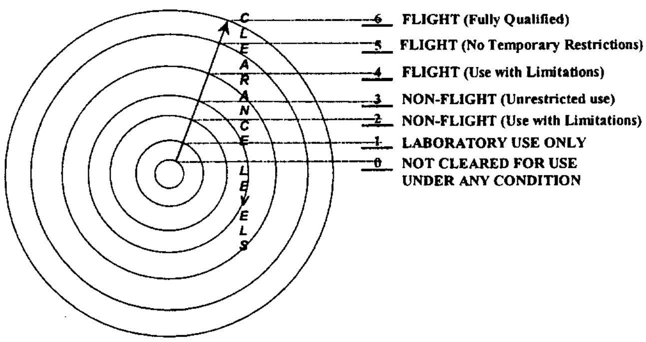

Figure 2.
Notional Equipment Operational Clearance Methodology

The exit criteria for each level should be established. Clearance to the next level should not be permitted unless the established minimum exit criteria for the current level has been met. To control the length of this paper, exit criteria for all levels are not presented. However, to illustrate how the graduation to next level of clearance takes place, level 0 exit criteria are provided below which show some top-level minimum criteria that should be satisfied to clear a particular item to the next level; that is, to level 1.

1) Functional requirements are properly defined and allocated
2) Integrity analyses are complete
3) FMECA is complete (functional, hardware/software)
4) Safety hazard analysis is complete
5) Interface requirements are documented
6) Detailed design criteria are documented
7) Conformity check is complete
8) Laboratory operating restrictions and limitations are documented
9) Laboratory test planning is complete

Air vehicle operational clearance: When we speak of the air vehicle as a whole, in contrast to the EOC discussed above, we are concerned only with establishing clearance levels 4 to 6, where flight operations are involved. As an example, minimum criteria to consider when clearing the air vehicle to level 4 are as follows:

1) All equipment operational flight clearances are at level 4 or higher
2) Flight test planning is complete
3) Aircrew and maintenance personnel are trained
4) Safety hazard analysis is complete

5) Flight and maintenance manuals are reviewed for adequacy
6) All aircraft operating restrictions or limitations are identified and documented
7) All problems from lower level testing are reviewed and dispositioned
8) All complaints from pilot simulations are reviewed and dispositioned
9) All problems from functional checks are reviewed and dispositioned
10) Independent review team review has been conducted (for air vehicle first flight)
11) All ground operation restrictions and limitations are identified and documented
12) Ground verification testing , flutter excitation, structural coupling, and electromagnetic interference tests are complete
13) Taxi runs are complete

Unless the minimum level 4 criteria are met, the air vehicle should not be cleared for first flight. In all cases, the individual hardware, software, or other removable/replaceable items of the air vehicle should have achieved an equivalent, or higher, level of clearance to that sought for the air vehicle. As mentioned above, the prime contractor, responsible for the development of the system, is also responsible for ensuring clearances. However, in addition to the contractor's clearances, the final approval authority for the conduct of first flight resides with the Government. With a large investment usually in billions of dollars and the fate of a program at stake, a comprehensive and complete review must be accomplished to determine airworthiness of the air vehicle. To conserve resources, it is only prudent to conduct a joint Government and industry review. Depending on the technical complexity of the program, a review conducted by a team of senior level experts from industry, Government and academia is highly recommended. Their recommendations to the appropriate Government official should form the basis for determination whether the air vehicle is safe and suitable for first flight. Again, more detailed criteria may be added given particular programmatic details.

Iterative application: Once level 6 clearance has been achieved for the air vehicle/equipment, any proposed change to the approved configuration baseline should enter the incremental clearance process at the lowest level and earn its way to the top. This iterative nature of the process application is what necessitates strict configuration control of the baseline configuration by the SM and the chief engineer. It is the linchpin in successful life cycle management of OSS&E.

Product Acceptance Criteria (PAC)

The methodology of product acceptance becomes of utmost importance in establishing and maintaining weapon system operational safety, suitability, and effectiveness. In the performance-based environment, it is almost certain that production products delivered to the customer will not be of the same physical configuration as the original qualified article. Proper documentation, an audit trail of qualifications, and a structured methodology for product development could avoid unnecessary expensive testing costs when accepting production products. Under the purview of the Joint Aeronautical Commanders, a "Performance Based Product Definition Guide" [13] has been developed which addresses PAC methodology in more detail.

A robust systems engineering process should go beyond simply providing a product design which has been verified through the qualification process to meet stated requirements. Design owners should also define and document "design intent," which captures the physical and functional aspects of the design solution that are key to its successful function. In addition, design owners should quantify the amount of variation of these "key characteristics" which is allowable in order for the product to function as intended. This information set is a subset of the total product definition that completely defines the product configuration and the processes used to produce it.

Once the key characteristics and limits of acceptable variation are defined, the design owner can develop product acceptance criteria (PAC) linked directly to these characteristics, which are traceable to the performance based requirements. Note that product acceptance criteria may take many forms: from physical measurement and inspection of hardware, to an acceptance test procedure, to statistical process control. The specifics will vary from case to case, but a common attribute is that any product that meets the criteria will possess the necessary functionality regardless of differences in physical configuration. This scheme also provides a baseline against which the design owner can evaluate the acceptability of future design and process changes.

The essential point is that the design owners should have the means to determine the adequacy of the products that they deliver to their customers. And the customers should, in turn, have assurance that the criteria that are to be used for product acceptance are based on sound engineering practices and are linked directly to the system performance requirements. This qualification process should be complete at the end of the development phase so that the PAC are available for use during the production program and the sustainment phase.

3. CONCLUSION

Mishaps in the aircraft business are inevitable. There are many factors that contribute to mishaps and most of those factors cannot be completely controlled. Therefore, complete prevention of mishaps is an impossible task. Safety hazards should be identified and eliminated or reduced to acceptable levels of risk over the operational life of the system. And those risks should be managed throughout the life of a system.

A reality that aggravates this challenge, today and for the foreseeable future, is managing risk within an environment of DoD downsizing and scarce budgets. OSS&E will continue to be a primary concern of the USAF. The process must continuously adapt to scarce resources in order to deal effectively with the changing situations in the world. Partnerships with industry, use of available proven processes and methodologies, and use of best practices are steps in the right direction to cost-effective improvement of OSS&E and mishap reduction.

Issuance of a high-level Air Force policy is only the first step toward this endeavor. The policy must be effectively promulgated throughout the Air Force for the entire product line. It is incumbent upon program managers, chief engineers and their staffs, maintainers, and operators to maintain a diligent approach to this serious matter. Concerned parties must understand their specific roles and responsibilities and must work in partnership with industry as a cohesive team to meet this challenge. The chief engineer is the critical link between the contractor and the customers. His task is to ensure implementation of a disciplined engineering approach that establishes and preserves technical integrity throughout the life of Air Force systems. Yet, the degree of success depends on the level of cooperation that stakeholders give to the chief engineer. Collaboration potentially can assure OSS&E of USAF systems, which furthermore extends to reducing the DoD economic burden.

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Identification of Life Cycle Cost Reductions in Structures With Self-Diagnostic Devices

Clemens Brand, Christian Boller
DaimlerChrysler Aerospace AG
Military Aircraft, PO Box 801160
D-81663 München, Germany

1. Introduction

Life cycle cost (LCC) has become an essential parameter not just for accountants but also in engineering. It is not only the cost for product development or manufacturing which are the significant portions in aerospace applications but also those for maintenance, repair and maybe even disposal. Structures made of emerging materials such as carbon fibre reinforced plastics (CFRP) lead to new challenges for aircraft operators, one being the limited experience regarding maintenance and repair related LCC of these structures when compared to the experience gathered so far with metallic structures.
Another big challenge is the increasing number and age of aircraft and the desire of military aircraft operators to keep fighter flight control systems as flexible as possible. This situation makes prediction of real service load spectra more and more difficult when compared to the situation in the past. The solution to this problem is increased monitoring in the 'advanced' age of aircraft which leads definitely to increased LCC. A way to reduce this LCC portion is automation, where various solutions for structural health monitoring have been proposed [e.g. 9]. These solutions include the integration of sensing devices into the structure in a way that non-destructive testing can become an integral part of the structural material.
Within this paper an answer will be given to the question: *How far can automation and thus self-diagnostic systems help to reduce LCC?* This will be done by assembling maintenance data of different metallic and also composite components and deriving some cost estimating relationships (CER) before discussing potential LCC savings when integrating a self-diagnostic system. Most of the discussion will be made on the basis of the metallic components before predicting some possible LCC reductions with regard to CFRP components just entering their life cycle. Conclusions will finally be drawn with regard to future developments of structural health monitoring systems used for self-diagnosis of aircraft structures.

2. Ageing Aircraft and the Consequences

A look into the statistics of what is considered as ageing aircraft shows that the number of such aircraft is increasing annually. For civil aircraft this number has already exceeded 3.000 worldwide and an even larger number can be determined for the military sector. Following the various initiatives launched after the Aloha Airlines Boeing 737-200 accident in April 1988 and the regulations issued with regard to ageing aircraft, the amount of inspection required for ageing aircraft has been significantly increased. This additional inspection effort is however still within the range of LCC allowed by the operator. An operator's driven request is therefore related to automating the inspection effort and thus reducing inspection cost.
One answer to this request can be in using robots [10]. However solutions available today are still limited to be used on the aircraft's outer surface only and still requires manpower to interpret the figure monitored by the camera being built into the robot. This procedure is still quite time consuming and thus requires the aircraft to be taken out of service for quite a substantial time. Furthermore such an approach does not allow to inspect any hidden places in the structure (e.g. frames) without removing and reinstalling a significant number of parts.
A much more promising solution can be obtained from smart structures considerations. This 'smart' solution is based on integrating or adapting sensing elements into or onto a structural component using the sensors to either monitor a loads sequence and thus determine life consumed or to identify damage itself. A description of this 'smart' approach is given below.

3. Actual Trends in Structural Health Monitoring

Aircraft structures are based on one of the two design principles: *safe-life* or *damage tolerant design*. When *safe-life* is considered loads monitoring is the appropriate solution. From the load sequences monitored the actual fatigue life is calculated and thus allows to determine the incident when the component needs to be taken out of service. The advantage of this approach is that the component can virtually undergo any load sequence and is not dependent on a predefined load spectrum and the allowable flight hours as having been done so far. Loads monitoring can furthermore be used to predict residual life based on the actual load spectrum monitored.
Loads monitoring is also a basis for monitoring crack propagation in the context of a *damage tolerant* design approach. In that case crack propagation is calculated from the load sequence using fracture mechanics models. This however requires that the location of the crack is known, which is only possible when traditional non-destructive testing is included.
The biggest challenge however occurs when damage initiation is the feature to be monitored. Due to statistical effects this incident of damage initiation can easily vary in the range of the assumed life to damage initiation. It is one reason for the high inspection efforts required so far and the high penalties put upon allowable stresses or fatigue lives to meet required security levels. This burden may however be reduced through a structure adapted or integrated health monitoring system since such a system performs inspection automatically and furthermore allows to clearly determine the incident of crack initiation at individual locations, thus taking advantage of each components individual life without compromising the safety issues.
The principle of structure integrated health monitoring is briefly described in Fig. 1. It consists of a sensing device, possibly followed by an amplifier, a filter and a signal analyser before processing and thus interpreting the sensor signal data in a computer. Limiting the monitoring system to these elements allows to monitor loads (including impacts) or sig-

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nals being generated by the damage itself and being monitored by techniques such as acoustic emission. This however makes the monitoring system very much dependent on monitoring the occurrence of damaging events. Much more independence can be achieved if an actuation device is added to the structural component as well, because a signal can now be sent into the structure at any time, just as when performing ultrasonics, only that the monitoring system is now structure-inherent. A technique suitable for that purpose is acousto-ultrasonics.

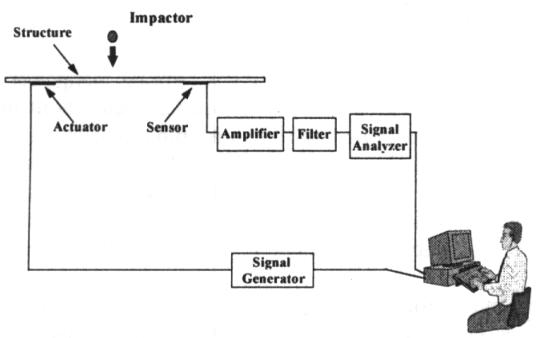

Fig. 1: The Acousto-Ultrasonics Principle

For the sensing device virtually any type can be used as long as it is able to monitor the respective frequencies being either generated by the load, damage or the actuation device. Two types have however been favoured during the past which is fibre optic and piezoelectric sensors respectively.

Fibre optic sensors are known to be advantageous due to their light weight, all passive configurations, low power utilisation, immunity to electromagnetic interference, high sensibility and bandwidth, compatibility with optical data transmission and processing, long lifetimes and low cost (as long as using silicon fibres). Disadvantages exist with the ability of repair as long as optical fibres have to be integrated into the material and placed according to major occuring stresses and strains for allowing to obtain reliable data. Fibre optic sensors have been proven to work for sensing strain as well as stress waves resulting from acoustic emission. Their integration into composite materials does not compromise the mechanical properties as long as the percentage of optical fibres is significantly low compared to the remaining fibre material.

Piezoelectric sensors are traditionally used for monitoring accelerations resulting from low or high frequency vibrations such as for monitoring vibrations in modal tests, Lamb waves or acoustic emission. Usually piezoceramic crystals are used which are relatively high weight and brittle. Recently piezoelectric ceramics have however been made available as small plates of different thickness, which can be cut to sensors of arbitrary geometry. These sensors may be bonded on the surface of a structure easily while integration into a structure is a greater challenge due to possible significant differences in mechanical properties between host and piezoelectric material. Recent research work is also looking at developing piezoelectric fibres to be integrated into composite materials. In the context of the acousto-ultrasonic system mentioned above, piezoelectric devices have the advantage of being used as actuation devices as well. This is why a monitoring system based on piezoelectric devices will be considered here.

Piezoelectric elements can be individually attached to or integrated into a structure and the different elements need to be connected by wires. However this is not the ideal solution for a kit which has led to development of what has been denoted as the smart layer [11, 12]. The principle of such a layer is shown in figure 2. It consists of two Kaptone foils, where tiny piezoelectric sensors as well as the required electric wiring is integrated in between, similar to the way this is done for electronic components. These layers can be either integrated into a composite structure or patched on the outside of any kind of structure (e.g. metallic, polymer, composite, etc.). Beside damage and cure monitoring they are also an interesting solution regarding monitoring of repairs. Smart patches can be configured with that technology which can be used for autonomously monitoring damage critical components. A software for generating the input and analysing the output signal is also provided. Sensor signals might be pre-processed on a built-in chip before being remotely transmitted to a full signal processing station.

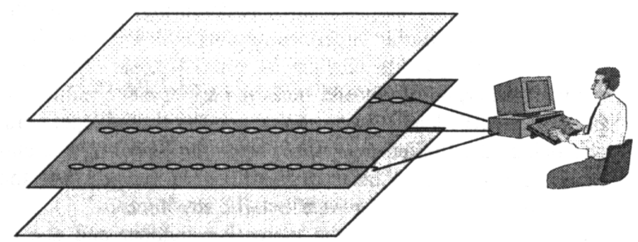

Fig. 2: Smart layer concept

Within the following chapters such a smart layer solution will be considered with respect to potential LCC savings on aircraft components. Since such solutions are especially attractive in the ageing aircraft environment, different metallic components will be considered first followed by an estimate on what possible LCC savings could be achieved one day with CFRP components.

4. The Life Cycle Cost Process

4.1 Background

Life cycle cost analysis is defined as "a general method of economic evaluation which takes into account all relevant costs of a building design, system, component, material or practice over a given period of time adjusting for differences in the timing of those costs" [4].

This includes in general costs for [5]:

1. Research and development (R & D) (C_{R+D})
   Initial planning, market-analysis, feasibility studies, software, documentation, project management etc.
2. Production and Construction ($C_{Manuf.}$)
   Industrial engineering, manufacturing labour, material, tooling and machines, process development, quality control and initial logistics support requirements (e.g. manufacture of spare parts).
3. Operation and support (O & S) (C_{O+S})
   Maintenance, storage for spares, fuel costs, test and support equipment, transportation and handling, technical data, system modifications etc.
4. Retirement and disposal ($C_{disposal}$)
   Disposal of non-repairable items throughout the life cycle, system/product retirement, disassembly and material recycling .

LCC is thus determined as the following summation of these cost parameters:

$$LCC = C_{R+D} + C_{Manuf.} + C_{O+S} + C_{Disposal}$$

The target of life cycle cost analysis is the development of a cost profile that models the cost distribution over the complete life cycle of a product as detailed as possible. According to [5] the method for building a life cycle cost model can be subdivided into the following steps:

1. Identification of all activities contributing to costs within the product's life cycle.
2. Assignment of activities identified under 1. in a cost breakdown structure (CBS) where a rough overall example of such a structure is given in fig. 3. Possible variants regarding different product variants, manufacturing processes and maintenance concepts should be included as well.
3. Establishing cost estimation relationships (CER), either self-developed or using parametric cost estimation models and tools (e.g. [8]).
4. Decision upon the reference date to be considered, which is either the value of LCC today or at a future date (e.g. the day of disposal), where the conversion follows an equation

$$x(t1) = (1 + \frac{y}{100})^{(t2-t1)} \cdot x(t2)$$

   with x, y, $t1$ and $t2$ corresponding to cost, interest rate (% p.a.) and two different points of time respectively.
5. Introduction of learning curves to account for technological improvements over time.
6. Summarisation of the different cost profiles within the CBS.

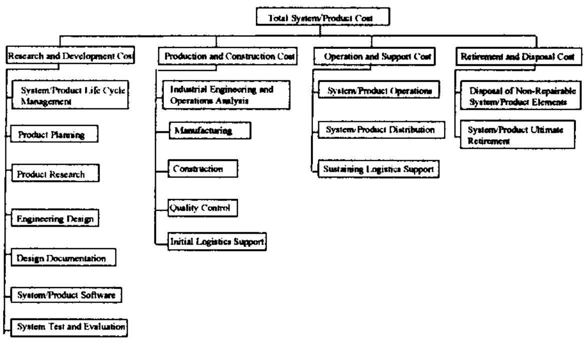

Figure 3: Cost Breakdown Structure [5]

The problem to be tackled with structural health monitoring is purely related to inspection, which is a sub-division within the O&S cost element. Assuming that the structural health monitoring device such as a smart layer is a device purchased through a supplier and thus neither generating non-recurring development cost nor interfering with the standard structural design, LCC reductions can thus be considered in an isolated approach as a reduction in inspection cost only. To however briefly describe the whole frame of the LCC model, a short overview of the O&S element is given below.

4.2 Operation and Support Model

Within the military aircraft environment O&S cost can be determined according to a methodology described in [3] thus containing information about

- maintenance planning
- repair analysis
- support and test equipment
- supply support
- manpower, personnel and training, etc.

There are also software tools available today for determining O&S cost (e.g. [6]). However such tools can easily require around 100 input parameters such as being related to:

- Parts, which includes unit cost, production volume, repair cost, mean time between failures (MTBF), etc.;
- Equipment, considering the system (e.g. aircraft) into which the considered part is built in;
- Environment, including the wide range from annual inflation and discount rate, annual billet cost for maintenance technician, number of repair depots, etc..

An overview of the calculation procedure is shown in fig. 4. A detailed look at this O&S split does however not give much information with regard to inspection cost. Due to this the respective data had to be retrieved directly from interviewing skilled maintenance personnel and converted into a model which is described in more detail below.

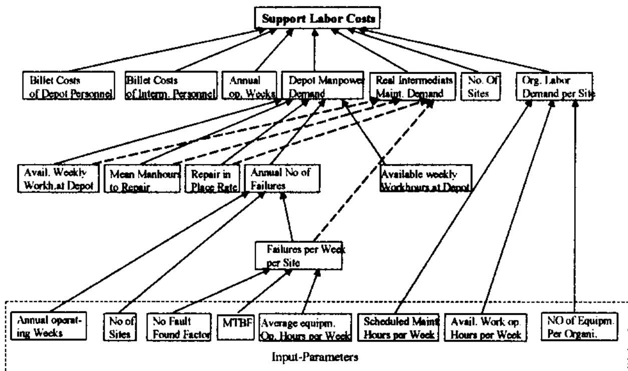

Figure 4: Calculation principle for the maintenance cost (simplified)

5. Case Studies

5.1 General

To determine the possible LCC potentials of implementing a structural health monitoring system (SHMS) into or onto an aircraft structure, a pragmatic procedure was established being based on a limited amount of maintenance data. This data was obtained as average numbers observed over a ten years period from experienced maintenance personnel. Two types of aircraft components were considered:

- Metallic components, where a large experience was gathered and thus data for different components could be obtained;
- CFRP components, where only very limited experience and thus data could be retrieved.

The approach was therefore outlined such that a CER model with respect to inspection effort could be determined for the metallic components and then converted to conditions for CFRP structures using the limited data for CFRP mentioned above.

5.2 Metallic Components

In the first step an analysis of the inspection effort distribution of metallic components of the TORNADO airframe was performed.

The distribution of the aircraft structure visual inspection effort is shown in fig. 5. It shows that the majority of this inspection is related to the aircraft fuselage and only very little to surface check for corrosion.

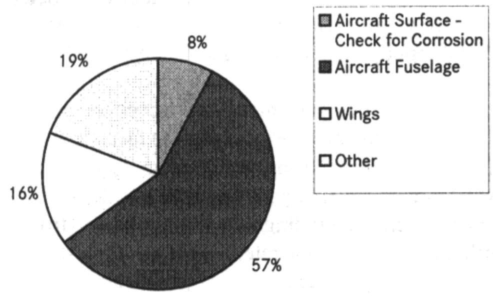

Fig. 5: Distribution of airframe visual inspection effort

The biggest part of the airframe inspection effort is due to visual inspection (61%), followed by unplanned NDT (31%) and planned NDT inspections (8%), see figure 6. The unplanned NDT inspections are in general due to the examination of assumed failures and repaired parts.

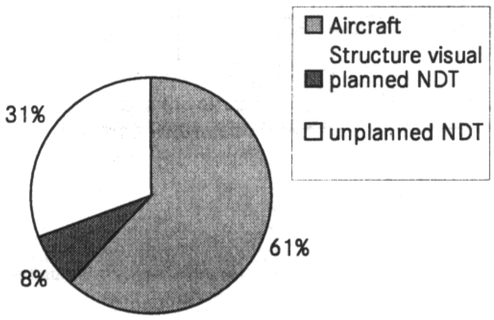

Fig. 6: Distribution of airframe inspection effort

With regard to metallic materials, six different components of the TORNADO fighter aircraft were considered which included:

- Two different types of fittings (fig. 7),
- Two different types of covers (fig. 8),
- A tail section skin (fig. 9), and
- The taileron (fig. 10).

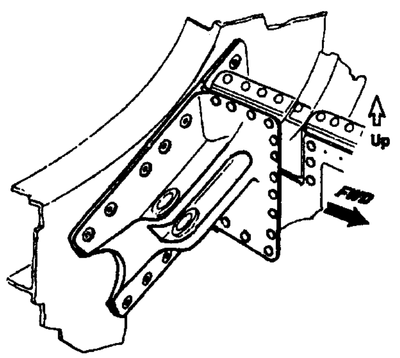

Fig. 7: Main Landing Gear Fitting

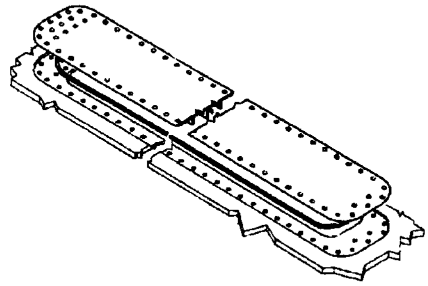

Fig. 8: Cover

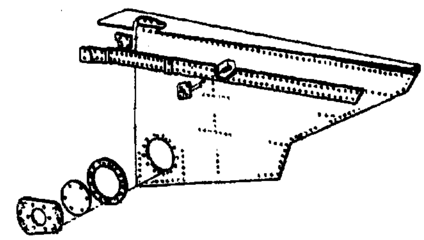

Fig. 9: Tail Section Skin

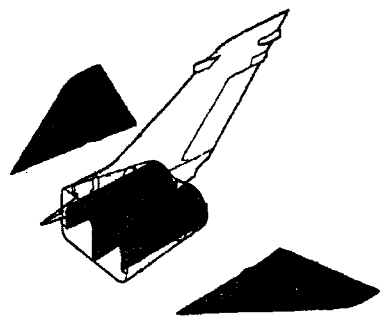

Fig. 10: Taileron

Inspection data being available for these components were:

- average inspection time,
- inspection frequency,
- MTBF,
- damage type, and
- average repair effort

Inspections being performed before and after flight as well as those being defined as minor, periodic and during depot were considered.

In many cases just maintenance cost is given, which also includes repair. Analysing the data of the six components considered here led to the conclusion, that a 50 to 50% split of the depot maintenance cost between inspection and repair for the 6 sample parts respectively is a good approach (fig. 11).

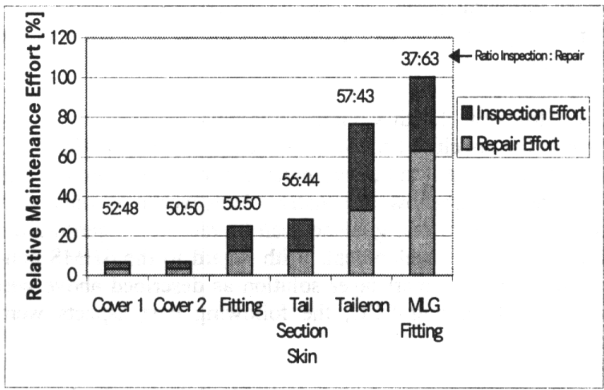

Fig. 11: Distribution of depot maintenance effort for different metal structure parts

To determine an inspection related CER model for the metallic components a more detailed analysis of the inspection effort was done which resulted in the following parameters x_i driving the CER:

- surface area [m^2] (x_1),
- number of rivets (x_3), screws (x_2) and drilled holes (x_4),
- severity of loads (x_6),
- inaccessibility of the component (x_5),
- inspection criteria (corrosion (x_7), ruptures (x_8) or loosening (x_9))

With the exception of surface area and number of rivets, screws and holes, which are explained by themselves, the parameters were defined as follows:

- Inaccessibility
  - Very easy access to part – no assembly necessary: $x_5=1$
  - At least one assembly step necessary to access part: $x_5=2$
  - Difficult access to part: More than one assembly step necessary: $x_5=3$
- Load
  Low: $x_6=1$
  Medium: $x_6=2$
  High: $x_6=3$
- Inspection criteria
  Here flags have been set with flag equal to 1 meaning that the criterion is valid and 0 if being not valid.

To clearly identify the total inspection effort this was split into the following shares being related to:

- Dismantling and assembly I_1
- Visual inspection against corrosion I_2
- Visual inspection against loosening I_{2b}
- NDT inspection against ruptures/corrosion I_3

Based on the above described parameters and having all inspection efforts referenced to the inspection effort of the fitting with the highest inspection cost (MLG fitting), the following equations were derived:

- Dismantling and assembly
  This is mainly a function of part dimensions (surface) and inaccessibility. The following CER was found for the prediction of the dismantling and assembly time (see fig. 12):

$$I_1 = (12{,}66 + 71 \cdot x_1) \cdot (x_5 - 1)$$

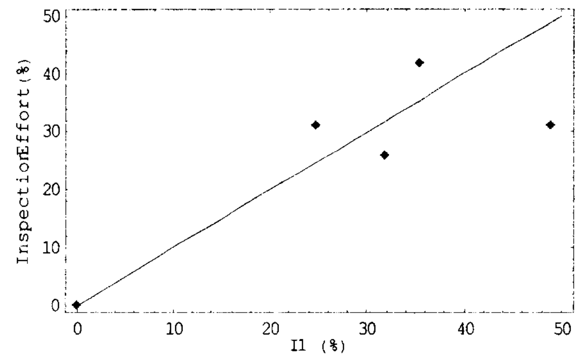

Fig. 12: CER for Assembly Effort

- Visual inspection
  Checking a part for corrosion or loosening of screws have been the major drivers here. The result shown in fig. 13 was determined by the following equations for corrosion

$$I_{2a} = 2{,}6 \cdot x_1 \cdot x_7$$

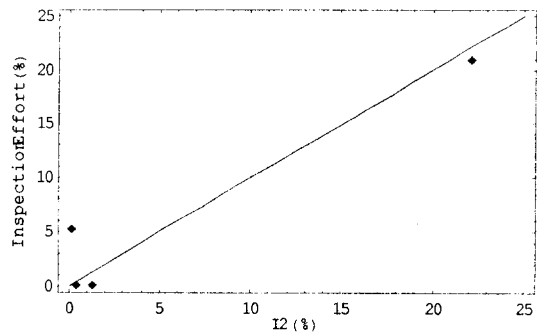

Fig. 13: CER for Visual Inspection Effort

and loosening of screws

$$I_{2b} = 0{,}77 \cdot x_9 \cdot x_2 \cdot x_6$$

respectively.

- NDT inspection
  The NDT inspection effort was found to be nearly constant for all parts that are inspected against ruptures:

$$I_3 = 22 \cdot x_8$$

The total inspection effort per part is summarised to be:

$$I_{total} = \sum_{i=1}^{3} I_i$$

Since the CERs are so far related to depot inspection only an integration has to be performed to obtain the inspection related LCC. This has been done using the table shown below and including the frequency of the different inspection types.

Inspection Type	Taileron	Tail Sec. Skin	Fitting 1	Fitting 2	Cover 1	Cover 2
Depot	•	•	•	•	•	•
Periodic	•	•		•		
Minor		•				
Before/After Fl.	•				•	•

Table 1: Inspection Frequency Distribution of the Sample Parts

A comparison of inspection related LCC between the prediction using the CER-model and the real LCC efforts is given in fig 14. With the exception of cover 1 and fitting 1 where a difference of up to 80% is observed, the predictions are fairly acceptable. The larger deviations are aminly due to inaccuracy of the database.
An extension of the database might certainly help to furthermore improve the model.

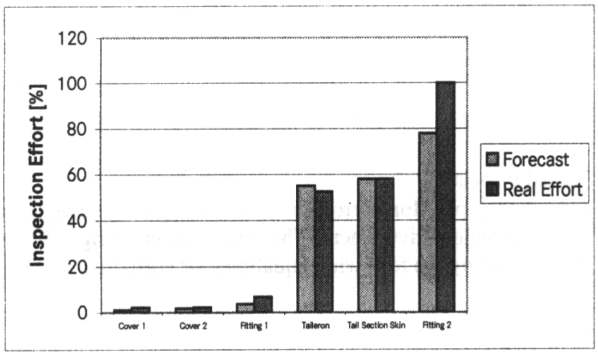

Fig. 14: Validation of the CER Model

5.3 CFRP Components
As mentioned earlier the amount of inspection and/or maintenance data being related to CFRP components was very much limited to either some demonstrator components (e.g. main landing gear doors of TORNADO) or the little experience gathered so far with the seven Eurofighter Typhoon test aircraft flying around with the different Eurofighter partners. Although these components have been designed to be maintenance free, inspection is actually still performed with regard to the relative novelty of CFRP in high performance aircraft structures as well as the need to verify that the requirement of non-required maintenance has been met. The inspection effort which is actually performed on these components is relatively high and has therefore to be considered at the very beginning of any learning curve. To determine how this inspection effort may decrease in the future, a look to learning curves for safe-life metallic components of the past may be useful. Such a curve is shown for a Boeing 707 airframe in fig. 15 .

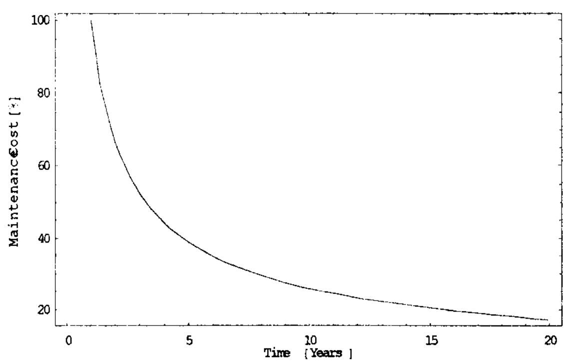

Fig. 15: Maintenance Cost Model for Boeing 707

What can be concluded from that figure is, that maintenance and thus NDT effort has not vanished after 20 years although the components considered have been safe life. It is thus that a similar trend can be expected for the CFRP components used today which have also been designed safe life and long term maintenance free.
Another question with CFRP is to what extent the inspection effort increases if the component design is converted from safe-life to damage-tolerant and what weight savings can be expected under these conditions. So far the available data is much to rudimentary but in the longer term analysing such an aspect might be worthwhile doing for giving an answer to this question.

5.4 Structural Health Monitoring System
Due to the novelty of SHMS, the estimation of resulting LCC reductions has still to be very much based on assumptions and is therefore somehow speculative. However it is only with these estimations that guidance can be received regarding the focus of future development. With regard to the SHMS considered here the smart layer solution as described above was selected. Regarding LCC, the following cost aspects were considered:

- Production cost, which consisted of the purchasing cost as obtained from the supplier and
- Maintenance cost

R&D cost was considered to be included in the production cost and retirement and disposal cost was considered to be negligible.

SHMS are actually still in a R&D stage. The solutions being therefore available today are still mainly prototypes and thus at the very initial stage of a learning curve. Considering the smart layer system, this can be split into three major elements being:

- The smart layer itself consisting of the Kaptone foils with integrated piezoelectric elements and the respective wiring.
- A chip with integrated antenna being either implemented onto the smart layer or close to it, allowing to perform sensor signal pre-processing and sending the pre-processed signals to a central data processing unit.
- The software in general, allowing to process the sensor signals and to determine damage with respect to location and severity.

As done for the different components before, the cost figures for the SHMS have been referenced to the inspection related LCC as well.
For the smart layers of 30 x 60 cm in size and being equipped with 12 piezoelectric elements, the cost per layer is around 13% today. A target price of 0,3% can however be expected, once a serial production can be started and the manufacturing process is much more automated .
For the electronic unit consisting of a standard ASIC chip and an antenna the target price for a serial production should not exceed 0,08%.
Software cost is difficult to estimate but some comparison can be possibly made with the avionics sector. Assuming a ratio software to hardware cost of 50:50 for the smart layer system leads to software cost in the area of 0,6% for the serial part.
Attaching the smart layer to the respective component and testing of functionality should be done within 30 minutes each when being in the saturation phase of the learning curve. An equivalent absolute value in the range of 0,1% to 0,3% has therefore to be added which however depends on local labour rates. For the manufacturing labour for the SHMS 0,2% are considered.
With respect to O&S cost of a SHMS about 50% of the manufacturing cost can be applied as maintenance labour effort.
Adding all these different cost elements together allows to determine in what order of magnitude LCC of such a structural health system can be expected. Figure 16 compares the cost structure of the prototype and the serial part.

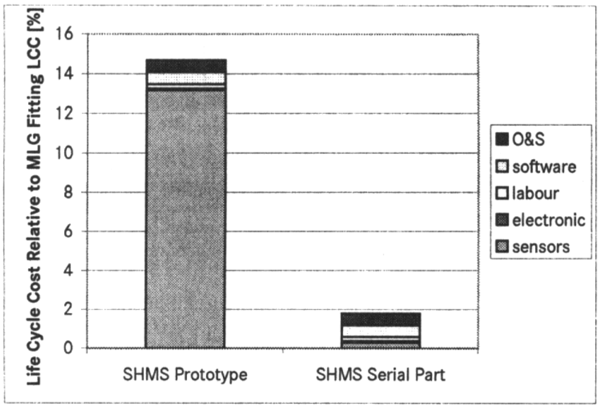

Fig. 16: Cost Structure of the SHMS Prototype and the Serial Part

When comparing the results obtained in fig. 16 with a standard learning curve for electronic components it can be seen, that the estimate quite well meets standard experience and the assumptions have not been unrealistic (fig. 17).

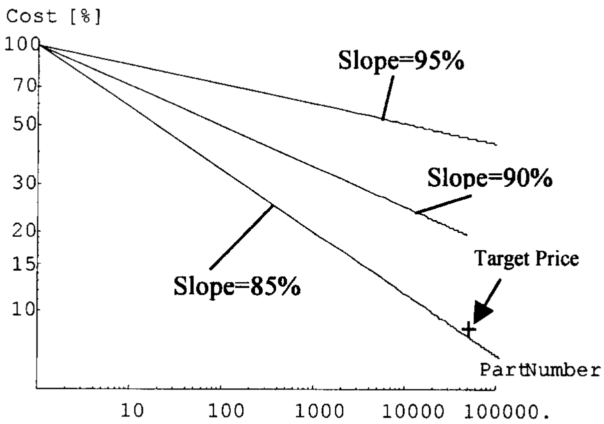

Fig. 17: Learning curves for Manufacturing of Electronic Elements

5.5 Trading the Inspection Cost

Compared to the CERs having been determined and described in chapters 5.1 and 5.2 respectively, it is now possible to estimate how far a SHMS can be beneficial for metallic and composite components of either shape, loading or degree of accessibility. Before however trading these numbers it should be clear that although a SHMS aims at reducing inspection cost, it is quite unlikely that it is able to reduce inspection cost to zero. A better question to ask is therefore: *What is the portion of the structural health monitoring LCC when compared to the actual LCC portion for inspection of the component considered?* This ratio is therefore shown for metallic components under consideration of the SHMS prototype and serial part costs and for a CFRP component in the figures below (fig. 18, 19 and 20). As metallic components the above described TORNADO components and as CFRP component the TORNADO main landing gear door were selected.

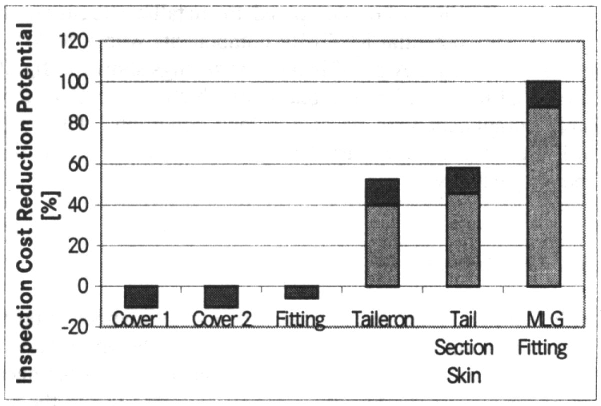

Fig. 18: Potential LCC Savings through SHMS for Metallic Components (Assumption: SHMS Prototype Cost)

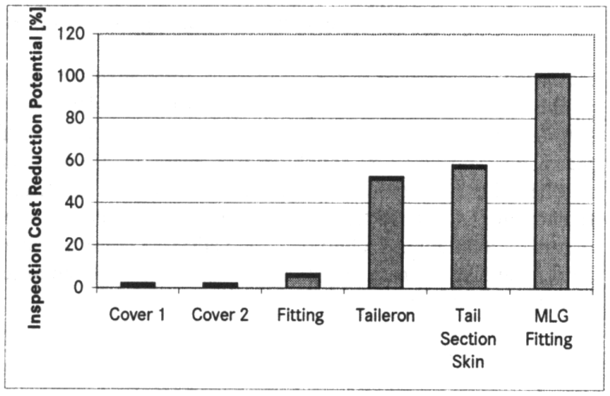

Fig. 19: Potential LCC Savings through SHMS for Metallic Components (Assumption: SHMS Serial Cost)

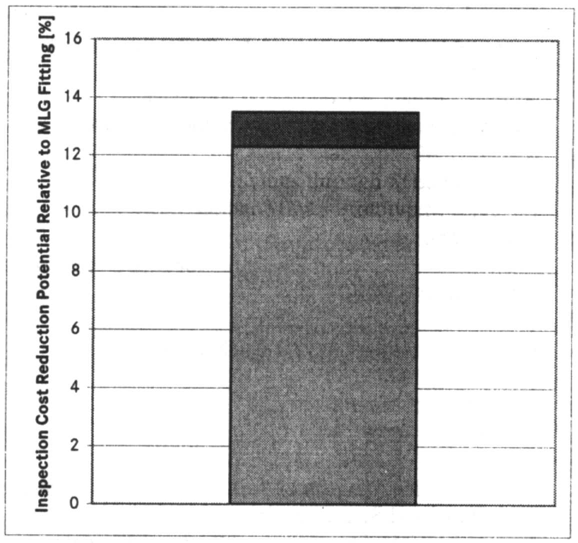

Fig. 20: Potential LCC Savings through SHMS for CFRP (Assumption: SHMS Serial Cost)

What can be seen for the metallic parts is, that there are types of components such as the covers, where a SHMS does not make much sense under the assumption of the SHMS prototype cost while on the other hand components being highly loaded and difficult to access can highly benefit from implementing a SHMS. Under the assumption of the SHMS serial part cost even for the cover parts a cost benefit can be achieved.

Although only one CFRP component could be considered here, a similar trend can be considered to the one determined for the metallic components. However due to the relative novelty of CFRP when compared to metallic structures, the cost savings potential for CFRP components with a SHMS is actually still high. A proof is the cost savings shown in fig. 20 for the CFRP main landing gear door which is an easily accessible component with no severe load conditions. This trend will therefore change when CFRP will become as standard as metals are today.

6 Conclusions

This little study has shown, that with a small number of representative components a trend can already be shown on how far SHMS can help to reduce inspection related LCC. What needs to be done is to identify the appropriate CERs where the significant parameters can be limited to a manageable number. Based on these parameters it is possible to perform trade studies which allow to identify which components of an aircraft are worth to be considered for adapting an SHMS and which are not.

Definitely an increase in the number of components included in the CERs can help to improve the costing model. This is certainly what will be done in a next step. It is however already now possible to conclude that there is a significant number of components on aircraft where a SHMS can lead to remarkable LCC reductions as soon as SHMS becomes commercially available. Technology for SHMS is quite advanced already and it is just a question of time, when this commercialisation will start.

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14. Abstract

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There were four sessions covering the following topics:
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