PROPULSION SYSTEM OPTIMISATION FOR MINIMUM GLOBAL WARMING POTENTIAL

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Abstract

Recent concerns about the contribution of aviation to global warming have triggered the question of how the thermodynamic cycle of high bypass ratio turbofans could be modified to reduce their environmental impact.

This paper describes a systematic approach to solve the problem. Low-complexity tools for estimating turbofan performance and gas turbine emissions have been developed and linked. Subsequently, an optimising tool, based on genetic algorithms, has been "wrapped" around the resulting software assembly.

Different optimisation studies have been performed by varying the objective function and the active constraints. The results have been analysed qualitatively by observing the trends rather than searching for quantitative accuracy.

The results of the study show that, with the given relationship between emissions and global warming potential, a turbofan engine optimised for minimum cruise global warming potential is characterized by lower operating pressures and temperatures than those found in a turbofan optimised for minimum cruise SFC. Although this makes it a fuel-inefficient solution, it is also shown that a better SFC performance can be retained by choosing solutions that are close, but not coincident, to the mathematical optimum for global warming potential.

Nomenclature

BPR	Bypass ratio
CO_2	Carbon dioxide
CPR	Core compressor pressure ratio
CR	Cruise
DP	Design point
EI	Emission index
FPR	Fan pressure ratio
FRAC	Ratio of primary zone air to total combustor air
GA	Genetic algorithm
GWP	Global warming potential of a pollutant species
GWP_T	Global warming potential per second and per kN of thrust
H_2O	Water vapour
ICAO	International Civil Aviation Organisation
$ICAO_{NOX}$	ICAO LTO NO_X parameter
ISA	International standard atmosphere
LTO	Landing and take-off
MDO	Multi-disciplinary optimisation
NO_X	Oxides of nitrogen
OD	Off-design
OPR	Overall pressure ratio (CPR·FPR)
SFC	Specific fuel consumption
SLS	Sea-level static
SLSMAX	SLS maximum rating conditions
SPFN	Specific thrust
T/O	Take-off
T1	Free-stream total temperature
T3	Compressor delivery temperature
T4	High pressure turbine nozzle guide vane entry temperature
TR	Thrust ratio: ratio of take-off thrust to cruise thrust
W1	Engine inlet mass flow

1 Introduction

From an environmental perspective, turbofan engines have, to date, been designed to comply with the LTO cycle emissions and noise patterns regulations. Today, however, there are great concerns that aviation might also have a significant impact on global air quality, therefore contributing substantially to the global warming problem. With the forecasted 5% per annum growth in air traffic, the situation is likely to be exacerbated in the future [1] and it is possible that cruise greenhouse gas emissions regulations will very soon be imposed.

Such regulations may expect to result in a major design shift in propulsion technology. Since present day technology is already at the margins of the theoretical limits of the classic gas turbine cycle, the industry has been pushing towards novel solutions. However, it is important to investigate possible short-term design alterations to existing turbofan technology.

It has been suggested that the path of continual increases in overall pressure ratio, turbine entry temperature and bypass ratio, although effective for achieving low SFC and limited LTO emissions, may be in conflict with the requirement of low global warming impact.

During the work of the Air Transport - Greener by Design Technology Sub-Group, a need has been identified for research to be undertaken on the methodology for designing high bypass ratio turbofan engines so as to minimise impact on climate change [2].

This study is the result of a broader research effort that the authors are directing towards the field of aero-engine multi-disciplinary optimisation (MDO).

1.1 MDO for Aero-Engines

Thanks to the present day high-powered computers, MDO has now become one of the main research areas in engineering [3].

Most of the aero-engine MDO efforts that have been initiated today can be broadly classified according to the numbers of disciplines considered, the complexity of the models of the various disciplines, the optimisation strategy and the level of generalization of the tool (Fig. 1). The level of generalization is an indication of the optimisation tool's ability to handle different propulsion system configurations, different modules, different number of disciplines or different optimisation strategies, with little or no reprogramming.

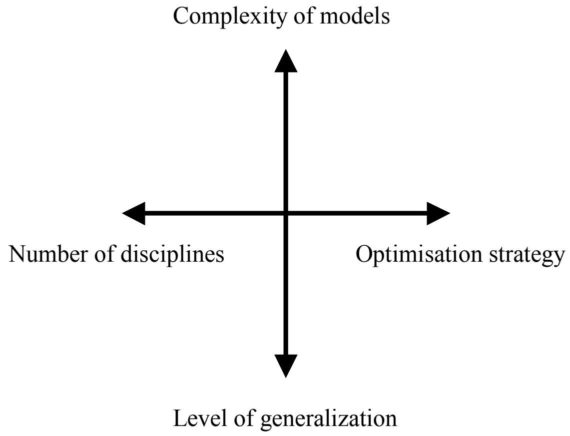

Fig. 1. Classification of an MDO system

Although most of the above-mentioned aero-engine MDO systems fall in the "low (one to three) number of disciplines, medium to high complexity models" category, the authors believe there is scope for tools with a high number of models, but of a lower complexity level, and are currently developing one such system. This choice implies that in analyzing the results, the attention should be mainly on their trends against the varying constraints and objectives, rather than the actual values.

This paper illustrates the results of turbofan optimisation studies when only performance and emissions are considered. Further disciplines will be incorporated to the system in the near future.

1.2 Aviation and Climate Change

Aviation's contribution to global warming has been proven, and thoroughly investigated, in the report by the Intergovernmental Panel on Climate Change (IPCC) [4]. This reference, however, does not provide much insight into the way aero-engines should be designed to minimise this contribution.

The United Kingdom airline, airport and aerospace manufacturing sectors, under the aegis of the United Kingdom Department of Trade and Industry, have recently formed a working group, entitled Air Transport – Greener by Design, to examine the issues related to the aviation and the environment, and to propose practical solutions. One of the objectives was to determine whether the current trend of increasing OPR in turbofan engines, aimed at minimising specific fuel consumption (SFC), is compatible with the objective of diminishing their global warming impact. The result is that there is a clear conflict between the two objectives, as can be seen from the following diagram (from [2]).

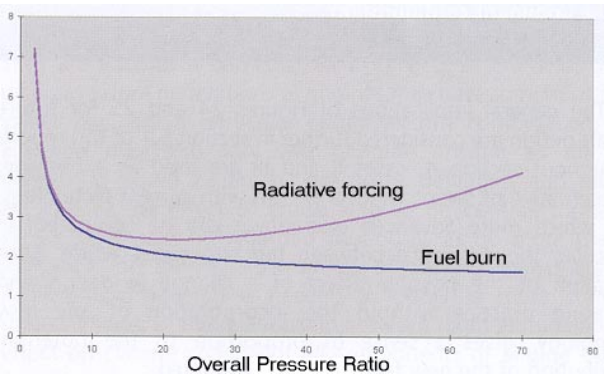

Fig. 2. Radiative forcing and fuel burn vs. OPR [2]

The y-axis can be interpreted as a relative scale. Radiative forcing is defined as the global, annual average relative imbalance to the atmosphere-land-ocean system caused by anthropogenic perturbations [4], and is a useful parameter for assessing the global warming impact of any particular human activity.

Fig. 2 shows that, assuming optimum T4 for each OPR value, the fuel burn decreases continuously as OPR increases. The radiative forcing curve, conversely, shows a minimum: this is because at high OPR values the emissions of NO_X (a major contributor to global warming) rise much faster than the decrease in fuel burn.

This preliminary study assumed a fixed level of combustor technology (today's state of the art) and certain values of radiative forcing coefficients of the pollutant species.

Preliminary work by Rolls-Royce plc has analysed the effects of bypass ratio variation on LTO cycle and cruise NO_X emissions. Here also a conflict between the two objectives was identified, as the following graph clearly shows [5,6].

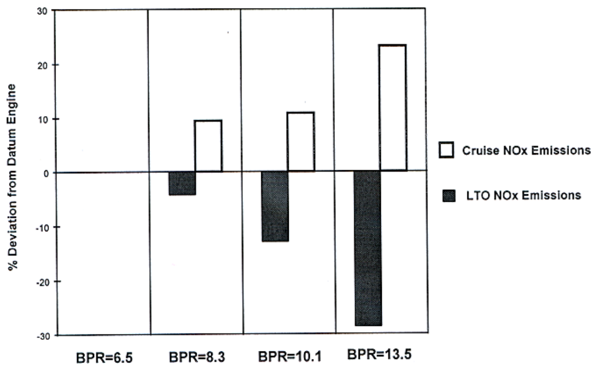

Fig. 3. LTO and cruise NO_X emissions vs. BPR [5,6]

In this graph the datum engine has a BPR=6.5, and is shown next to the y-axis. The other three engines have different values of BPR, but similar levels of combustor technology, the same thrust at top of climb conditions and the same rated take-off thrust. It can be seen that when BPR is increased, cruise NO_X emissions also increase, while LTO NO_X emissions decrease. This is justified by the argument that at sea level static conditions the higher BPR engines operate at less arduous T4 conditions than the lower BPR solutions. Conversely, the lower BPR engines benefit from a lower thrust lapse rate with forward speed, leading to lower NO_X emissions at cruise.

However, since the complete details of this study have not been reported in the original literature, it is not clear to the authors what other parameters have been kept constant among the various engines considered in Fig. 3.

2 Aims and Scope

The preliminary studies summarised above show that interest is rising in the design of turbofan engines for minimum global warming impact and also that research in this direction is promising.

However, it is useful to approach the problem from a more general perspective, because in the cases presented above, the effect of only one cycle parameter per study was considered.

This paper illustrates the results of a systematic optimisation study carried out on a turbofan engine configuration through a GA-based optimiser. The objective was to find the optimum set of cycle parameters that would minimise the engine's cruise specific fuel consumption (SFC) or global warming potential (GWP) and satisfy a variety of constraints imposed on the performance parameters and emissions, both at cruise and take-off. Because of the low-order models utilised throughout this study, conclusions have been drawn from the trends of the results, rather than from their absolute values.

In order to predict engine performance and emissions, appropriate gas turbine and combustor emissions estimation tools have been developed. These have been calibrated against available data or other similar tools. The GWP is calculated from the emission indices of the pollutant species, through a series of coefficients that have been used previously in similar studies [7].

As the engines considered in this study are intended for long-range aircraft, cruise is treated as the design point. Take-off, the only other operational point considered, is treated as the engine's off-design.

The cycle parameters that have been optimised are cruise bypass ratio (BPR_{CR}), fan pressure ratio (FPR_{CR}), core compressor pressure ratio (CPR_{CR}), turbine entry temperature ($T4_{CR}$) and take-off turbine entry temperature ($T4_{T/O}$).

The main constraints have been imposed on (an alternative selection for a similar problem is utilised by Nadon et al. [8]):

1. Cruise specific thrust ($SPFN_{CR}$). For a fixed thrust requirement, specific thrust is related to engine size (and weight): defining a minimum value for it will therefore stop the optimiser from searching unrealistic solutions;
2. Thrust ratio (TR). This is the ratio of take-off to cruise thrust, and is a requirement dictated by the airframe on which the engine is to be installed;
3. Take-off compressor outlet temperature ($T3_{T/O}$). This constraint translates the material capability of the last compressor stages, which is the main limiter to the levels of overall pressure ratio that can be achieved in a turbofan;
4. ICAO LTO NO_X parameter ($ICAO_{NOX}$). Current ICAO standards impose an upper limit to the value of this parameter, which takes into consideration NO_X produced during taxiing, take-off, climb, approach and landing. In this study the production of NO_X during taxiing, approach and landing is considered to be nil, because of the very low power setting, and the contribution during climb is assumed to be related to the take-off value. Two levels of $ICAO_{NOX}$ have been considered, to reflect current standards and a future, more stringent, scenario. Although similar parameters have been defined for the other pollutants produced during the LTO cycle (carbon monoxide, unburned hydrocarbons and smoke), NO_X is the primary concern during take-off and hence is the only species considered here.

Various optimisation studies have been performed, with different objectives and constraints. The performance of the optimised solutions has then been compared with that of a reference engine that has been chosen to represent current standards.

It is worth underlining that mission analysis is not within the scope of the present study, therefore the required take-off and cruise thrust are not re-calculated according to the SFC of the engine and to its weight. This implies that the TR constraint is an external input and remains fixed throughout the optimisation runs.

3 The Aero-Engine Performance Model

The turbofan performance module is a newly developed, steady-state, design point and off-design, performance estimation tool.

Fig. 4 shows the two-spool engine configuration that has been considered, with an intake (I), two compressors (C), a burner (B), two turbines (T) and two nozzles (N).

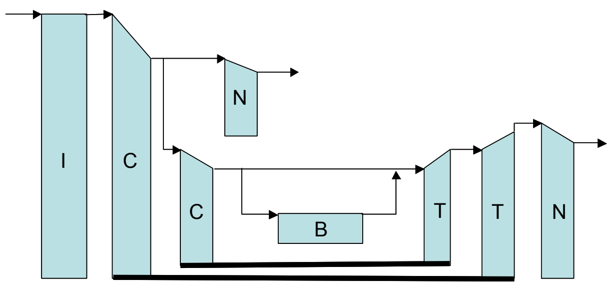

Fig. 4. The turbofan engine configuration

The relevant modelling features of the turbofan performance module are the following:

1. Steady-state simulation
2. Working fluid is an ideal mixture of ideal gases
3. No use of component maps
4. Compressor efficiencies for off-design points are approximated through a correction based on the relative difference between $(T4/T1)_{DP}$ and $(T4/T1)_{OD}$
5. Turbine efficiencies for off-design conditions are the same as at design point
6. Component pressure losses for off-design conditions are the same as at design point
7. The required amount of cooling bleed flow is a function of $T4_{T/O}$ and $T3_{T/O}$

For the off-design calculations, matching is sought on the two turbine areas and on the two nozzle areas. For this to be possible, four iteration variables are therefore necessary, and these have been chosen to be $W1_{OD}$, BPR_{OD}, FPR_{OD} and CPR_{OD}. A standard Newton-Raphson method is used to search for the solution.

The turbofan performance module has been validated against GasTurb™, a successful and widely used code for the performance estimation of industrial and aero gas turbine-based engines [9]. The validation process has confirmed that the accuracy of the tool is adequate to its purpose within this study.

4 Environmental Impact Estimation

The planned optimisation studies require an estimate of the take-off NO_X emissions and of the cruise GWP. Adequate models have been used; additionally a technique has been developed to correlate some important combustor variables, required by the NO_X model, to the varying cycle parameters.

4.1 Global Warming Potential (GWP) Model

The anthropogenic production of greenhouse gases results in an atmospheric radiative imbalance. The equilibrium is restored through a generalized increase in temperature throughout the biosphere [4].

Radiative forcing is a measure, in W/m^2, of the global, annual average of radiative imbalance to the biosphere (land, ocean, atmosphere) caused by anthropogenic perturbations.

Although it is claimed that radiative forcing is the most correct way to assess the effects of anthropogenic emissions [4], another parameter, the global warming potential (GWP), is more often used in engineering studies, and is utilised in this paper. The GWP parameter relates the impact of the emission of a mass of gas to that of the emission of an equivalent mass of CO_2. Also, it attempts to assess the impact of the emission over a pre-defined time horizon (here 100 years), therefore trying to estimate the cumulative climate change and the decay of the various pollutant species.

Although other aviation-related pollutant species have also a radiative forcing contribution, only CO_2, H_2O and NO_X are considered in this study.

Research carried out by Klug et al. has estimated the GWP of NO_X and H_2O as a function of altitude [7]. At a typical cruise level, the orders of magnitude of GWP_{NOX} and

GWP_{H2O} were found to be 100 and 0.1, respectively; however great uncertainty exists over the precise value of these parameters.

In this study, each turbofan cycle generated by the GA-based optimiser is assessed on the basis of its GWP per second of sustained cruise flight and kN of thrust (GWP_T). According to the definition of GWP of a particular pollutant species, this can be written as:

$$GWP_T = SFC \cdot \sum_i \left(EI_i \cdot GWP_i \right) \qquad (1)$$

In Eq. 1 the index i refers to the species considered, in this case CO_2, H_2O and NO_X.

4.2 NO_X Emissions Estimation

From the previous discussion, the need for a NO_X emission estimation model is evident.

Various options are available for estimating gas turbine NO_X emissions. They can be classified as “relative correlations”, “fuel flow methods” and “absolute methods”, but all of them rely, in different degrees, on empirical considerations and/or measured data. An overview of the three techniques is given by Deidewig et al [10], here it will only be said that the first two, although generally more accurate, rely on the availability of measured or calculated EI at SLS conditions. In a numerical optimisation study, as the one performed here, these data are not available, therefore absolute methods must be used. In such methods the amount of NO_X emissions can be estimated by knowing the combustor inlet conditions and a few key combustor design parameters.

Although various absolute correlations for gas turbine NO_X emissions are available, one of the most widely used is that developed by Lefebvre [11]. This correlation, Eq. 2, is strongly based on empirical data although its general format is obtained from general considerations on mixing rates, chemical reaction rates and combustor residence time. In the format presented in Eq. 2, valid for conventional spray combustors only, the EI_{NOX} value is expressed in g/kg.

$$EI_{NO_X} = \frac{c \cdot P_3^{1.25} \cdot V_{PZ} \cdot e^{0.01 \cdot T_{ST}}}{m_A \cdot T_{PZ}} \qquad (2)$$

Values for P3 (combustor inlet pressure), T_{ST} (stoichiometric flame temperature) and m_A (total combustor air flow) can be obtained from the performance module. Reasonable estimates of the volume (V_{PZ}) and temperature (T_{PZ}) of the combustion (primary) zone are needed. The calibration constant c has been set to the value of $2 \cdot 10^{-8}$, as suggested by Le Dilosquer [6]: this value, lower than the original multiplier suggested by Lefebvre, reflects the improvements in low-NO_X combustor technology.

One of the optimisation experiments carried out has analysed the effect of introducing advanced combustion technology in the turbofan engine. This is interpreted as pre-mixed pre-vaporized combustion and has been modeled with Eq. 2, substituting T_{ST} with T_{PZ} in the exponential term [11].

4.3 Preliminary Sizing of Combustor

The estimates of primary zone volume (V_{PZ}) and temperature (T_{PZ}), required by Eq. 2, must be obtained from the available cycle data, which are the optimisation variables (BPR_{DP}, FPR_{DP}, CPR_{DP}, $T4_{DP}$, $T4_{OD}$) and the other cycle parameters that are kept fixed during the process.

This is achieved following a methodology suggested by Walsh and Fletcher, in which a series of combustor design variables are adequately chosen to satisfy the requirements of high combustion efficiency, ignitability at windmilling conditions, wide stability limits and low pressure loss [12].

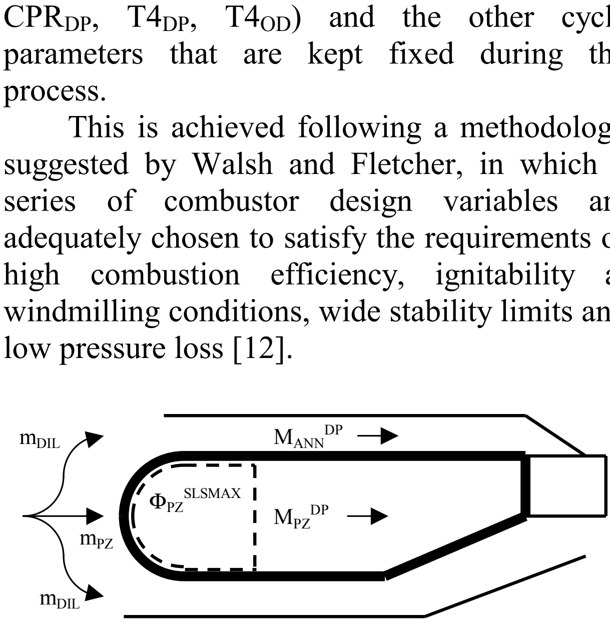

Fig. 5. Diagram of a gas turbine combustor

With reference to Fig. 5, the above-mentioned combustor design variables are:

1. Primary zone equivalence ratio at SLS maximum rating conditions (Φ_{PZ}^{SLSMAX}). A sufficiently high value (near stoichiometric) will avoid weak extinction at low power. From this parameter, the ratio of primary zone air to total combustor air ($FRAC=m_{PZ}/(m_{DIL}+m_{PZ})$) can be obtained. FRAC is assumed to remain approximately constant throughout the operational envelope and this allows the primary zone temperature required in Eq. 2 to be calculated.
2. Design point annulus and primary zone average Mach numbers (M_{ANN}^{DP} and M_{PZ}^{DP}). An adequate choice of their values should be made to avoid high pressure losses while ensuring good mixing between primary and dilution air. From M_{ANN}^{DP}, M_{PZ}^{DP} and other combustor variables (amongst which are T_{PZ} and FRAC), the cross-sectional areas of the combustor can and of the annuli can be derived.
3. Combustor can volume (V_{CAN}: in Fig. 5 the can is contoured by a thicker continuous line). This variable influences the combustor loading (CL) and the combustion intensity (CI) parameters, defined as:

$$CL = \frac{m_A}{V_{CAN} \cdot P_3^{1.8} \cdot 10^{0.00145 \cdot (T_3 - 400)}} \quad (3)$$

$$CI = \frac{ff \cdot LHV \cdot \eta_{COMB}}{V_{CAN} \cdot P_3} \quad (4)$$

In these definitions m_A is the total combustor air, P3 and T3 are, respectively, combustor inlet pressure and temperature, ff is the fuel flow, LHV is the lower heating value of the fuel and η_{COMB} is the combustion efficiency. Both CI and CL are related to combustion efficiency, stability and ignitability, and low values are desired. Walsh and Fletcher suggest to evaluate CL at windmilling conditions and CI at SLS maximum rating conditions, choosing the greater of the two can volumes obtained [12]. Combustor inlet pressure, temperature and air flow at windmilling conditions are estimated through correlations also described by Walsh and Fletcher [12]. From the can volume (V_{CAN}) and the can cross-sectional area, an estimate of the can length and of the residence time can then be derived.

In every cycle analysed by the optimiser, the primary zone volume, required in Eq. 2 and contoured in Fig. 5 by a dashed line, is assumed to be a fixed fraction of the overall can volume. This fraction has been set to 0.2, a typical value found in combustors of commercial aero-engines. With this final assumption it is possible to have a preliminary sizing of the combustor and an estimate of the NO_X emissions associated with it.

The procedure, although very simple in its approach, reflects the correct dependencies between combustor design variables and cycle parameters, and has been tested on a case-study of a commercial aero-engine combustor of which the design variables were known. By varying M_{ANN}^{DP}, M_{PZ}^{DP} and Φ_{PZ}^{SLSMAX} within the boundaries suggested by Walsh and Fletcher an exact match has been achieved on the derived and real values of cross-sectional areas and FRAC. The predicted can volume was 20% lower than the real data, which indicates the expected level of accuracy of the sizing technique.

5 The GA-Based Optimiser

Genetic algorithms are optimisation techniques based on probabilistic principles that simulate the mechanism of evolution in living beings.

GAs rely only on function evaluations, and are therefore suitable for search in irregular and poorly understood spaces. This is the case for gas turbine performance optimisation, in which the governing non-linear equations often do not have a solution.

The GA utilised for this study has been developed in house, based on the guidelines provided by Davis [13]. It implements most of the classic GA features, including penalty functions for treating non-linear constraints.

The developed GA-based optimiser has been validated on constrained and unconstrained mathematical test functions, and was found to perform well both in terms of accuracy and computational time.

6 Optimisation Studies

As previously stated, the cycle parameters that have been optimised are BPR_{CR}, FPR_{CR}, CPR_{CR}, $T4_{CR}$ and $T4_{T/O}$. The upper boundaries for these variables reflect the capability of current technology, and are shown, together with the respective lower boundaries, in Tab. 1.

Tab. 1. Upper and lower boundaries for the optimised variables

	BPR_{CR}	FPR_{CR}	CPR_{CR}	$T4_{CR}$	$T4_{T/O}$
Units	/	/	/	(K)	(K)
From	2	1.2	4.0	1300	1300
To	15	1.9	30.0	1800	2000

Constraints have been set on the values of cruise specific thrust ($SPFN_{CR}$), thrust ratio (TR), take-off compressor delivery temperature ($T3_{T/O}$) and ICAO LTO NO_X parameter ($ICAO_{NOX}$).

For $SPFN_{CR}$ and TR, reference values of 200 N·sec/kg and 5, respectively, have been selected. These values reflect the performance of a typical turbofan powering a long-range aircraft, such as the Rolls-Royce RB211-524 G/H, having a bypass ratio of about 4.5 and delivering about 50 kN of thrust at cruise and 250 kN at take-off.

For take-off compressor delivery temperature, a typical upper limit of 950 K has been considered.

Two different limits have been considered for the ICAO LTO NO_X parameter: 120 and 100 g_{NOX}/kN. These values are in the ballpark of the CAEP (Committee on Aviation Environmental Protection) standards, although quite high compared to current legislation.

For cruise, an altitude of 10670 m and a Mach number of 0.85 have been assumed. For take-off, SLS conditions have been considered. To both operational points, ISA+0 conditions apply.

Several cases have been analysed and are listed in Tab. 2. For each of them an identification number is assigned, the objective and the values of the constraints are shown and the assumed level of combustion technology is indicated. The values for the constraints on $SPFN_{CR}$, $T3_{T/O}$ and TR, that are constant across all cases, are not mentioned.

Tab. 2. Summary of the optimisation cases

N	Objective	Combustion technology	Constraints	
			Δsfc (%)	$ICAO_{NOX}$
1	Min. sfc	Standard	No limit	<120
2	Min. sfc	Standard	No limit	<100
3	Min. GWP	Standard	No limit	<120
4	Min. GWP	Standard	<10	<120
5	Min. GWP	Advanced	No limit	<120

Optimisation case 1 is considered as the reference case: values of SFC, GWP and $ICAO_{NOX}$ obtained for the other cases have been expressed in terms of relative deviation from this reference solution.

Case 2 represents a low-$ICAO_{NOX}$ scenario, but still optimised for minimum cruise SFC. Case 3 reflects a minimum cruise GWP, scenario with standard $ICAO_{NOX}$ regulations. Case 4 is similar to case 3, but a maximum SFC penalty of 10% with respect to case 1 has been imposed. Finally, case 5 is again similar to case 3, but pre-mixed pre-vaporized combustion technology has been assumed.

7 Results and Discussion

A summary of the results obtained for the five case studies is shown in Tab. 3.

In the first four rows the optimum set of cycle parameters is shown. The optimum value of FPRCR is always 1.9, so only the overall pressure ratio (OPR) is shown.

In the next three rows the relative SFC, GWP and $ICAO_{NOX}$ deviations (in %) with respect to the SFC-optimised engine (case 1) are listed.

In the last five rows the gray shading highlights the constraints that have been considered for a particular optimisation study. The black dots indicate if a constraint is saturated, i.e. if its value is at its specified maximum or minimum.

Tab. 3. Results of the optimisation studies

N	1	2	3	4	5
BPR_{CR}	5.01	4.91	4.33	4.16	4.36
OPR_{CR}	43.8	41.2	11.5	19.8	39.5
TET_{CR}	1555	1522	1300	1300	1469
$TET_{T/O}$	1792	1756	1536	1519	1822
Δsfc_{CR}	0	+0.6	+21.1	+10.0	+1.2
ΔGWP_{CR}	0	-9.9	-46.2	-43.5	-63.9
$\Delta ICAO_{NOX}$	0	-16.7	-84.9	-74.6	-67.6
$SPFN_{CR}$	•	•	•	•	•
TR	•	•	•	•	
$T3_{T/O}$					•
$ICAO_{NOX}$	•	•			
Δsfc_{CR}				•	

During the optimisation, additional checks were made on the combustor geometries produced by the preliminary combustor design module. In particular, attention was focused on the residence time, for which values above 3 msec were found in all cases, and the combustor loading at cruise, for which values below 10 kg/(sec·atm$^{1.8}$·m^3) were found in all cases. These figures are considered to be within the allowable ranges for current civil aircraft combustors [12].

Case 1 represents the reference, SFC-optimised, engine. For this solution the contribution of NO_X to the GWP is about twice that of CO_2 ($GWP_{NOX}\cdot EI_{NOX} \cong 2\cdot GWP_{CO2}\cdot EI_{CO2}$).

When compared with case 1, the GWP-optimised solution (case 3) is characterized by a low OPR and by low T4s: this confirms the general trend pointed out by the Greener by Design Workgroup [2]. Conversely, the design BPR does not change as much, although this is due to the constraint imposed on cruise specific thrust. Due to the reduced cycle pressures and temperatures, the $ICAO_{NOX}$ constraint is no longer saturated.

These trends match up with the trends observed for case 2, in which lower LTO NO_X emissions have been imposed. This is an expected outcome, as in both cases the main driver is NO_X emissions.

The optimum GWP-engine is therefore a "simpler" engine than the SFC-optimised one, needing fewer compression stages and no cooling flows.

The performance implication of these considerable changes in the cycle parameters is a halving of the GWP at cruise and an increase by about 20% of the cruise SFC.

In case 4 minimum cruise GWP has been sought, while imposing a maximum SFC penalty. It is interesting to note that although the SFC penalty has halved, most of the GWP reduction is still obtained. Fig. 6 analyses this concept further, by showing the relative difference in GWP achieved against the allowable relative SFC penalty. Again, all values are relative to case 1 and each point in the graph represents a cruise GWP-optimum design.

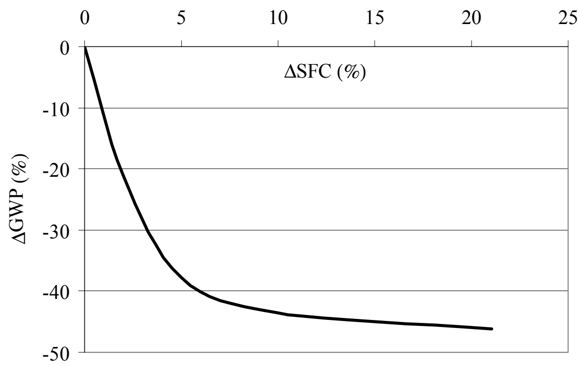

Fig. 6. ΔGWP plotted against ΔSFC

Case 5 illustrates one other possible way to achieve low levels of cruise GWP. By utilizing advanced combustion technology, in this case pre-mixed pre-vaporized combustion, an even greater advantage than that in case 3 can be obtained, still maintaining a very good SFC performance.

8 Conclusions

In the research described in this paper, a GA-based optimiser has been "wrapped" around an integrated turbofan performance and emissions estimation tool, and different optimisation studies have been performed by varying the objectives and the constraints, with particular emphasis on reducing environmental impact.

The main outcome of this study is that a turbofan optimised for minimum cruise GWP has a lower OPR and lower T4s than the reference, cruise SFC-optimised, solution, and a similar BPR. This set of cycle parameters make it a very fuel-inefficient engine, with a cruise SFC more than 20% higher than the reference solution.

However, a better SFC performance can still be retained by choosing solutions that are close, but not coincident, to the mathematical optimum for global warming potential.

By improving combustion technology, in this case through pre-mixed pre-vaporized combustion, further reductions in cruise GWP can be achieved. Additionally, the SFC penalty for the GWP-optimised solution is reduced to only 1.5%.

From a methodological point of view, the idea of using low-order models has proven to be useful, by providing reasonably accurate results within an acceptable computational time. The GA-based optimiser has performed well, although the time-consuming procedure of fine-tuning its parameters has proven vital for its efficiency.

Some strong assumptions have been made in this study, particularly related to the relationship between emissions and global warming potential and to the estimation of NO_X. The next step forward is therefore to assess the sensitivity of the results to changes in these uncertainty factors.

It is also worth underlining that the concepts analysed in this research are by no means the only ones that can be thought of for reducing the global warming potential of aero-engines. Several alternative approaches have been investigated by other research groups, amongst which are novel fuels and thermodynamic cycles, aircraft with a higher airframe/engine integration and more efficient air traffic control procedures.

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