Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46451

CONCEPTUAL DESIGN AND MISSION ANALYSIS FOR A GEARED TURBOFAN AND AN OPEN ROTOR CONFIGURATION

Linda Larsson
linda.larsson@volvo.com
Volvo Aero Corporation
Trollhättan, Sweden

Tomas Grönstedt
tomas.gronstedt@chalmers.se
Chalmers University
Gothenburg, Sweden

Konstantinos G. Kyprianidis
konkypr@chalmers.se
Chalmers University
Gothenburg, Sweden

ABSTRACT

In this multidisciplinary study a geared open rotor configuration is assessed and compared to an ultra high bypass ratio geared turbofan engine. Both designs assume a 2020 entry into service level of technology. The specific thrust level for minimizing block fuel and the resulting engine emissions for a given mission is sought. The tool used contains models that effectively capture: engine performance, mechanical and aerodynamic design, engine weight, emissions, aircraft design and performance as well as direct operating costs.

The choice of specific thrust is a complex optimization problem and several disciplines need to be considered simultaneously. It will be demonstrated, through multidisciplinary analysis, that the open rotor concept can offer a substantial fuel saving potential, compared to ducted fans, for a given set of design considerations and customer requirements.

NOMENCLATURE

Δh_0	Stagnation enthalpy change
η_{pol}	Polytropic efficiency
A	Annulus area
AR	Axial Aspect Ratio
BPR	Bypass Ratio
CO_2	Carbon dioxide
D	Propeller diameter [m]
DDTF	Direct Drive Turbo Fan
DOC	Direct Operating Cost
DREAM	valiDation of Radical Engine Architecture systeMs
$EINO_x$	Nitrogen Oxides Emissions Index
EIS	Entry Into Service
FAR	Federal Aviation Regulations
FB	Fuel Burn
FL	Flight Level
FP7	Seventh Framework Program
FPR	Fan Pressure Ratio
GOR	Geared Open Rotor
GTF	Geared TurboFan
GTFSR	Short Range Geared TurboFan
h_b	Blade height
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
IPC	Intermediate Pressure Compressor
ISA	International Standard Atmosphere
IPT	Intermediate Pressure Turbine
K	Blade volume factor
LT	Long Term
LTO	Landing and Take-Off
LR	Long Range
MT	Medium Term
N	Rotational speed
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OPR	Overall Pressure Ratio
PW	Power
RQL	Rich-burn/Quick-quench/Lean-burn
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SR	Short Range
T4	Burner exit temperature
T/O	Take-Off
TEC	Turbine Exhaust Case
TET	Turbine Entry Temperature
U_{mid}	Mid section blade speed
UHBR	Ultra High Bypass Ratio
UDF	Un-Ducted Fan

INTRODUCTION

To reduce the environmental and climate impact from air traffic, the aero industry and research community strive towards minimizing CO_2 and NO_x emissions. It is therefore of interest to decrease fuel consumption. For turbofan engines it is widely acknowledged that increasing propulsive efficiency by reducing specific thrust decreases specific fuel consumption. There are of course limits to the actual fuel saving potential. Although specific fuel consumption drops with increasing propulsive efficiency there is a point where the losses due to the transfer efficiency are greater than the gain from the increase in propulsive efficiency and this introduces a constraint in the search for the optimal engine design. Furthermore, engine weight and nacelle drag increase with reducing specific thrust and hence increasing nacelle diameter. Consequently there is for each engine configuration, technology level, set of customer requirements and design constraints a specific thrust level which gives minimum fuel burn. The optimal design is essentially a tradeoff between specific fuel consumption, engine installed weight and nacelle drag.

Jackson [1] provides an interesting discussion on how specific thrust levels were expected to evolve in the mid-70's based on the economic and technological projections of that time period; the author provides an update to that discussion based on current economical and technological projections in [2]. Wilde [3] provides a good reference on how the future for civil turbofan engines for medium and long range applications was envisaged in the late 70's. Some early discussions on future trends in commercial aviation from the aircraft manufacturer's and airliner's perspective can be found in [4] and [5].

On several occasions during the last 40 years the open rotor engine concept has risen as a candidate for improving fuel consumption. The propulsive efficiency may be increased further compared to ultra high bypass ratio turbofan engines without as much an increase in nacelle drag and losses due to the transfer efficiency. It is, and has long since been the case that the propulsive efficiency for a turboprop is better than that of a turbofan engine [6], and this is due to the lower velocities. The main limitation with turboprops today is the flight speed.

For a conventional propeller with straight blades compressibility effects begin to dominate and decrease the propeller efficiency at flight Mach numbers around 0.6. To tackle this limitation advanced propeller research was initiated in the 60s and 70s by Hamilton Standards [7]. With swept propeller blades the shock losses can be decreased and higher cruise speeds may be achieved. A way to reach further improvements is to recover the swirl losses produced in the propeller by adding another propeller stage. It was shown in [8] that the efficiency in cruise can be increased by as much as 8 points using contra-rotation.

In the 1980's the open rotor, propfan or unducted fan was evaluated in several flight tests. The hope was that it could become a fuel efficient propulsion option for high subsonic flight speed. General Electrics together with NASA entered a full scale flight test engine technology demonstrator program called the Unducted Fan (UDF) (see [9], [10], [11]). This study provided the proof of concept for a direct driven configuration where a contra-rotating power turbine drives two propellers without the need for an intermediate gearbox. This concept was flight tested in 1987 [12]. At around the same period, Pratt and Whitney together with Allison demonstrated a geared concept called the PW-Allison 578-DX Propfan. This demonstrator flew in 1989 [12]. The two previously mentioned concepts never got any further than flight testing. This is not the case for the Ukrainian/Russian D-27 which powers the Antonov 70 military transport aircraft [13].

A review on the several technical and economic obstacles that were identified in the late 80's with respect to the realization of the Ultra-High Bypass Ratio (UHBR) turbofan concept is provided by Borradaile [14] and Zimbrick and Colehour [15]. Peacock and Sadler [16] give an update on the subject, focusing further on engine design constraints and the technology advancements required for producing a competitive UHBR configuration.

Although most of the open rotor programs of the 80's were put on hold, the concept has now resurfaced. In the FP7 project DREAM, "valiDation of Radical Engine Architecture systeMs" [17], the feasibility of two different open rotor architectures are evaluated. Much effort is being put in to evaluating noise. In another FP7 program, Clean Sky, two demonstrators of the open rotor concept are being designed and built. This work is led by Rolls Royce for the first of the two demonstrators and Snecma for the second [18].

Potential year 2020 scenarios are explored by Birch [19] while Ruffles [20] provides an overview of current aero engine technology and some insight on the future of aircraft propulsion. Sieber [21] and Scimming [22] provide an excellent discussion on contra-rotating fan designs. Finally, for a review on the development of civil propulsion from the early 50's to recent years the interested reader is referred to Saravanamuttoo [23].

In this study two feasible propulsion alternatives for short haul aircraft are compared in terms of block fuel. Block fuel can be defined as the amount of fuel consumed during a given mission. A geared open rotor configuration is evaluated against a geared turbofan of the year 2020 including an engine weight and mission assessment. The geared turbofan is a two shaft configuration with a conventional reduction gearbox between the intermediate compressor and fan. The open rotor configuration chosen is a geared contra-rotating pusher configuration. The core consists of a two spool turbojet while the propulsor consist of a power turbine that drives two contra-rotating propellers with swept blades. A planetary gearbox is located between the propellers and power turbine.

DUCTED FAN FUEL OPTIMAL SPECIFIC THRUST LEVELS FOR 2020

The potential uninstalled Specific Fuel Consumption (SFC) benefits from reducing specific thrust for a year 2020 Entry Into Service (EIS) conventional turbofan engine are illustrated in Figure 1.

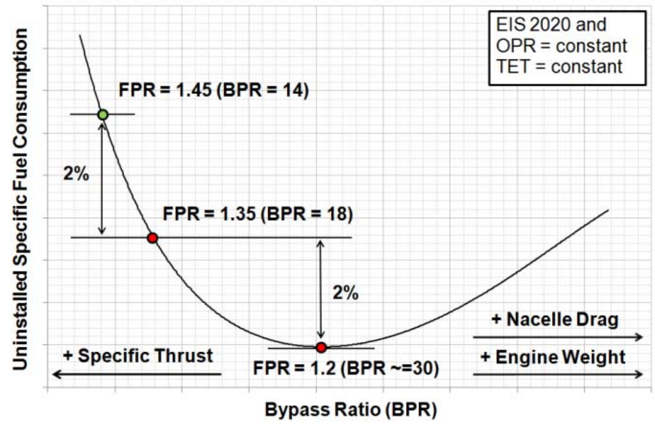

Figure 1 *Estimated uninstalled specific fuel consumption benefits from reducing specific thrust for a year 2020 entry into service conventional turbofan engine*

In order for the results to be general the benefit is given in relative terms instead of absolute numbers. These design-point calculations were produced assuming constant engine Overall Pressure Ratio (OPR) and Turbine Entry Temperature (TET), and reflect mid-cruise conditions and optimal By-Pass Ratio (BPR) for SFC; off-design performance effects as well as nacelle drag and engine weight was not considered. As can be observed, reducing specific thrust can improve the propulsive efficiency but inevitably it worsens the transmission efficiency. At a Fan Pressure Ratio (FPR) of roughly 1.2 there seems to be no thermodynamic benefit from further reducing specific thrust. A similar behavior is observed in the ideal case of the fan and low pressure turbine polytropic efficiencies being equal to unity, as illustrated in Figure 2.

Some important observations can be made:

- Improving fan and low pressure turbine polytropic efficiency directly improves SFC; the potential SFC benefits from reducing specific thrust however remain largely unaffected. As fan tip pressure ratio reduces, pressure losses in the bypass duct tend to have an increasingly dominant effect on transmission efficiency and, therefore, on the impact of propulsive efficiency improvements on SFC.
- Improving fan and low pressure turbine polytropic efficiency increases the optimal BPR value, at a constant specific thrust. Although not illustrated in Figure 1 and Figure 2, improving core specific output and component efficiency will have a similar effect. Bypass ratio can therefore be considered as a good indicator of engine technology level.
- Limited SFC improvement may be envisaged by reducing specific thrust beyond a fan pressure ratio of 1.45. The increased fan diameter will result in significant engine weight and nacelle drag penalties which can very well negate the projected uninstalled SFC benefits. A larger fan, low pressure turbine and nacelle will also increase the production cost significantly.

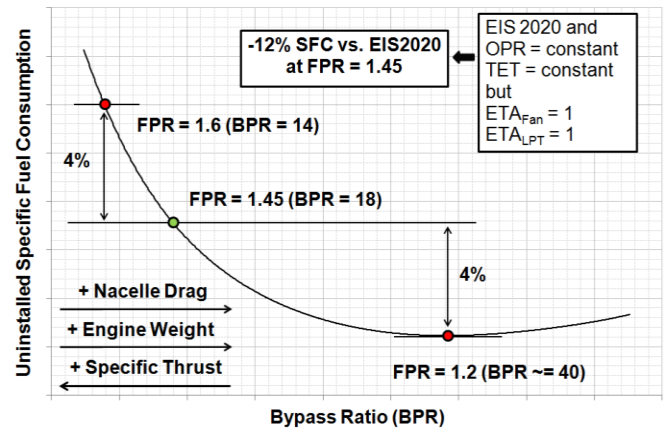

Figure 2 *Estimated uninstalled specific fuel consumption benefits from reducing specific thrust for a conventional turbofan engine with an ideal LP system and EIS 2020 core*

For determining the fuel optimal specific thrust and BPR levels, the effects of engine weight and nacelle drag on aircraft performance need to be considered. Block fuel exchange rates produced with a rubberized wing aircraft model (assuming year 2000 EIS) are presented in Table 1 for the business case (assuming 3000 nmi for the Long Range model and 500 nmi for the Short Range model) and are considered to be reasonable numbers.

Relative block fuel benefits from reducing specific thrust for a year 2020 entry into service direct drive fan conventional core engine for long haul applications calculated in [24] are illustrated in Figure 3. The engine take-off (T/O) thrust at ISA SLS conditions is 66000 lbf and all FPR and BPR values quoted are at mid-cruise conditions. A 10% in increase in fan diameter and a 4% reduction in FPR (which roughly translates to a 14% reduction in specific thrust) results in a 2% improvement in mid-cruise uninstalled SFC; using the exchange rates reported above this would imply an improvement in block fuel of some 2.6%. Nevertheless, the engine weight has increased significantly by roughly 17% and in conjunction with the higher nacelle drag the block fuel benefit reduces to only 0.85%. More details on this fuel optimal design and the constraints set to derive it are given in [24]. It is worth noting that a recent study by Hemmer et al. [25], albeit based on significantly more pessimistic OPR and TET levels, concluded on similar fuel optimal FPR levels for the geared and contra-rotating architectures for long range applications.

Table 1 *Block fuel exchange rates for long range and short range rubberized wing aircraft models*

Perturbation	Exchange rates	
	LR	SR
1000 kg weight penalty	0.73%	1.26%
+1% SFC	1.28%	1.09%

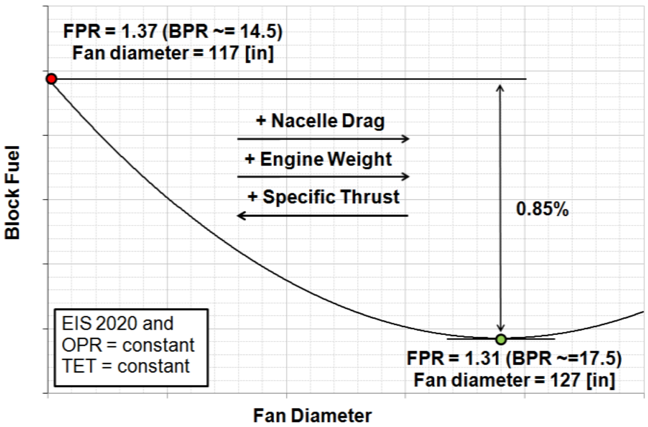

Figure 3 *Estimated block fuel benefits from reducing specific thrust for a year 2020 entry into service conventional turbofan engine for long range applications*

From the flat curve presented in Figure 3, it is clear that only limited benefits in block fuel may be envisaged by reducing specific thrust as these are highly dependent on the engine thrust to weight ratio. Technology risk considerations (i.e. shortcomings in meeting projected engine weight and turbomachinery efficiency targets) will probably move the fuel optimal level of specific thrust to higher values. Noise considerations (i.e. stringent noise legislation) may very well dictate fan size and specific thrust levels that are not fuel optimal, as has been the case in the past [16]. The optimal specific thrust level for minimum direct operating costs is highly dependent on the assumptions made for the volatility of economic parameters such as fuel price and interest rates. Furthermore, production and maintenance costs tend to be proportional to engine weight which is inversely proportional to specific thrust at a given technology level and fan diameter at a given thrust. It can therefore be concluded that the commercial competitiveness of reduced specific thrust turbofan designs will largely depend on how the aviation market evolves in the years to come until 2020.

THE GEARED TURBOFAN AND OPEN ROTOR ENGINE DESIGN

Several issues need to be considered when designing and evaluating the open rotor concepts. For long haul applications thrust requirements would dictate an excessively large propeller diameter, but for aircraft designed to carry 150 pax up to a distance of 3000 nmi feasible open rotor engine designs may be produced. The open rotor can provide propulsive efficiencies around 90% (i.e., turbofan equivalent fan pressure ratios of 1.1). For turbofan designs at the same level of specific thrust, however, it was shown earlier that the improvement in propulsive efficiency would be completely negated by the reduction in transfer efficiency (primarily due to bypass duct pressure losses), and the increase in engine weight and nacelle drag.

METHODOLOGY

The prediction of engine performance, aircraft design and performance, direct operating costs, and emissions for the two engine designs is made using the EVA code [26]. The engine performance output is used as input in the conceptual design tool Weico for carrying out mechanical and aerodynamic design to derive engine component weight and dimensions. These two tools are integrated together and run in sequence using a commercial integration and optimization environment [27]. Multi objective optimization, design studies, parametric studies, and sensitivity analysis can readily be performed within this environment.

DESIGN SPACE CONSTRAINTS

The optimality of an engine design for block fuel depends primarily on specific fuel consumption, engine installed weight and nacelle drag; it's feasibility on the other hand will depend on the constraints set. A simple example of utilizing a conceptual design tool (such as presented in [28]) for design space exploration, with active constraints is visualized through Figure 4. It is worth noting that nacelle drag should be added as a third dimension when plotting design space exploration results that consider varying levels of specific thrust; this was omitted in this case as means to simplify the plot.

The aircraft exchange rates at the nominal design were used for plotting a constant block fuel line (effectively ignoring nacelle drag effects and non-linearities); the plotted iso-line therefore defines, in a simple manner, the boundaries of trading SFC for weight. During a block fuel optimization with such a tool, different engine designs are continuously evaluated by the optimizer as it searches for the optimal solution. Designs that fail to meet the constraints set by the user are discarded as unfeasible. It is therefore paramount that realistic design constraints are set before any engine optimization.

For every engine design there are numerous practical limitations that need to be considered. The design space constraints set for this study are given in Table 2 and are considered reasonable for a year 2020 entry into service turbofan engine for short haul applications.

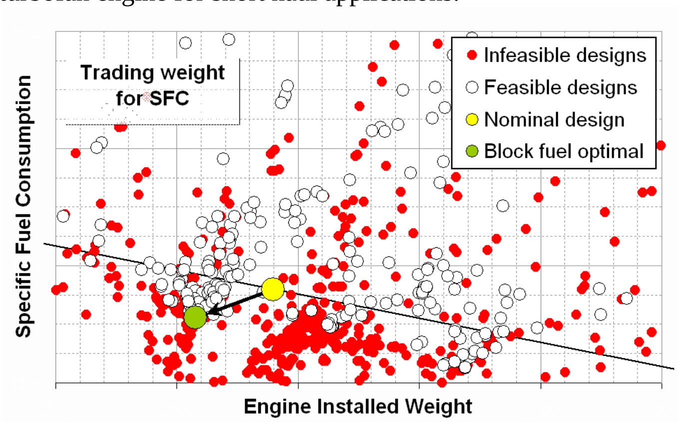

Figure 4 *Visualization example of constrained design space exploration [28]*

Table 2 *Design space constraints for the geared turbofan and geared open rotor engine configurations for short haul applications*

	Lower bound	Upper bound
FAR take-off distance (at ISA sea level conditions)	-	2.0 km
Climb to 31000 ft	-	25.0 min
HPC design pressure ratio (single-stage HPT)	-	5.5
HPC delivery temperature	-	970 K
HPC last stage blade height	12 mm	-
Combustor outlet temperature	-	1850 K
Turbine blade mean metal temperature (external surface)	-	1250 K
Time between overhaul	18000 hr	-

For a conventional core the High Pressure Compressor (HPC) delivery temperature, and hence the engine OPR is typically constrained by the mechanical properties of the HPC disc or HPC rear drive cone or High Pressure Turbine (HPT) disc material. Furthermore, as OPR increases the air density in the gas path increases and as a result the compressor blades tend to become smaller. Losses from tip clearances become increasingly important and a minimum compressor blade height limitation needs to be applied to maintain state of the art compressor efficiency. Core architecture selections set an upper limit to the HPC design pressure ratio that can achieved when driven by a single-stage HPT; similar limitations apply to the Intermediate Pressure Compressor (IPC) design pressure ratio that can achieved when driven by a single-stage Intermediate Pressure Turbine (IPT).

Designing a combustor at very low air to fuel ratio levels is also limited by the need for adequate combustor liner film-cooling air as well as maintaining an acceptable temperature traverse quality [29]; this sets an upper bound on combustor outlet temperature. Furthermore, a maximum permissible mean metal temperature needs to be set to consider turbine blade material limitations. A lower bound on engine time between overhaul also needs to be set to limit the frequency of workshop visits. For short range applications the minimum engine time between overhaul was set to 18000 hr. This reflects the fact that designs for short range applications are typically operated at high power conditions for a significant larger amount of their operational lives. Significantly lower levels of maximum combustor outlet temperature and turbine blade mean metal temperature had to be selected, compared to what could be selected for engine designs for long haul applications that are often operated at derated thrust levels and spend most of their life at cruise; (see Figure 5) for projected trends for engines designed for long haul applications.

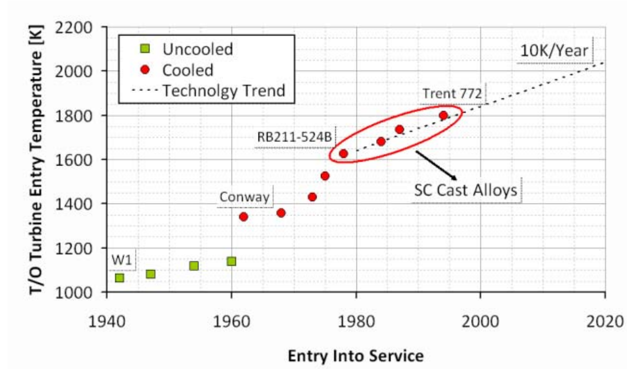

Figure 5 *Evolution of turbine blade material technology and maximum allowable turbine entry temperatures (based on data from [30])*

To derive the engine thrust requirements, a maximum FAR (Federal Aviation Regulations) take-off field length and a maximum time to height for a load factor of 1 and ISA conditions was set. The choice of both is typically based on customer operational requirements. The aircraft needs to be able to: (i) take-off from a large number of airports around the world and (ii) climb to the initial cruise altitude sufficiently fast to ease operations with local air traffic control (which can reduce waiting time on the ground). A cumulative distribution of the world's major runway lengths, based on data from [31], is illustrated in Figure 6. For short haul applications fairly stringent constraints are typically set for the maximum take-off distance and time to height (in this study 2.0 km and 25 min, respectively). This practice results in slightly bigger engines but allows for greater flexibility for engine derating at a smaller block fuel cost.

The aircraft for short haul applications used in this study is designed to carry 150 pax for a distance of 3000 nmi; the figure of merit used in the optimization is block fuel and is based on a business case of 500 nmi with an assumed load factor of 1. For the step-up cruise procedure, a minimum residual rate of climb of 300 ft/min was set as a constraint for flying at the cruise altitude for maximum specific range.

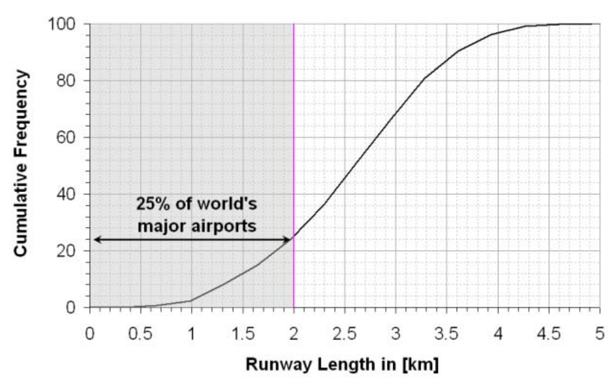

Figure 6 *Cumulative distribution of world's major runway lengths (based on data from [31])*

RESULTS AND DISCUSSION

PERFORMANCE, OPTIMAL FUEL DESIGNS

Optimizing a turbofan and an open rotor engine design for minimum block fuel essentially has to consider the trade-off between improving thermal and propulsive efficiency and reducing engine weight and nacelle drag. The cycle optimization results for the geared fan and geared open rotor power plants are given in Table 3 and significant block fuel benefits are projected for the open rotor engine.

The fuel optimal specific thrust for the open rotor is significantly lower compared to the turbofan engine for the reasons discussed earlier. Reduced specific thrust designs for 2020 can prove attractive in terms of direct operating costs, provided that fuel prices can remain high and increase further. There are risks involved with introducing new technology originating from the large design uncertainties that exist at the beginning of any new development project. These risks involve, for example, delayed introduction of the product to the market, increased development costs and late design changes. Such risks need to be managed appropriately in order for the open rotor engine to remain an attractive option.

In Table 3 it can be noted that the fuel optimal design for the geared open rotor gives 14% lower SFC than the geared turbofan. For the mission this translates into 15% reduction in fuel burn considering engine weights and nacelle drag. The bypass ratio is presented in mid cruise conditions. For the open rotor the BPR differs considerably between different operating points, i.e., at Take Off (T/O) it is around 50, at Top Of Climb (TOC) it is around 75 and at mid cruise it is around 87. The geared turbofan BPR does not vary in the same magnitude between different conditions.

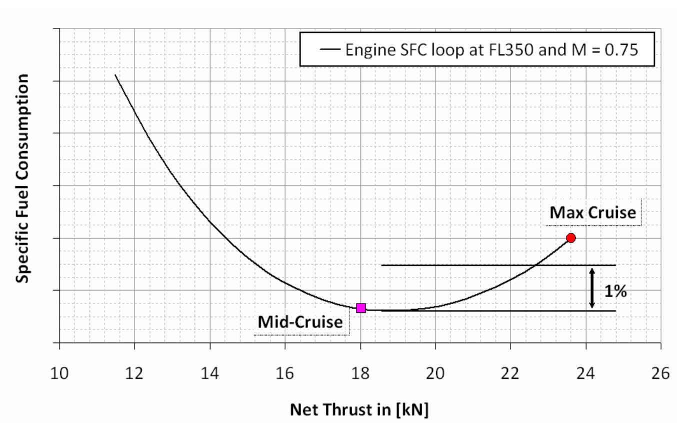

Figure 7 *Quality of engine-aircraft matching for the fuel optimal geared turbofan configuration*

The quality of the engine-aircraft matching for the two configurations is illustrated in Figure 7 and Figure 8. It can be observed that for the geared turbofan the mid-cruise operating point is located roughly at the bottom of the SFC loop. For the geared open rotor the SFC loop is very steep and the bottom of the loop is located very close to the max cruise operating point; this off-design behavior can be attributed to the reducing propeller efficiency as the engine is throttled down. It is therefore paramount to not oversize the engine as this would lead to a mid-cruise operating point that is too far away from the bottom of the SFC loop.

Table 3 *Comparison of the fuel optimal geared turbofan and geared open rotor engine designs (datum is the geared turbofan)*

(Performance parameters at top of climb conditions unless stated otherwise)	**Geared Turbofan EIS 2020**	**Geared Open Rotor EIS 2020**
Fan/propeller diameter m	1.8	4.2
Hot day end of runway take-off thrust kN	92	92
Overall pressure ratio	40.6	40.6
IPC pressure ratio	5	7.5
HPC pressure ratio	5.5	5.5
Fan mass flow kg/s	177	1010
Core mass flow kg/s	15.1	13.5
Mid-cruise fan tip pressure ratio (FL350)	1.46	1.07
Mid-cruise bypass ratio (FL350)	11.2	87
Mid-cruise SFC (FL350)	datum	-14%
Mid-cruise thermal efficiency (FL350) (core + transmission efficiency)	datum	-1.3
Mid-cruise propulsive efficiency (FL350)	datum	+16.0
Engine installed weight	datum	+11%
Fan / propeller weight	datum	+73%
LPT weight	datum	+20%
Core weight	datum	+31%
Nacelle weight	datum	-88%
Block fuel weight	datum	-15%
Cruise $EINO_x$	datum	-5.2%
Direct operating costs	datum	-6%

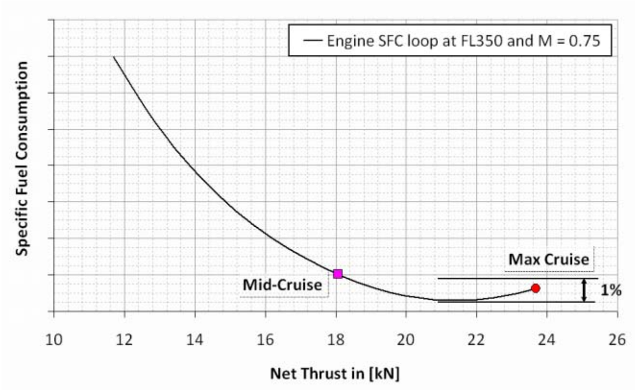

Figure 8 *Quality of engine-aircraft matching for the fuel optimal geared open rotor configuration*

CYCLE SELECTION

For both configurations the high pressure compressor pressure ratio was selected in such a way that the required power could be delivered by a single stage turbine. The optimal OPR was concluded to be roughly the same for both engine designs. Where component efficiencies are concerned the same technology level was assumed i.e. EIS 2020.

The core mass flow in the open rotor engine is smaller than in the geared turbofan since the latter is driven at a lower nozzle pressure ratio in order to achieve a good velocity ratio. Cooling flows have been selected to maintain an HPT turbine metal temperature of 1250 K at end of runway hot day T/O conditions.

The GTF fan pressure ratio was chosen to achieve an optimal velocity ratio between the core and bypass exhaust velocities at cruise conditions. A theoretical derivation of the optimal velocity ratio for a turbofan engine is presented by Guha [32]. The ideal velocity ratio for an open rotor engine can be derived in a similar manner. It should be noted that whereas for a turbofan engine it is defined as the ratio of the ideal velocity of the bypass nozzle over the ideal velocity of the cores nozzle, for an open rotor it is defined as the ratio of the ideal propeller flow velocity and core nozzle ideal velocity. Both these velocity ratios are in the order of 0.8.

The open rotor propeller diameter was chosen so that the disc loading i.e. PW/D^2, of the two propellers in cruise is around 250 kW/m^2. This number is in the range of what has been considered feasible in [8]. The rotational speed of the propeller was chosen to give a tip speed of around 200 m/s. This has been shown to be a reasonable compromise between noise and propeller efficiency [8].

PRELIMINARY DESIGN, AERODYNAMICS, WEIGHT AND MECHANICAL DESIGN

The geared turbofan and the open rotor engine have been designed using similar assumptions on component technology level in terms of Mach numbers and aerodynamic loading as well as assumptions on material technology and mechanical constraints.

Table 4 *Key design parameters for the geared engine*

Design flight Mach number	0.73
Fan tip Mach number	1.31
Axial Mach number at fan entrance	0.60
Axial Mach number at high speed booster entrance	0.48
High speed booster average stage loading	0.42
Axial Mach number at high pressure compressor entrance	0.40
High pressure compressor average stage loading	0.38
High pressure turbine $A \cdot N^2$ parameter	45 (10^9 square inches rpm^2)
High pressure turbine stage loading	3.2
Low pressure turbine stage loading	2.5 (relatively lightly loaded geared turbine)
High pressure turbine axial average aspect ratio	1.5
Low pressure turbine axial average aspect ratio	3.5 (inlet) 6.0 (outlet)
High speed booster axial average aspect ratio	2.5
High pressure compressor axial average aspect ratio	2.5 (inlet) 1.0 (outlet)
Fan axial average aspect ratio (wide chord blades)	2.25
Zweifel coefficients	1.0
High speed booster blade volume factor	0.106 (rotor) 0.092 (stator)
High pressure compressor blade volume factor	0.012
High turbine pressure blade volume factor	0.302 (rotor) 0.39 (stator)
Low pressure turbine blade volume factor	0.1365 (rotor) 0.1155 (stator)

Clearly the large fan of the geared engine is a major contributor to total weight whereas the open rotor derives a major part of its weight from the open rotor propellers, associated structural components and a heavier gearbox.

Turbomachinery stage numbers have been calculated based on average stage loadings, i.e.

$$\overline{\psi} = \frac{\Delta h_0}{\sum U_{mid}^2} \tag{1}$$

where U_{mid} is the blade speed at mid radius and Δh_0 is the stagnation enthalpy change over the turbomachinery component.

Table 5 *Key design parameters for the open rotor engine*

Design flight Mach number	0.73
Propeller tip speed	200 m/s
Total propeller loading	250 kW/m^2
Axial Mach number at low pressure compressor entrance	0.55
Low pressure compressor average stage loading	0.41
Axial Mach number at high pressure compressor entrance	0.40
High pressure compressor average stage loading	0.35
High pressure turbine A·N^2 parameter	50 (10^9 square inches rpm$^{2)}$
High pressure turbine stage loading	3.3
Intermediate pressure turbine stage loading	3.4
Low pressure turbine stage loading	3.4
High pressure turbine axial average aspect ratio	1,5
Intermediate pressure turbine axial average aspect ratio	4.0
Low pressure turbine axial average aspect ratio	3.5 (inlet) 6.0 (outlet)
Low pressure compressor axial average aspect ratio	2.5
High pressure compressor axial average aspect ratio	2.5 (inlet) 1.0 (outlet)
Zweifel coefficients	1.0
Low pressure compressor blade volume factor	0.106 (rotor) 0.092 (stator)
High pressure compressor blade volume factor	0.012
High turbine pressure blade volume factor	0.302 (rotor) 0.39 (stator)
Intermediate pressure turbine blade volume factor	0.250 (rotor) 0.150 (stator)
Low pressure turbine blade volume factor	0.1365 (rotor) 0.1155 (stator)

Axial Mach numbers at component inlets and compressor tip Mach numbers together with centrifugal stressing requirements formulated with the $A{\cdot}N^2$ parameter contribute to establish additional constraints. Aerodynamic analysis is performed at the top of climb operating point whereas mechanical designs of, primarily shaft components, gear boxes and casings is established at take-off conditions. Key parameters for the two engines are collected in Table 4 and Table 5.

In order to establish estimates on engine length, turbomachinery aspect ratios have been chosen using correlations from Grieb [33] that are based on actual engine data. Blade numbers are computed based on compressor diffusion factors and turbine Zweifel coefficients. For the turbines the Zweifel coefficient chosen is 1.0. This is consistent with what is recommended for modern turbines by Dixon and Hall, [34]. For a year 2020 engine it would be possible to choose a coefficient as high as 1.2, but since these are high speeds turbines a more conservative approach is taken. Correlations on average blade thicknesses are used to establish blade volume factors. These are used to calculate blade volume according to

$$V = \frac{K \cdot h_b^2}{AR^2} \qquad (2)$$

where V is the volume, K is the blade volume factor, h_b is the blade height and AR is the average axial aspect ratio. The resulting weights form the input to estimating disc rim stresses and compute turbine and compressor disc weights. The design parameters are listed in Table 4 for the geared turbofan and Table 5 for the open rotor.

The materials assumed for the fan, low pressure compressor, booster and for the first two stages of the high pressure compressor is titanium. For the remaining stages of the HPC a nickel based alloy is assumed. The HPT blade material is assumed to be a fifth generation single crystal alloy. The other turbines are assumed to be nickel based. Composites are chosen for the open rotor propeller blades. The resulting weight distributions are presented in Table 6 and Table 7.

Rotational speeds for the geared engine low pressure and high pressure spools are 58 revolutions per second and 570 revolutions per second respectively. For the open rotor engine the low pressure and high pressure spools operate at 260 revolutions per second and 580 revolutions per second respectively. The open rotor propellers run with a rotational speed of 15 revolutions per second and have a tip diameter of 4.2 meters. This should be contrasted to the tip diameter of the geared fan which has been calculated to be 1.8 meters.

Geared turbofan weight assessment

The geared turbofan engine is comprised of the following components/component groups:

- Fan component
- Engine core including
  - A three stage high pressure booster (included in core to be consistent with open rotor)
  - A six stage high pressure compressor
  - Combustor (conventional annular combustor)
  - A single stage high pressure turbine
- A three stage low pressure turbine
- A gear box with a gear ratio of 3.5
- Nacelle including thrust reverser
- Hot and cold structures
- Shaft, bearings, accessories and nozzles

The geared turbofan weight distribution is summarized in Table 6.

Table 6 *Geared turbofan weight distribution*

Fan (including cold structures)	770 kg
Engine core	180 kg
Low pressure turbine including turbine exhaust frame and low pressure shaft	420 kg
Gearbox	215 kg
Nacelle including thrust reverser	800 kg
Accessories, nozzles, bypass duct, bearings	270 kg
Total weight	2655 kg

Open rotor engine weight

The open rotor engine is comprised of the following components/component groups:

- Propeller weights and rear structures
- Engine core including
    - A five stage low pressure compressor
    - A five stage high pressure compressor
    - Combustor (conventional annular combustor)
    - A single stage high pressure turbine
    - A single stage intermediate pressure turbine
- A three stage low pressure turbine
- A planetary differential gear box with a gear ratio of 8.0
- Nacelle
- Hot and cold structures
- Shaft, bearings, accessories and nozzles

The open rotor weight distribution is summarized in Table 7. The open rotor engine comes out slightly heavier primarily due to the heavy propellers and rear weight structures. The core of the open rotor engine is estimated at roughly 50 kg higher mass. This should be attributed to the intermediate pressure turbine that is not present in the geared engine.

SENSITIVITY ANALYSIS

The block fuel impact of potential shortcomings in component efficiency/technology has been evaluated by doing a sensitivity study. The efficiency has been varied for each component. In the Table 8 the effect on fuel burn from 1 % change in polytropic efficiency for each component and 10% change in bypass duct pressure losses is listed.

Table 7 *Open rotor engine weight distribution*

Engine core	230 kg
Low pressure turbine and turbine exhaust frame	510 kg
Gearbox	505 kg
Propeller weights and rear structures	1335 kg
Nacelle	95 kg
Accessories, nozzles, bypass duct, bearings	275 kg
Total weight	2950 kg

Table 8 *Sensitivity of component efficiency change on block fuel for the two different engine concepts.*

		GTF	GOR
	$\Delta\ \eta_{pol}$	Δ FB	Δ FB
Fan/Propeller	- 1%	0.40%	0.85%
Booster/Low pressure compressor	- 1%	0.17%	0.37%
High pressure compressor	- 1%	0.30%	0.35%
High pressure turbine	- 1%	0.31%	0.41%
Intermediate pressure turbine	- 1%		0.35%
Low pressure turbine	- 1%	0.68%	0.55%
Bypass duct pressure loss	10 %	0.23%	

First of all, when looking at the sensitivities shown in Table 8 it should be kept in mind that they have been produced assuming constant T4 and cooling flow levels, hence thrust has been allowed to vary.

The low pressure system has the highest impact on block fuel. This, in general, is expected for low specific thrust designs. For high OPR engines the efficiency of the high pressure components, IPC/booster, HPC as well as HPT/IPT, have a great influence on performance. By improving the compressor and turbine efficiencies, significant fuel burn benefits can be realized. On the other hand shortcomings in core and low pressure system component efficiency targets will lead to significant block fuel penalties.

It can be observed that the sensitivities due to changes in component efficiency are higher for the GOR than for the GTF. This can be explained for the core components by the fact that when varying the component efficiencies the core velocity varies and the velocity ratio moves away from the optimal value. This effect is more profound on the open rotor than on the GTF, since the jet velocities for the open rotor are lower. The fact that the sensitivity figure is higher for the propellers than for the fan can be attributed to the fact that a larger part of the thrust is produced by the propellers compared to the fan.

EMISSIONS

A NO_x emissions assessment of the presented engine configurations has been performed. The same combustor concept has been considered for both designs i.e., conventional Rich-burn/Quick-quench/Lean-burn (RQL) combustion technology. The results were produced using a combination of basic combustor design rules, feedback from the Original Equipment Manufacturers (OEM) involved in the EU FP6 NEWAC project, and public domain semi-empirical correlations [24]. A comparison of the results obtained against ICAO Annex 16 Volume II legislative limits [35], as well as the Medium Term (MT) and Long Term (LT) technology goals set by CAEP [36], is illustrated in Figure 9.

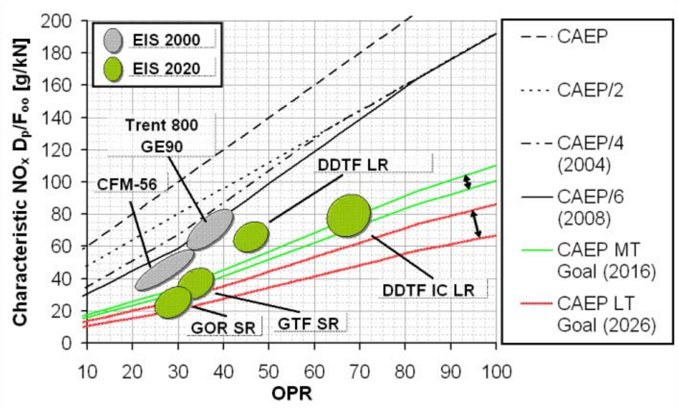

Figure 9 *NO_x Emissions assessment for the fuel optimal geared turbofan configuration turbofan and geared open rotor configurations*

Balloons have been used to indicate the uncertainty in the NO_x predictions due to the lower technology readiness level associated with the introduction of such combustor designs in the proposed future cycles. Results from [37] for two direct drive fan concepts, one with a conventional core and one with an intercooled core, for long range applications have also been plotted.

A sufficient margin against the ICAO CAEP/6 Landing and Take-Off cycle (LTO) NO_x certification limit may be achieved for all the configurations that have been assessed assuming year 2020 EIS. Despite the similar OPR at values at top of climb, the Geared Open Rotor (GOR) is expected to be operated at relatively lower turbine temperatures at static conditions, primarily due to propeller efficiency effects. As a result the Short Range Geared Turbo Fan (GTFSR) engine will be operating at significantly higher thrust and OPR level which will increase both $EINO_x$ and D_pPNO_x/F_{oo} levels for these conditions.

At mid-cruise the $EINO_x$ levels for the GOR concept will be somewhat lower compared to the GTFSR, primarily because of off-design performance effects. With CO_2 emissions being directly and linearly correlated with fuel flow and hence block fuel, it can easily be concluded that the GOR concept offers a reduction of up to 15% in CO_2.

ECONOMIC CONSIDERATIONS

The aero engine designs proposed herein have been optimized for minimum block fuel for a given aircraft mission (business case), which implies minimum global warming impact if one considers CO_2 emissions only. The market competitiveness of these fuel optimal designs however will be highly dependent on the development of jet fuel prices in the years to come until 2020; a further consideration for European markets may also be the development of the Euro/US$ exchange rate, as well as interest and inflation rates.

For the economic calculations conducted in this study certain assumptions were made. The assumed jet fuel price was 172c$/US gallon. It is worth noting that at the time of writing the average jet fuel price was 269c$US gallon (source: Platts [38]). Interest and inflation rates were assumed to be 6% and 2%, respectively, while the US$ to Euro exchange rate was assumed to be 0.8222.

Under these assumptions, the cost of fuel as a fraction of the total Direct Operating Costs (DOC) was predicted to be 13% for short range applications designs. An increase in block fuel by 1% translates in an increase of 0.13% in DOC, and as can be observed it is directly dependent on the ratio of fuel cost over DOC. A doubling of the fuel price would change this ratio to roughly 23%, and would also result in 13% higher DOC levels.

Higher levels of DOC, as a result of a significant increase in fuel price, would most probably be absorbed by airlines through an increase in fares. This could make fuel efficient designs increasingly market competitive, as the DOC optimal designs would further approach the fuel optimal designs. It would therefore be worthwhile to redirect further research investments towards developing fuel efficient aero engine designs, as has also been the case in the late 70s and through large part of the 80s. The introduction of carbon taxes could also have a similar effect.

It is worth noting that an increase in inflation rates from 2% to 3% can increase the net present cost by as much as 17%, over a period of 30 years. An increase in interest rates from 6% to 7% can increase DOC by 2.5% for short applications designs.

CONCLUSIONS

In this paper a comparison between a geared turbofan engine and a geared open rotor engine with year 2020 technology level was carried out. Design constraints in the form of customer requirements (such as time between overhaul, runway length, time to height etc.) as well as technology limitations (such as component efficiencies, maximum stage loading, minimum blade height etc.) were taken into consideration.

Although the open rotor engine is somewhat heavier, the reduced SFC and nacelle drag makes up for this and the resulting mission fuel burn is improved by approximately 15% compared to the geared turbofan engine. It can also be observed that for the open rotor configuration the location of the mid cruise operating point is not at the bottom of the SFC loop. Sizing the engine and choosing an appropriate design point for the propeller involves complex trade-offs, since for short haul aircraft large parts of the business case mission is spent climbing to cruise altitude, rather than cruising.

There is not only a great potential to reduce fuel consumption for the open rotor engine, and consequently decrease the CO_2 emissions however the open rotor engine also demonstrates similar cruise $EINO_x$ figures compared to turbofan concepts, as well as similar margins from ICAO NO_x certification limits.

With current fuel prices, 6% lower DOC can be expected from the geared open rotor concept than from the GTF. This figure is very sensitive to the fluctuation of fuel prices. If the fuel price increases then the impact of fuel consumption on the

DOC will be even higher. The question then rises is: ***"Can the potential reduction in DOC outweigh the technological risks involved in introducing an open rotor configuration into the market."*** The answer is left to be given by the choices the aero engine industry makes in the years to come.

REFERENCES

[1] A.J.B. Jackson, 1976, "Some Future Trends in Aero Engine Design for Subsonic Transport Aircraft", ASME Journal of Engineering for Power, Vol.98, pp. 281-289.

[2] A.J.B. Jackson, 2009, "Optimisation of Aero and Industrial Gas Turbine Design for the Environment", PhD thesis, Cranfield University, United Kingdom.

[3] G.L. Wilde, 1978, "Future large civil turbofans and powerplants", RAeS Aeronautical Journal, Vol. 82, pp. 281-299.

[4] R.E. Bates and J. Morris, 1983, "A McDonnell Douglas Perspective - Commercial Aircraft for the Next Generation", AIAA Aircraft Design, Systems and Technology Meeting Proceedings, AIAA-83-2502, Fort Worth, Texas, USA.

[5] R. Watts, 1978, "European air transport up to the year 2000", RAeS Aeronautical Journal, pp. 300-312.

[6] C.N. Reynolds, R.E. Riffel, S. Ludemann, "Propfan Propulsion systems for the 1990's", AIAA-87-1729, 1987

[7] H.S. Wainauski, C. Rohrbach, T.A. Wynosky "Prop-fan performance terminology" SAE, 871838, 1987

[8] W. C. Strack, G. Knip, A.L. Weisbrich, J. Godston, E. Bradley, "Technology and Benefits of Aircraft Counter Rotation Propellers", NASA technical memorandum 82983, 1982

[9] "Full scale technology demonstration of a modern counterrotating unducted fan engine concept, engine test" NASA CR-180869

[10] "Full scale technology demonstration of a modern counterrotating unducted fan engine concept, design report" NASA CR-180867

[11] C. Reid, "Overview of flight testing of GE aircraft engines UDF engine" AIAA/ASME/SAE/ASEE 24th joint propulsion conference, 1988, Boston, Massachusetts, paper number: AIAA-88-3082

[12] "Whatever happened to propfans?", Flight international, 20070612

[13] M. Daly, B. Gunston, "Janes Aero-Engines" Issue twenty-seven, 2010

[14] J.A. Borradaile, 1988, "Towards the optimum ducted UHBR engine", Proceedings of AIAA/SAE/ASME/ASEE 24th Joint Propulsion Conference, AIAA-89-2954, Boston, Massachusetts, USA.

[15] R.A. Zimbrick and J.L. Colehour, 1988, "An Investigation of Very High Bypass Ratio Engines for Subsonic Transports", Proceedings of AIAA/SAE/ASME/ASEE 24th Joint Propulsion Conference, AIAA-88-2953, Boston, Massachusetts, USA.

[16] N.J. Peacock and J.H.R. Sadler, 1992, "Advanced Propulsion Systems for Large Subsonic Transports", ASME Journal of Propulsion and Power, Vol. 8, No. 3, pp. 703-708.

[17] Dream project website, http://www.dream-project.eu , 2010-11-14

[18] Clean sky project web site, www.cleansky.eu, 2010-11-14

[19] N.T. Birch, 2000, "2020 vision: the prospects for large civil aircraft propulsion", RAeS Aeronautical Journal, pp. 347-352.

[20] P.C. Ruffles, 2000, "The future of aircraft propulsion", Proceedings of the IMechE, Part C: Journal of Mechanical Engineering Science, Vol. 214, No. 1, pp.289-305.

[21] J. Sieber, 1991, "Aerodynamic Design and Experimental Verification of an Advanced Counter-Rotating Fan for UHB Engines", Third European Propulsion Forum, Paris.

[22] P. Schimming, , 2003, "Counter Rotating Fans - An Aircraft Propulsion for the Future", Journal of Thermal Science, Vol.12, No.2, pp.97-103.

[23] H.I.H. Saravanamuttoo, 2002, "The Daniel and Florence Guggenheim Memorial Lecture - Civil Propulsion; The Last 50 Years", ICAS 2002 Congress Proceedings, Toronto, Canada.

[24] K.G. Kyprianidis, 2010, "Multi-disciplinary Conceptual Design of Future Jet Engine Systems" PhD Thesis, Cranfield University, United Kingdom, April.

[25] H. Hemmer, T. Otten, M. Plohr, M. Lecht, and A. Döpelheuer, 2007, "Influence of the Bypass Ratio on Low Altitude NO_x Emissions", 1st CEAS European Air and Space Conference Proceedings, CEAS-2007-137, pp. 1185-1193, Berlin, Germany.

[26] K.G. Kyprianidis, R.F. Colmenares Quintero, D.S. Pascovici, S.O.T. Ogaji, P Pilidis, and A.I Kalfas, 2008, "EVA - A Tool for Environmental Assessment of Novel Propulsion Cycles", ASME Turbo Expo GT2008-50602, June.

[27] Isight 3.5, http://www.simulia.com/

[28] A. Rolt and K.G. Kyprianidis, 2010, "Assessment of New Aero Engine Core Concepts and Technologies in the EU Framework 6 NEWAC Programme", ICAS 2010 Congress Proceedings, Paper No 408, September.

[29] A.H. Lefebvre, 1999, "Gas Turbine Combustion", Taylor & Francis, 2nd edition, ISBN 1-56032-673-5, PA, USA.

[30] P. Spittle, 2003, "Gas Turbine Technology", Journal of Physics Education, Vol. 38, No. 6, pp. 504 - 511, November.

[31] L.R. Jenkinson, P. Simpkin, and D. Rhodes, 1999, "Civil Jet Aircraft Design", Arnold London, 1st edition, ISBN 0-340-74152-X, United Kingdom.

[32] A.Guha, 2001, “Optimum Fan Pressure Ratio for Bypass Engines with Separate or Mixed Exhaust Streams” Journal of Propulsion and Power Vol 17, No. 5, September-October

[33] H. Greib, 2004, “Projektierung von Turboflugtriebwerken”, Birkhäuser Verlag, ISBN 3-7643-6023-2

[34] S.L. Dixon, C.A. Hall, 2010, ”Fluid Mechanics and Thermodynamics of Turbomachinery”, Elsevier, 6th edition, ISBN 978-1-85617-793-1

[35] ICAO, 1993. International Standards and Recommended Practices - Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Volume II - Aircraft Engine Emissions. 2nd edition plus amendments, Montreal, Canada.

[36] P. Newton, C. Holsclaw, M. Ko, and M. Ralph, 2007. Long Term Technology Goals for CAEP/7. Presented to the Seventh Meeting of CAEP, February.

[37] K.G. Kyprianidis, T. Grönstedt, S.O.T. Ogaji, P. Pilidis, and R. Singh, 2011, “Assessment of Future Aero-engine Designs with Intercooled and Intercooled Recuperated Cores”, ASME Journal of Engineering for Gas Turbines and Power, Vol. 133, No. 1, January, doi: 10.1115/1.4001982.

[38] Platts, 2010, http://www.platts.com/