

TERA- A Tool for Aero-engine Modelling and Management

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ABSTRACT

One of the distinguishing features of the civil aero-engine market is its high competitiveness. The costs and risks associated with new projects are such that the difference between two apparently equally attractive options could result in success from one and a threat to the survival of the company from the other. To conceive and assess engines with minimum global warming impact and lowest cost of ownership in a variety of emission legislation scenarios, emissions taxation policies, fiscal and Air Traffic Management environments, a Techno-economic and Environmental Risk Assessment (TERA) model is needed. TERA incorporates multi-disciplinary modules for modelling gas turbine and aircraft performance, estimation of engine weight, noise and emissions as well as environment impact and operating economics. The TERA software is integrated with a commercial optimiser and provides a means for cycle studies. It is to be expected that new legislative and fiscal constraints on air travel will demand an extension to the customary range of asset management parameters. In such a business environment there is potential for TERA to develop into a useful tool for aircraft and engine asset management. This paper presents a description of this tool as well as gives some results from scenario studies.

KEYWORDS

Gas Turbine, Environment, Global Warming Potential, Emissions, Noise, Optimisation, Risk Assessment, Techno-economic

NOMENCLATURE

ACARE	Advisory Council for Aeronautical Research in Europe
BADA	Base of aircraft data
CRTF	Contra-rotating turbofan
DDTF	Direct drive turbofan
DOC	Direct operating cost
E	Isentropic efficiency
FLOPs	Flight optimisation systems
FN	Net thrust [kN]
GCM	General circulation model
GTF	Geared turbofan
GWP	Global warming potential
MTOW	Maximum Take Off Weight
P	Total pressure [kPa]
Prlpc	Low pressure compressor (FAN) pressure ratio
SFC	Specific fuel consumption [g/kNs]
T	Total temperature [K]
TERA	Techno-economic and Environmental Risk Assessment
TSTF	Three spool turbofan
UHC	Unburnt Hydro Carbons
VITAL	enVIronmenTALly friendly aero-engine – EU FP6 project
W	Mass flow [kg/s]
WF	Fuel flow [kg/s]
WP	Workpackage

INTRODUCTION

Environmental considerations are increasingly becoming an integral part of aircraft and jet engine designs. With aero-engines contributing greatly to atmospheric imbalance via emissions of CO₂, NO_x, H₂O etc as well noise around airport, air travel is under scrutiny. Worldwide, organizations are trying to define and determine means of reducing the impact of travel by air. The Advisory Council for Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020. Concerning the environment, ACARE fixed, amongst others, the following objectives for 2020 for the overall air transport system, including the engine, the aircraft and operations:

- A 50% reduction in CO₂ emissions per passenger-kilometre (assuming kerosene remains the main fuel in use) with the engine contribution corresponding to a reduction of 15 to 20 % in specific fuel consumption, whilst keeping specific weight constant;
- A reduction in perceived noise (EPNdB) to one half of the current average level, considered as equivalent to a 10 dB reduction per aircraft operation, taking into account that the engine is the major contributor to noise.

The ACARE environment target has led to several technology programs one of which is the VITAL (Environmentally Friendly Aero Engine) project. VITAL, supported by the European Union (EU) within its Framework Programme 6 (FP6), aims at a significant reduction of aircraft noise, fuel consumption and CO₂ emissions. More specifically, VITAL is to ensure 6dB noise reduction per aircraft operation and 7% reduction in CO₂ emissions compared to engines in-service prior to 2000. Figure 1 illustrates the trend in aircraft noise reduction and the breakthrough targeted by VITAL.

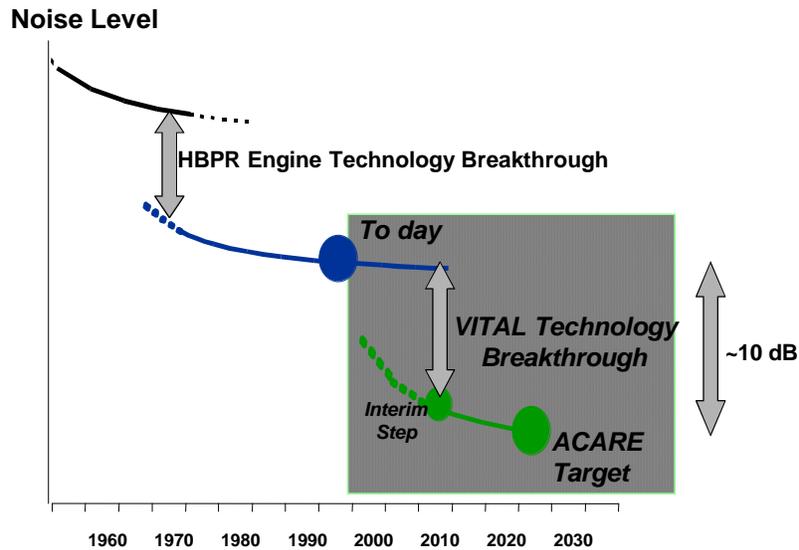


Figure 1
Figure 1 Trends in aircraft noise reduction
 Source: Guénon, 2003

VITAL concentrates on new technologies for the low pressure shaft of the engine, which will enable the development of low noise and low weight fan architectures for very high bypass ratio engines. To achieve its objectives, VITAL would investigate three innovative fan concepts, leading to low speed fans such as (Figure 2): the Direct Drive TurboFan (DDTF) supported by Rolls Royce, the Geared Turbofan (GTF) by MTU and the Contra Rotating TurboFan (CRTF) by Snecma.

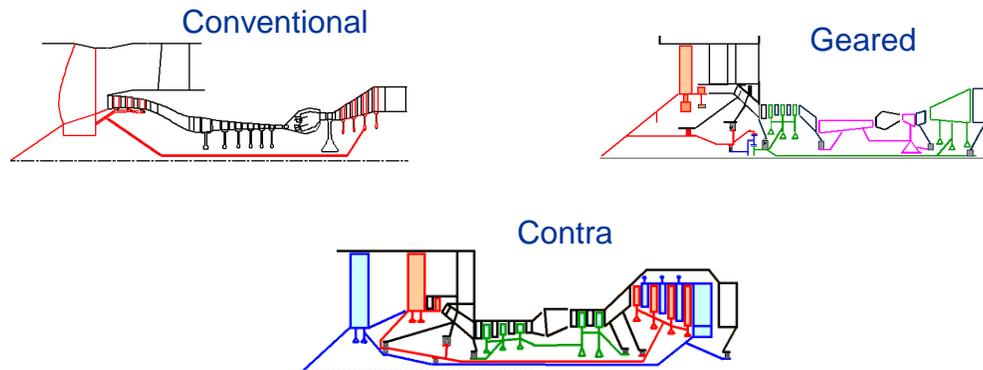


Figure 2 VITAL Fan concepts

To provide a means of assessing the VITAL technologies as well as conceiving and assessing engines with minimum global warming and lowest cost of ownership in a variety of emission legislation scenarios, emissions taxation policies, fiscal and Air Traffic Management environments, it was necessary to develop TERA. TERA would provide a platform to assess the technological, economical and environmental risks of aircraft engines.

In the future, when these new fan concepts are incorporated into production power plants, there will be a requirement to monitor the engine cost of ownership (fuel burn, maintenance time and cost), and the noise and gaseous emissions. New legislative and fiscal constraints on air travel will drive an extension to the customary range of asset management parameters.

A description of the TERA architecture and modules follows.

ARCHITECTURE AND MODULES

TERA was a concept invented at Cranfield University, based on research work conducted in such areas as powerplant asset management, powerplant multi-disciplinary optimisation and influence of powerplant design and operation on atmospheric pollution. However in the current context, high fidelity preliminary design modules are developed and integrated with a commercial optimiser (iSIGHT, a product of Engineous Software Ltd). These TERA software can then be applied to the optimisation of one or more goal functions, with the possible goal functions including but not limited to - mission fuel burn, engine noise, engine gaseous emission i.e. NO_x, global warming potential (GWP) and engine direct operating cost (DOC). Figure 3 presents the basic philosophy of TERA, Table 1 shows the University partners responsible for developing one or more of the TERA modules and Figure 4 show the integrated version of TERA in the commercial optimiser package.

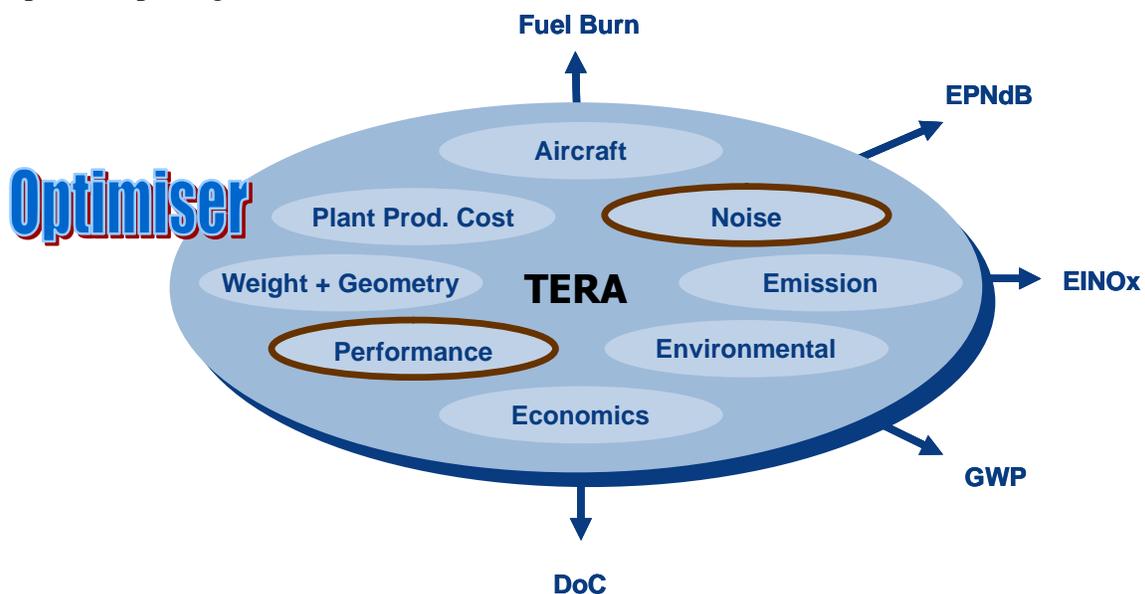


Figure 3 TERA Philosophy

Table 1: TERA Modules and Developing Partners

Aircraft performance	Cranfield, UK
Engine performance	Cranfield, UK
Economics (DoC)	Cranfield, UK
Environment (GWP)	Cranfield, UK
Noise	Supaero, France
Emissions	Supaero, France
Weight and Geometry	Chalmers, Sweden
Manufacturing plant cost	Stuttgart, Germany

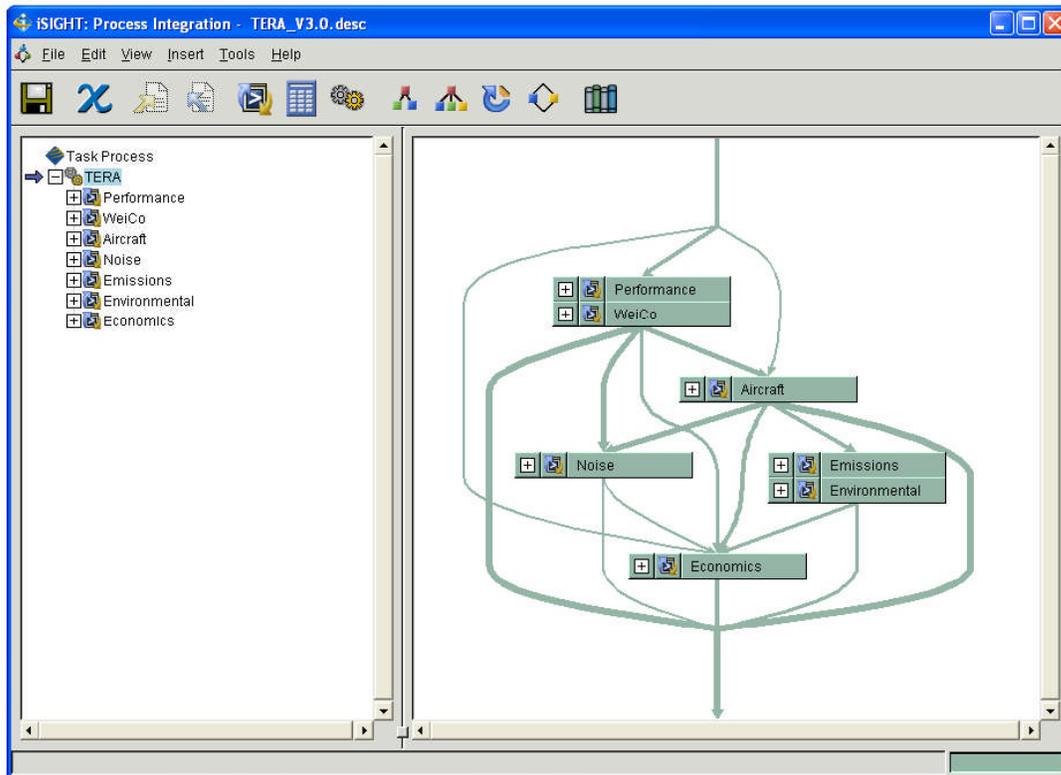


Figure 4: Integrated TERA modules in optimiser environment.

A brief insight into each of the TERA modules now follows.

Aircraft Performance

The aircraft performance model has been codenamed HERMES, which in Greek mythology is a fleet footed messenger of the gods, and represents a system that provides results as well as flies.

A set of requirements was developed and implemented into the aircraft engine performance model. These include the following:

- The model should calculate aircraft performance data such as lift and drag coefficients, distance for take-off, etc. from available information on the geometry and mass of the aircraft
- The model should calculate the fuel usage, time elapsed and distance covered for the baseline and derivative aircraft performing a given mission
- The model should allow for the modelling of different aircraft and engines
- For specified maximum take-off weight, payload and fuel load the model should compute the range of the aircraft

The option to run a main or a main plus diversion mission are considered in the aircraft model; also included is a routine that optimises the aircraft for given engine performance, weight and geometry to meet a defined range. The result from HERMES has been compared with data obtained from two sources, an aircraft flight optimisation system or FLOPS and a base of aircraft data or BADA. FLOPS program was obtained from the NASA Langley research centre and used as one of the benchmark to validate HERMES. BADA on the other hand is a product of EUROCONTROL experimental centre, under the European Organisation for the safety of air navigation. More detailed description of the aircraft model can be found in Laskaridis et al (2005).

Engine Performance

Cranfield university in-house gas turbine performance code, TURBOMATCH, has been adopted for use in the current TERA. TURBOMATCH is a flexible gas turbine performance modelling code with decades of experience built into it. The code also has novel cycle performance modelling capability. With TURBOMATCH as the core, a computer program interface was written to allow its automated use in terms of preparing input files, making calls to it and extracting data required by other TERA modules in the required format.

Economics

The economic model is composed of three modules: a lifing module, an economic module and a risk module. The lifing module estimates the life of the high pressure turbine disk and blades through the analysis of creep and fatigue over a full working cycle of the engine. The economic module uses the time between overhauls together with the cost of labour and the cost of the engine (needed to determine the cost of spare parts) to estimate the cost of maintenance of the engine. The risk module uses the Monte Carlo method with a Gaussian distribution to study the impact of the variations in some parameters on the net present cost (NPC) of operation.

The accuracy of the economic model in DOC estimation is good (within about 15%) and so can be adapted for use in the cost analysis of future types of engines, such as ultra high bypass ratio turbofans, with little modifications (Pascovici et al, 2007).

Environment

The environmental impact for a given mission is assessed in terms of global warming potential (GWP). The GWP index represents an attempt to integrate the differential radiative forcing effect due to an anthropogenic emission along a pre-defined time

horizon. The effect is then related to the emission of an equivalent mass of CO₂. While the GWP approach is adequate when dealing with long-lived, well-mixed pollutants, such as CO₂, CH₄ and N₂O, its utilisation for estimating the climate change impact of aviation has been criticised (IPCC, 1999). The microphysical-chemical processes that drive the formation of ozone chemistry and contrails are influenced by the season and location of the emission: for this reason they can only be properly analysed with comprehensive GCM simulations.

In TERA, a parametric model has been used in the assessment of the GWP and the derivation of this model is outlined in Svensson (2004).

Noise

Noise certifications are based on measurements made at three points during landing and take-off that is, sideline, cutback (flyover) and approach. The total time-integrated noise over these three points represents the Effective Perceived Noise Level - EPNL – and must not exceed a limit depending on the number of engines and on the maximum take-off weight of the aircraft. The three main noise sources are considered: fan, jet and airframe. Core and turbine noise can be also evaluated even if they have a minor contribution to the total aircraft noise. Atmospheric absorption and ground effects are included to simulate the noise propagation from the aircraft.

An acoustic prediction code called SOPRANO is used to estimate the aircraft noise. SOPRANO is primarily developed by the company ANOTEC Consulting for noise reduction technologies assessment in the context of another European research project SilenceR. It is a semi-empirical code incorporating public noise prediction methods (Au et al, 2007) and its validation is being undertaken by the SilenceR partners.

With SOPRANO as the noise estimation program, interfaces were developed to link it with the other modules in TERA, particularly the Economic model from which the noise tax is estimated.

Emissions

Empirical approaches, of which there are numerous available, are used to provide the exhaust concentrations of pollutants of interest such as NO_x, CO and unburnt hydrocarbon. Several methods were assessed and one of them was selected for emissions modelling in TERA. Emissions are estimated with the correlations established by Rizk and Mongia (1994). To obtain their correlations, a large amount of data, obtained for a number of production engines, was used to derive prediction equations which calculate the emissions index for NO_x, CO and UHC amongst others. Initially, assumptions were made for the air distribution and other combustor characteristics such as pressure loss, volume, efficiency, fuel residence time, fuel evaporating time. However this would be updated once appropriate data becomes available. The Emission module provides the data required by the Economic and Environment modules for the estimation of emission taxes and GWP respectively.

Weight and Geometry

The WEIGHT module for the TERA analysis is based on the work by Onat and Klees (1979). Default values on parameter settings presented in the original report were updated extensively, in order to correspond more closely to state of the art jet engine technology. Several updates on the modelling strategy were introduced, such as new models for hollow fan blade, structures and containment weight prediction. The weight and geometry module provides an extensive list of engine and component weights, geometry and material which are required by other TERA modules i.e. **plant cost** to estimate engine and component cost, **aircraft** for computation of aircraft MTOW and nacelle drag as well as **noise** for computation of noise magnitudes from the turbomachinery.

Manufacturing Plant Cost

Production costs are generally affected by a large number of different factors, such as manufacturing technology levels, production cost, materials prices, available machine settings and production numbers. Also the manufacturer's supply chain has a large impact on production cost as well as factors like varying wage rates. Hence, the modeling of production cost is a complex issue with great dependency on given boundary conditions which can vary significantly per location or manufacturer. The plant cost module used in TERA primarily provides a direct production cost which reflect realistic cost trending and scaling but do not predict absolute cost or selling prices. Validation of this module has been carried out using a bottom-up approach i.e. estimating the costs from component to engine level.

TERA DEMONSTRATION

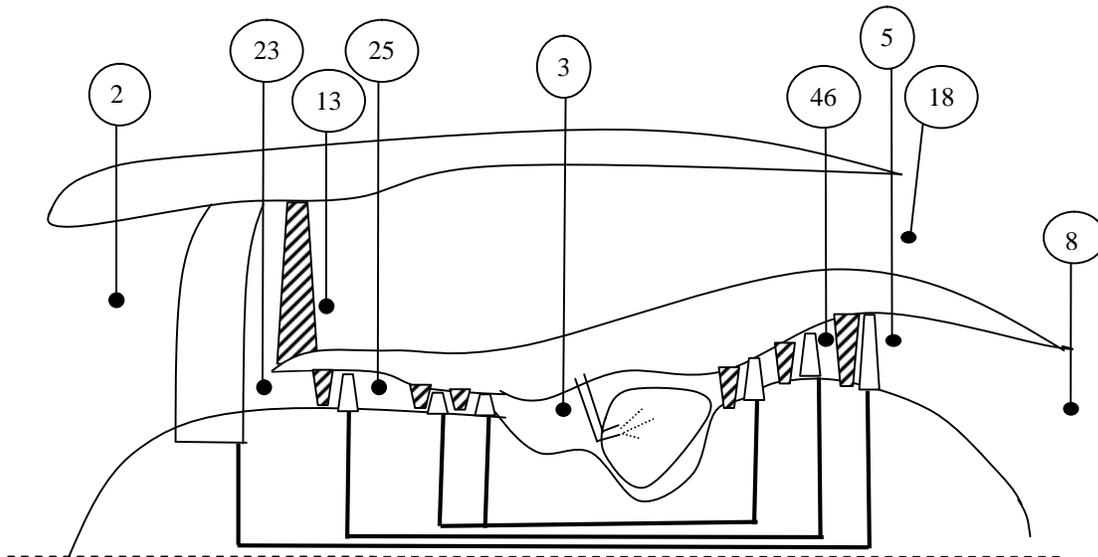


Figure 5 Schematic engine configuration and stations

To demonstrate the use of TERA, a three spool turbofan (TSTF) of conventional configuration for long range application is chosen. However unlike the conventional

turbofans, the TSTF would incorporate wider-chords, reduced number of blades (with each blade having to support a higher aerodynamic load), and larger overall fan diameter. Bypass ratio would be in the region of 13:1, and engine operation would be at lower rotational fan speeds for tip noise reduction purposes.

A schematic of such an engine is shown in Figure 5-while the main engine performance parameters for **cruise** condition only are shown in Table 2.

Table 2 shows the parameters that have been extracted from the modelled powerplant performance results for a clean run (no deterioration), then with 2% and finally with 4% of FAN polytropic efficiency degradation. The percentage deviation in performance for each degraded engine from the clean has been computed and entered in the table. Since the objective was to provide the required aircraft thrust, i.e. same thrust notwithstanding engine condition, the degraded engines gave rise to a decrease in core temperature and pressures and an increase in SFC. The core temperature reduced because the turbine entry temperature was kept constant (i.e. indicating a given level of technology) and more work extracted from the core to meet thrust demands.

Table 2: Main cycle parameters for the TSTF long range engine during cruise

Parameter	Clean	2% degraded	Deviation (%)	4% degraded	Deviation (%)
BPR	13.989	13.989	0.004	13.988	-0.009
OPR	58.132	58.184	0.089	58.162	0.052
SFC	14.346	14.524	1.241	14.740	2.746
FN	63.542	63.723	0.285	63.039	-0.792
E23	0.919	0.899	-2.270	0.877	-4.581
PrIpc	1.475	1.477	0.102	1.476	0.044
W2	593.890	604.480	1.783	605.410	1.940
T24	292.930	293.790	0.294	294.560	0.556
T18	292.930	293.790	0.294	294.560	0.556
T8	731.870	719.170	-1.735	707.640	-3.311
P18	54.702	54.758	0.102	54.727	0.044
P8	43.848	40.699	-7.182	38.993	-11.072
W18	554.270	564.150	1.783	565.010	1.938
W8	40.536	41.255	1.774	41.320	1.934
WF	0.912	0.926	1.525	0.925	1.439

This exercise was conducted for two scenarios - the baseline aircraft and for an optimised aircraft (airframe + engine) with the payload and range remaining unchanged. As the aircraft optimisation (thrust, weight and geometry scaling) was carried out within the aircraft module, the performance data from the performance module remained unchanged for both scenarios.

The aircraft mission range is 12,000km with a payload of 23.5 tonnes. The baseline maximum take-off weight is 230 tonnes and for the optimised aircraft, keeping same payload and range, the maximum take-off weight was determined to be 216.5 tonnes. The impact of the FAN polytropic efficiency deficiency, by 2% and 4% respectively, on the fuel burn (block fuel) for a baseline (non-optimised) and the optimised aircraft is shown in Figure 6. The fact that a drop in efficiency leads to an increase in fuel burn is to be expected but what is significant is the amount of increase. Given that the percentage change in block fuel has been computed from the clean versions for both degraded engines, it is interesting to see how the efficiency deterioration effect is more pronounced in the optimised than the baseline aircraft. One explanation for some of these differences could be in the scaling rules that have been implemented for the thrust and fuel flow within the aircraft module, however it is also possible to state that the more appropriately matched an engine is to an aircraft the more significant would be a deviation from an optimal operating point.

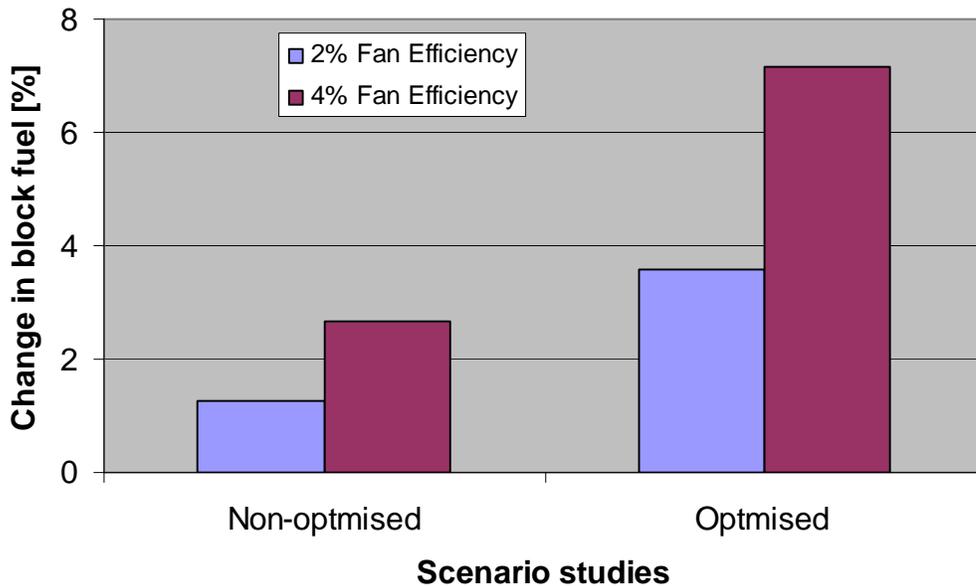


Figure 6 Effect of Fan Polytropic efficiency degradation on aircraft block fuel

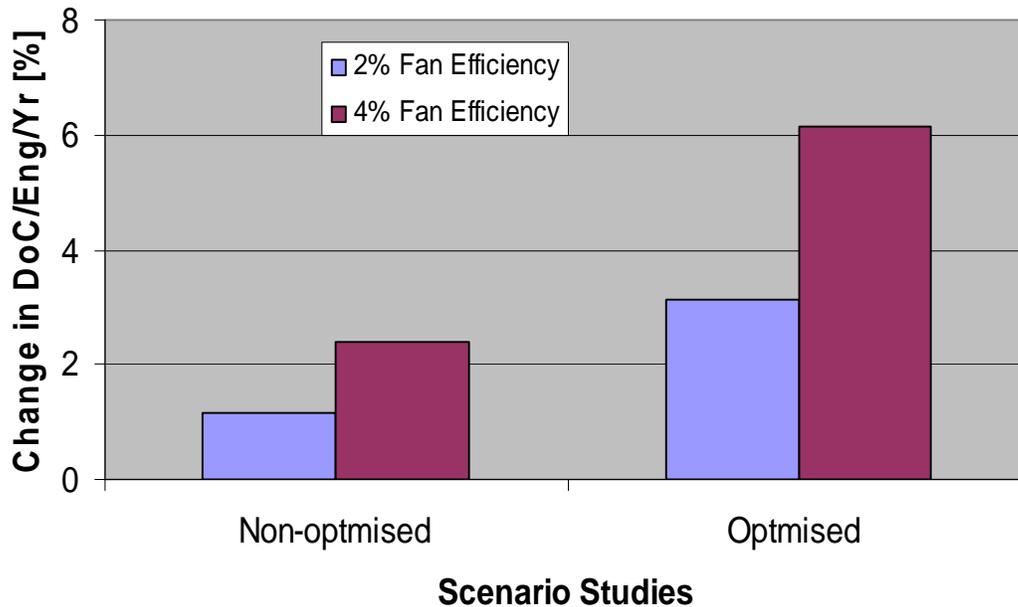


Figure 7 Effect of Fan Polytropic efficiency degradation on engine annual direct operating cost

The effect of an increased fuel burn resulting from reduced component efficiency (FAN) on the direct operating cost of the powerplant for a year is shown in Figure 7. Here again the magnitudes are not trivial given that the DOC runs into millions of euros per year.

The impacts of component efficiency degradation shown in Figures 6 & 7 on block fuel and DoC will be immediately appreciated by aircraft asset managers. But another way to view the results presented in Figure 6 and Figure 7 is to consider the magnitudes as possible approximate gains that would accrue from an improvement of the component efficiency by 2% and 4% respectively.

CONCLUSIONS

This paper describes TERA, a software tool that can be used to conceive and assess engines with minimum global warming impact and lowest cost of ownership in a variety of emission legislation scenarios, emissions taxation policies, fiscal and Air Traffic Management environments. TERA has been used in this paper to show the possible economic implications, in terms of engine DOC, of a reduction in polytropic efficiency of the FAN. This efficiency drop could have been the result of a design limitation (technical) or degradation from a fault. Though the development of TERA is still ongoing, the potential for it as a tool for aircraft and engine performance modelling and management is bright. TERA, it is envisaged, will be extended to stationary applications in the near future.

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