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Future Aero Engine Designs: An Evolving Vision

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1. Introduction

Public awareness and political concern over the environmental impact of civil aviation growth has improved substantially during the past 30 years. As the environmental awareness increases, so does the effort associated with addressing NO_x and CO_2 emissions by all the parties involved. In the Vision 2020 report made by the Advisory Council for Aeronautical Research in Europe (2001), goals are set to reduce noise and emissions produced by the ever increasing global air traffic. Emissions legislation, set by the International Civil Aviation Organisation (ICAO) and it's Committee on Aviation Environmental Protection (CAEP), is becoming ever more stringent, creating a strong driver for investigating novel aero engine designs that produce less CO_2 and NO_x emissions.

On the other hand, airline companies need to continuously reduce their operating costs in order to increase, or at least maintain, their profitability. This introduces an additional design challenge as new aero engine designs need to be conceived for reduced environmental impact as well as direct operating costs. Decision making on optimal engine cycle selection needs to consider mission fuel burn, direct operating costs, engine and airframe noise, emissions and global warming impact.

CO_2 emissions are directly proportional to fuel burn, and therefore any effort to reduce them needs to focus on improving fuel burn, by reducing engine Specific Fuel Consumption (SFC), weight and size. Reducing engine weight results in a lower aircraft maximum take-off weight, which in turn leads to reduced thrust requirements for a given aircraft lift to drag ratio. Reducing engine size – predominantly engine nacelle diameter and length – reduces nacelle drag and therefore also leads to reduced thrust requirements. For a given engine SFC, a reduction in thrust requirements essentially results in lower fuel burn. Lower engine SFC can be achieved by improving propulsive efficiency and thermal efficiency – either by reducing component losses or by improving the thermodynamic cycle.

Improvements in propulsive efficiency – and hence engine SFC at a given thermal efficiency – can be achieved by designing an engine at a lower specific thrust (i.e. net thrust divided by fan inlet mass flow). This results in a larger fan diameter, at a given thrust, and therefore in increased engine weight, which can partially, or even fully, negate any SFC benefits. Propulsive efficiency improvements at a constant weight are directly dependent on weight reduction technologies such as light weight fan designs and new shaft materials. Increasing engine bypass ratio aggravates the speed mismatch between the fan and the low pressure turbine. Introduction of a gearbox can relieve this issue by permitting the design of these two

components at their optimal speeds, and can hence reduce engine weight, as well as improve component efficiency. The first research question therefore rises:

How low can we really go on specific thrust?

Improvements in thermal efficiency – and hence engine SFC at a given propulsive efficiency – can be achieved for conventional cores mainly by increasing engine Overall Pressure Ratio (OPR). At a given OPR there is an optimal level of combustor outlet temperature T_4 for thermal efficiency. However, at a fixed specific thrust and engine thrust, an increase in T_4 can result in a smaller core and therefore a higher engine bypass ratio; in some cases, a potential reduction in engine weight can more than compensate for a non-optimal thermal efficiency. Increasing OPR further than current engine designs is hindered by limitations in high pressure compressor delivery temperature at take-off. Increasing T_4 is limited by maximum permissable high pressure turbine rotor metal temperatures at take-off and top of climb. Increasing turbine cooling flows for this purpose is also fairly limited as a strategy; cooling flows essentially represent losses in the thermodynamic cycle, and increasing them eventually leads to severe thermal efficiency deficits (Horlock et al., 2001; Wilcock et al., 2005). 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 (Lefebvre, 1999). The second research question therefore rises:

How high can we really go on OPR and T_4?

Aggressive turbofan designs that reduce CO_2 emissions – such as increased OPR and T_4 designs – can increase the production of NO_x emissions due to higher flame temperatures. The third research question therefore rises:

What is the trade-off between low CO_2 and NO_x?

The research work presented in this chapter will focus on identifying several novel engine cycles and technologies - currently under research - that can address the three research questions raised. These concepts will be evaluated based on their potential to reduce CO_2 and NO_x emissions for engine designs entering service between 2020 and 2025. Design constraints, material technology, customer requirements, noise and emissions legislation, technology risk and economic considerations and their effect on optimal concept selection will also be discussed in detail.

2. An evolving vision

Numerous feasibility studies have been published over the years focusing on future engine and aircraft designs that can reduce fuel consumption; a brief review of some of these publications will be carried out here.

One of the earliest discussions on the subject of improving engine fuel efficiency is provided by Gray & Witherspoon (1976), looking at conventional and heat exchanged cores, as well as non-steady flow combustion processes and open rotor configurations. A similar study focusing on geared and open rotor arrangements as well as heat exchanged cycles is presented by Hirschkron & Neitzel (1976).

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 is given by Jackson

(1976); the author has also provided an update to that discussion based on current economical and technological projections (Jackson, 2009). Wilde (1978), Young (1979), and Pope (1979) provide 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 perspective can be found in Swihart (1970) and Bates & Morris (1983), while Watts (1978) provides an airliner's view of the future. 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 (1988) and by Zimbrick & Colehour (1988). Peacock & Sadler (1992) give an update on the subject, focusing further on engine design constraints and the technology advancements required for producing a competitive UHBR configuration. Potential year 2020 scenarios are explored by Birch (2000) while an overview of current aero engine technology and some insight on the future of aircraft propulsion is given by Ruffles (2000). Sieber (1991) and Schimming (2003) provide an excellent discussion on counter-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 (2002).
The focus of the next section will be given on recent European research initiatives on enabling technologies relevant to the three research questions that have been set.

3. Enabling technologies and recent research

3.1 Propulsor technologies

Within the EU Framework Program 6 research project VITAL (enVIronmenTALly friendly aero engines, 2009) a number of low pressure system component technologies have been investigated (Korsia, 2009; Korsia & Guy, 2007). The emerging progress will allow the design of new powerplants capable of providing a step reduction in fuel consumption and generated noise.
The VITAL project concentrated on new technologies for the low pressure system of the engine, which enable the development of low noise and low weight fan architectures for UHBR engines. To achieve these objectives, the VITAL project has investigated three different low pressure configurations, leading to low noise and high efficiency power plants. The three configurations are the DDTF (Direct Drive TurboFan) supported by Rolls-Royce, the GTF (Geared TurboFan) by MTU and the CRTF (Counter-Rotating TurboFan) by Snecma.
The DDTF architecture offers a re-optimised trade-off between fan and turbine requirements considering the low weight technologies introduced by the VITAL programme. The GTF combines a fan with a reduction gear train, to allow different rotating speeds for the fan on one hand, and the booster and turbine on the other. The CRTF offers a configuration with two fans turning in opposite directions, allowing for lower rotational speeds, since the two fan rotors split the loads involved.
The technologies being built into the VITAL engines include (Korsia, 2009; Korsia & Guy, 2007):

- New fan concepts with the emphasis on two types: counter-rotating and lightweight fans.
- New booster technologies for different operational requirements; low and high speed, associated aerodynamic technologies, new lightweight materials and associated coating and noise reduction design.

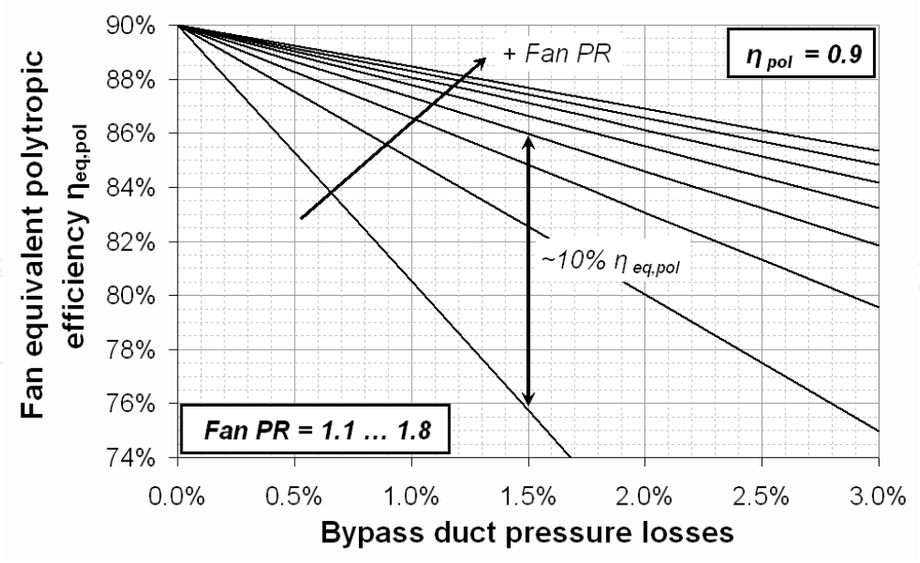


Fig. 1. Effect of fan tip pressure ratio and bypass duct pressure losses on fan equivalent polytropic efficiency

- Polymer composites and corresponding structural design and manufacturing techniques are studied in parallel with advances in metallic materials and manufacturing processes.
- Shaft torque density capabilities through the development of metal matrix composites and multi metallic shafts.
- Low pressure turbine weight savings through ultra high lift airfoil design, ultra high stage loading, lightweight materials and design solutions.
- Technologies for light weight and low drag installation of high bypass ratio engines related to nozzle, nacelle and thrust reverser.

The open rotor engine concept, for high subsonic flight speeds, has also risen as a candidate for improving fuel consumption on several occasions since the advent of the first high bypass ratio turbofan engine. Such engine configurations, often refereed to as propfans in the literature, are direct competitors to ultra high bypass ratio turbofan engines. Their are located at the ultra-low specific thrust region of the design space, where propulsive efficiency benefits for turbofans are negated by very low transfer efficiencies. As illustrated in Fig. 1, this is due to the dominant effect on transfer efficiency that bypass duct pressure losses have when looking at low fan tip pressure ratio engine designs, i.e. low specific thrust. Open rotor engines do not suffer from bypass duct pressure losses and can therefore achieve a very high propulsive efficiency at a good level of transfer efficiency. Compared to turbofans, propfans also benefit from reduced nacelle drag and weight penalties.

Several open rotor programs took place during the 80's, resulting in engine demonstrators and flight tests. The purpose of these projects was to develop propfan concepts that could fly efficiently at speeds comparable to high bypass ratio turbofans, i.e. close to Mach 0.8. General Electric proposed the UDF (UnDucted Fan), a pusher configuration with counter-rotating propellers driven by a counter-rotating low pressure turbine (GE36 Design and Systems Engineering, 1987). The 578-DX, a pusher configuration with counter-rotating

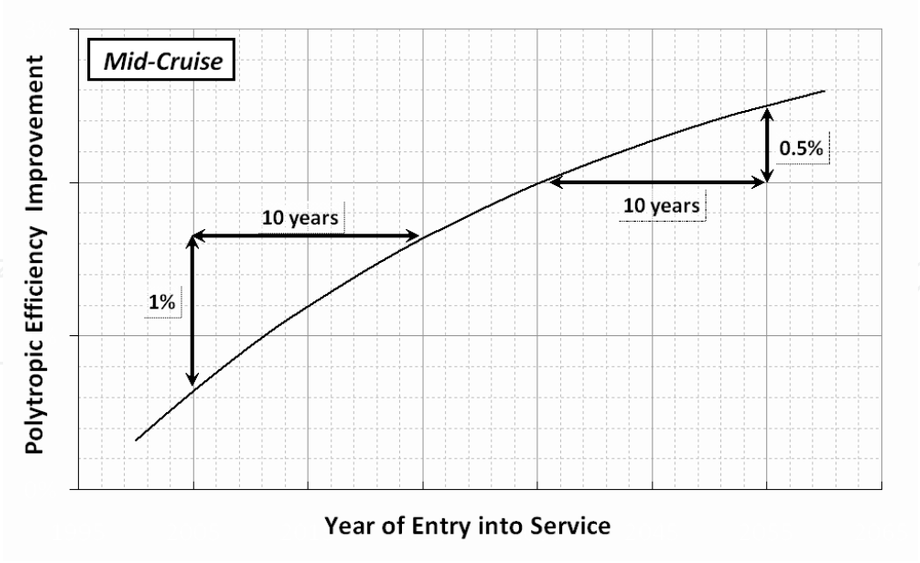


Fig. 2. Compressor efficiency improvement with year of entry into service.

propellers driven by a more conventional low pressure turbine through a differential planetary differential gearbox, was the result of a joint effort by Pratt & Whitney, Hamilton Standard, and Allison.

Both projects were eventually put on hold towards the end of the decade as fuel prices fell significantly. Nevertheless, the open rotor concept has now resurfaced within the EU Framework Program 7 research project DREAM (valiDation of Radical Engine Architecture systeMs, 2011) and the Clean Sky Joint Technology Initiative (2011). Within DREAM, the feasibility of two different open rotor architectures is evaluated including noise. Within Clean Sky, research work is being carried out by some of Europe's largest aero engine manufacturers, such as Rolls-Royce and Snecma, focused on designing, building and testing an open rotor demonstrator.

3.2 Core technologies

Improving core component efficiencies (including reducing losses in the cycle such as duct pressure losses) is one way of improving the engine thermal efficiency. Nevertheless, modern CFD-assisted designs are already quite aggressive and limited benefit may be envisaged by such future advancements (Kurzke, 2003); the increasing effort required to improve an already very good axial compressor design is illustrated in Fig.2.

Within the EU Framework Program 6 research project NEWAC (NEW Aero engine Core concepts, 2011) a number of advanced core component technologies have been investigated that include (Rolt & Kyprianidis, 2010; Wilfert et al., 2007):

- Improved high pressure compressor aero design and blade tip rub management.
- Flow control technologies including aspirated compression systems.
- Active control of surge and tip clearance in compressors.
- Active control of a cooled cooling air system.

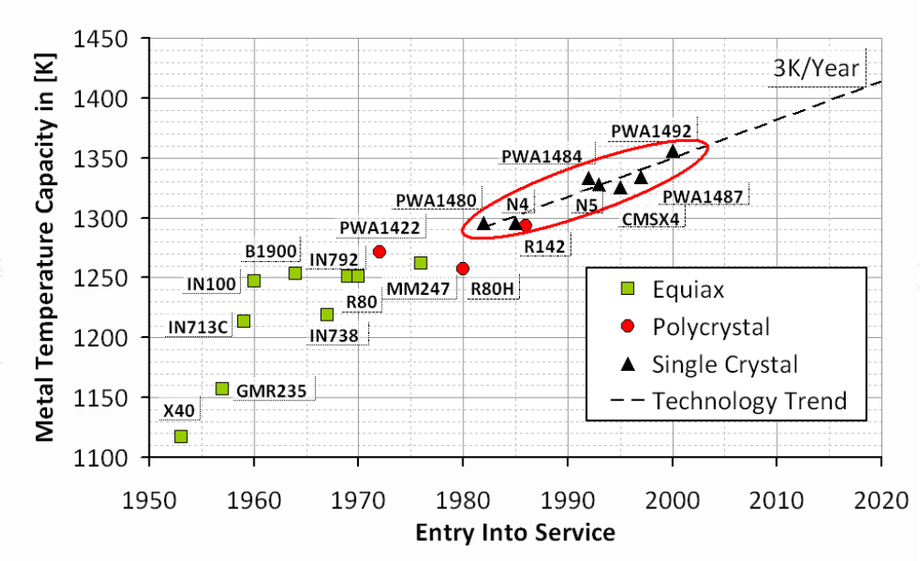


Fig. 3. Evolution of turbine material capability and future trend.

As mentioned earlier another way of improving engine thermal efficiency is to raise the cycle OPR. For conventional cores, increasing OPR and T_4 depends primarily on future advancements in material and cooling technology. The evolution of turbine material capability over a period of 50 years is illustrated in Fig. 3. As can be observed, only mild improvements have been achieved so far and this seems to be a continuing trend; the potential introduction of ceramics would form a major improvement in the field, but substantially more research is still required before realising this. Despite the low improvement rate in turbine material technology (roughly 3 [K/year]) aero engine designs have seen substantial increases in T_4 over the last 60 years (roughly 10 [K/year]); this is illustrated in Fig. 4 for engines designed for long-haul applications. The main reason behind these improvements in T_4 has been the introduction of cooling and Thermal Barrier Coatings (TBC) in turbine designs; the interested reader is referred to Downs & Kenneth (2009) for a good overview of the evolution of turbine cooling systems design.

It is perhaps debatable whether an improvement rate of 10 [K/year] in T_4 can be maintained in the future, and for that reason the design focus for more aggressive thermal efficiency improvements could very well be redirected to the introduction of heat-exchanged cores and advanced compressor technologies for future turbofan designs. In that respect, some of the technologies researched under the NEWAC project can be perceived as intermediate enabling steps for realising new engine core concepts that could improve the core thermal efficiency. These new core concepts comprise of:

- Ultra-high OPR core with intercooling.
- Medium OPR intercooled recuperated core.
- High OPR flow controlled core.
- High OPR active core including active cooling air cooling.

When considering intercooling for an aero engine design, a common textbook misconception is that the thermal efficiency of an intercooled core will always be lower than a conventional

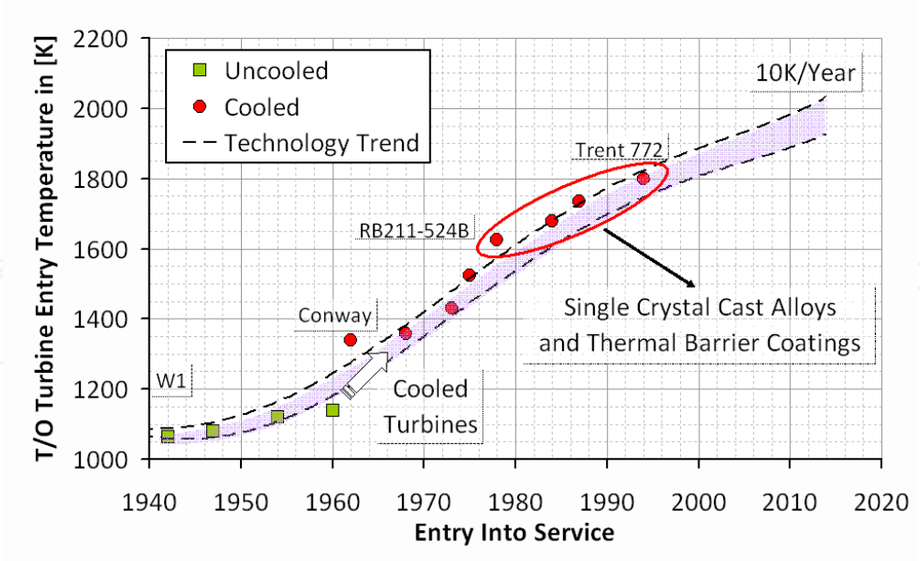


Fig. 4. Evolution of turbine entry temperature and future trend.

core's for a fixed OPR and specific thrust (Saravanamuttoo et al., 2001). The argument behind this is that the heat removed by the intercooler will largely need to be reintroduced in the combustor by burning more fuel, while the reduction in compression work and increase in bypass stream thrust (due to the heat rejection) will only partially compensate for the loss in cycle efficiency, at a fixed specific thrust and T_4. Adding the expected intercooler pressure losses in the cycle calculations would further worsen the SFC deficit and make the increase in specific thrust less marked.

However, cycle calculations based on half-ideal gas properties and no dissociation (i.e. isobaric heat capacity dependent on temperature), presented by Walsh & Fletcher (1998), give a slightly different picture on intercooling. For a given T_4, the optimal OPR for an intercooled core will be much higher than that for a conventional core. Comparing the two concepts at their optimal OPR levels, for a given technology level, can make the intercooled core more attractive with respect to thermal efficiency and not just specific thrust. Canière et al. (2006) and da Cunha Alves et al. (2001) also reached the same conclusion about the thermal efficiency of the intercooled cycle while studying this concept for gas turbines used in power generation. Papadopoulos & Pilidis (2000) worked on the introduction of intercooling, by means of heat pipes, in an aero engine design for long haul applications. Xu et al. (2007) performed a mission optimization to assess the potential of a tubular intercooler. Recent work by Xu & Grönstedt (2010) presents a refined tubular configuration estimating a potential block fuel benefit of 3.4%. The work addresses the limitation that short high pressure compressor blade lengths and related low compression efficiencies may impose on engines designed for short range missions, and suggest a novel gas path layout as a remedy to this constraint. A design study of a high OPR intercooled aero engine is described in Rolt & Baker (2009), while details on the aerodynamic challenges in designing a duct system to transfer the core air into and out of the intercooler are presented by Walker et al. (2009).

The introduction of recuperation in an aero engine, for high thermal efficiency at low OPR, has also been the focus of different researchers. Lundbladh & Sjunnesson (2003) performed a feasibility study for InterCooled (IC) and Intercooled Recuperated Aero engines (IRA) that

consider cycle benefits, weights and direct operating costs. Boggia & Rud (2005) provide an extended discussion on the thermodynamic cycle and the technological innovations necessary for realizing the intercooled recuperated core concept. Various aspects of the thermo-mechanical design of a compact heat exchanger have been presented by Pellischek & Kumpf (1991) and Schoenenborn et al. (2006). For a comprehensive review on the development activities for recuperated aero engines since the late 60's the interested reader can refer to McDonald et al. (2008a;b;c).
Finally, three different types of lean-burn combustor technology were also researched within NEWAC with the objective of reducing emissions of oxides of nitrogen (NO_x):

- Lean Direct Injection (LDI) combustor for high and ultra-high OPR cores.
- Partial Evaporation and Rapid Mixing (PERM) combustor for high OPR cores.
- Lean Premixed Pre-vaporized (LPP) combustor for medium OPR cores.

4. Design space exploration

4.1 Methodology, design feasibility and constraints

To effectively explore the design space a tool is required that can consider the main disciplines typically encountered in conceptual design. The prediction of engine performance, aircraft design and performance, direct operating costs, and emissions for the concepts analysed in this study was made using the EVA code (Kyprianidis et al., 2008). Another code, WeiCo, was also used for carrying out mechanical and aerodynamic design in order to derive engine component weight and dimensions. The two tools have been integrated together within an optimiser environment as illustrated in Fig. 5, based on lessons learned from the development of the TERA2020 tool (Kyprianidis et al., 2011). This integration allows for multi-objective optimization, design studies, parametric studies, and sensitivity analysis. In order to speed up the execution of individual engine designs, the conceptual design tool attempts to minimize internal iterations in the calculation sequence through the use of an explicit algorithm, as described in detail by Kyprianidis (2010).
Aero-engine designs are subject to a large number of constraints and these need to be considered during conceptual design. Constraints can be applied within the optimiser environment at the end of the calculation sequence i.e., after the last design module has been executed. During a numerical optimisation, the optimiser will select a new set of input design parameters for every iteration and the resulting combination of aircraft and engine will be assessed. Using user specified objective functions the optimiser will home in on the best engine designs, determining the acceptability/feasibility of each design through the constraints set by the user. Infeasible designs will be ruled out, while non-optimum design values will result in engine designs with non-optimum values for the objective function selected. The optimiser will therefore avoid regions in the design pool that result in infeasible or non-optimum engine designs.
Design constraints set by the user include among others:

- Take-off HPC delivery temperature and other important performance parameters.
- FAR (Federal Aviation Regulations) take-off field length for all engines operating and balanced field length for one engine inoperative conditions.
- Time to height.

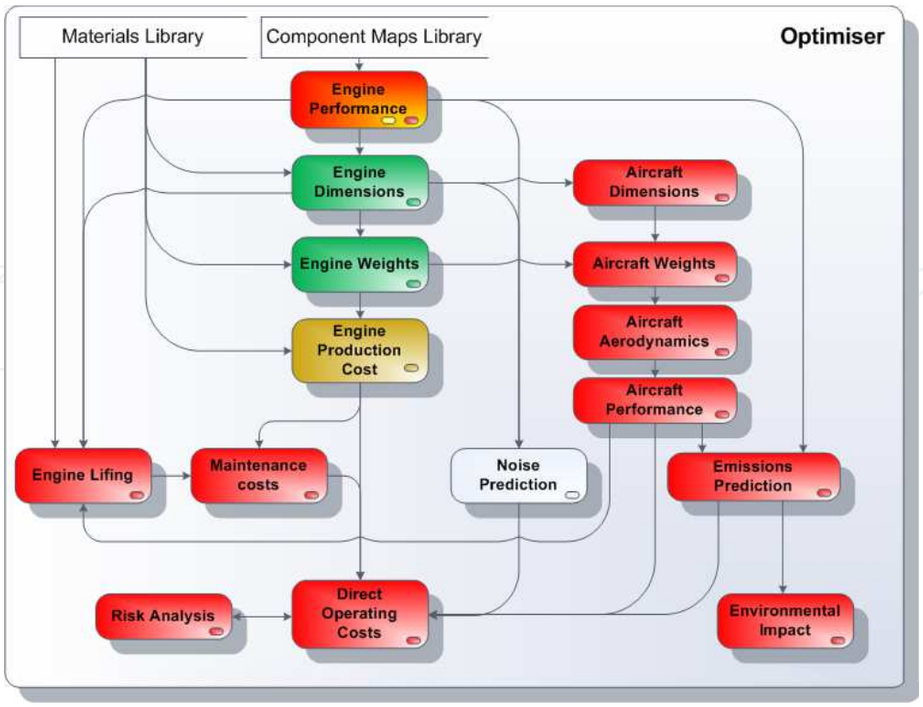


Fig. 5. Conceptual design tool algorithm (Kyprianidis, 2010).

- LTO (Landing and Take-Off) cycle $D_p NO_x / F_{oo}$ vs. ICAO certification limits and CAEP medium and long term goals.
- Cumulative EPNL vs. ICAO certification limits.
- Engine time between overhaul.

Where component design is concerned, 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 (Rolt & Baker, 2009). For an intercooled core, the OPR value is no longer constrained by a maximum allowable HPC delivery temperature. Nevertheless, the intercooling process increases the air density in the gas path 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 for the conventional core set an upper limit to the HPC design pressure ratio that can achieved when driven by a single-stage HPT. A transonic single-stage HPT design can allow for relatively higher HPC pressure ratios at the expense of a lower polytropic efficiency. A two-stage HPT can offer high HPC pressure ratios at a high polytropic efficiency but a trade-off arises with respect to the need for more cooling air and increased engine length associated with the introduction of a second row of vanes and blades. With respect to the intercooled core, the minimum design pressure ratio for the Intermediate Pressure Compressor (IPC) can in some cases be limited by icing considerations during the descent flight phase. The maximum area variation that may be achieved by the variable area auxiliary nozzle is also constrained by mechanical (and aerodynamic) considerations.

As discussed earlier, 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 (Lefebvre, 1999); 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] while for long range applications to 23000 [hr]. This reflects the fact that designs for short range applications are typically operated at high power conditions for a significantly larger part of their operational life. 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 range applications that are often operated at derated thrust levels and spend most of their life at cruise.

A rubberised aircraft wing model was used in these studies to capture 'snowball effects' with respect to maximum take-off weight variation, rather than using fixed engine thrust requirements. The aircraft drag polar and weight breakdown were predicted at component level from the aircraft geometry and high lift device settings for the take-off and approach phases. Fuel burned was calculated for the entire flight mission including reserves assuming ISA conditions, as illustrated in Fig. 6. Cruise is performed at the optimum altitude for specific range (fixed cruise Mach number) using a step-up cruise procedure as the aircraft gets lighter. A comprehensive take-off field length calculation is performed for all engines operating and one engine inoperative conditions up to 1500 [ft].

Two baseline aircraft models have been used herein; one model for long range applications and one for short range. The former model is largely based on public domain information available for the Airbus A330-200 while the latter model is based on the Airbus A320-200. The short range aircraft was designed to carry 150 [pax] for a distance of 3000 [nmi] and a typical business case of 500 [nmi]; for long range applications it was designed for 253 [pax], 6750 [nmi] and 3000 [nm], respectively. 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.

The maximum values for FAR take-off field length and time to height were set for a load factor of 1 and no cargo. The choice of both is based on customer operational requirements as 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 (and hence reduce waiting time on the ground). A cumulative distribution of the world's major runway lengths, based on data from Jenkinson et al. (1999), is illustrated in Fig. 7. For short range applications fairly stringent constraints are typically set for the maximum take-off distance and time to height; in this study these were set to 2.0 [km] and 25 [min], respectively. For long range applications a maximum take-off distance of 2.5 [km] was set instead. Stringent constraints result in bigger engines but allow for greater flexibility for engine derating at a smaller block fuel cost.

The choice of load factor and cargo is considered sensible but it does not necessarily constitute a typical airline practice. Validating absolute block fuel predictions with public domain airline data is not a trivial task as different airlines will follow different operational practices. For example for the long range aircraft model, the business case prediction is 10% lower than the published annually-averaged value, given in [lt/(km*pax)], by SwissAir for 2009 for the

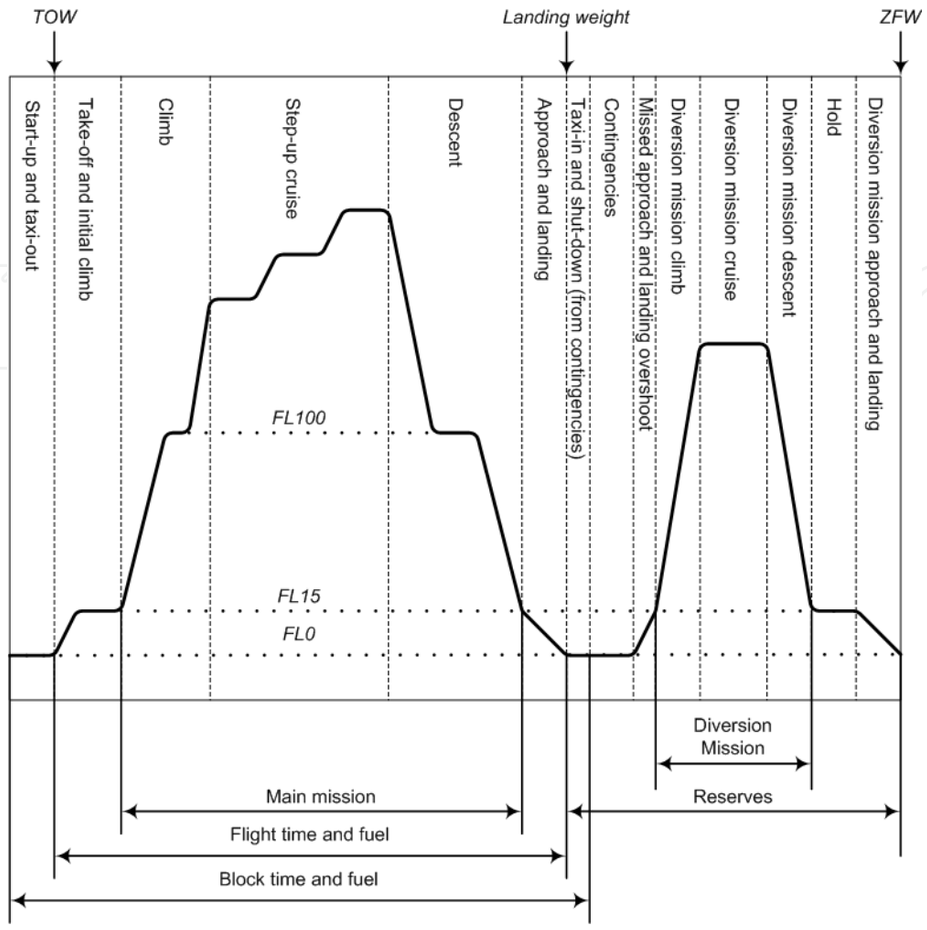


Fig. 6. Typical flight cycle.

Airbus A330-200 (Swiss International Air Lines, 2009). This does not necessarily mean that the model's business case is not a realistic one; nor that it wouldn't fit well with operational practices followed by other airlines. Furthermore, regional Air Traffic Management (ATM) practices can skew available block fuel data, while global ATM regulations may very well change significantly by 2020. It should be noted that fuel planning within the model respects the requirements defined for international flights by Federal Aviation Administration (n.d.) and Joint Aviation Authorities (2008).

Where conceptual design is concerned, exchange rates are perhaps a better type of parameter for evaluating the accuracy of a rubberised wing model, rather than just simply comparing absolute values. Block fuel exchange rates produced with the rubberised wing baseline aircraft models are presented in Table 1 for the business case of the long and short range models and are considered reasonable numbers.

During a block fuel optimization all engine aircraft combinations which do not fulfil the take-off and time to height criteria set will be discarded as infeasible. Due to the underlying physics, this will naturally lead to an optimal engine and aircraft combination for the defined objective function. All large engines will produce heavier aircraft with more drag and thus higher block fuel weight. Engines which are too small will not deliver enough thrust to satisfy the take-off and time to height criteria set.

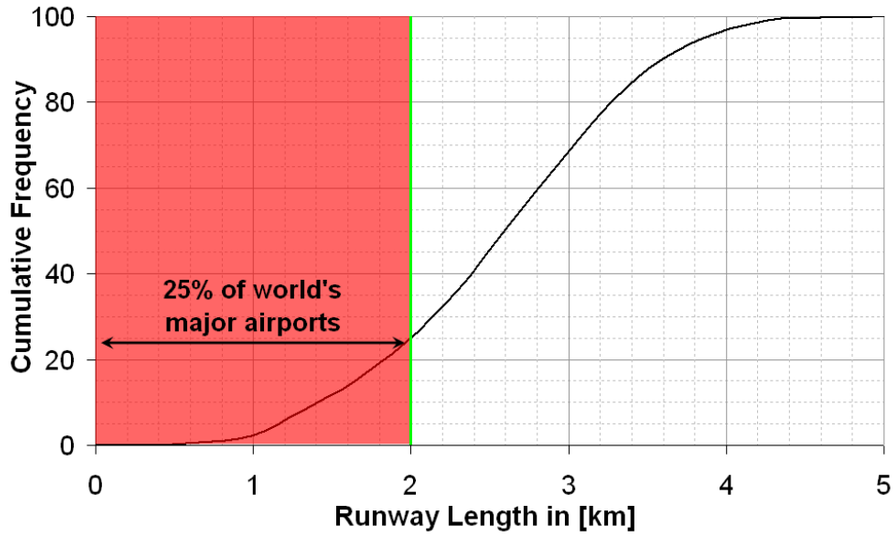


Fig. 7. Cumulative distribution of world's major runway lengths (based on data from Jenkinson et al. (1999)).

	Exchange rate	
Perturbation	Long range	Short range
1000 [kg] weight penalty	0.73%	1.26%
+1% SFC	1.28%	1.09%

Table 1. Block fuel exchange rates using the baseline long range and short range rubberised wing aircraft models.

4.2 Engine design optimality

Whereas optimisation constraints can help ensure the feasibility of an engine design, they do little to help with it's optimality. The optimality of the engine design will depend on the careful selection of the figures of merit used during the optimisation process, such as minimum block fuel, maximum time between overhaul, minimum direct operating costs, minimum noise and LTO NO_x emissions etc.

Determining the optimal aero-engine design is essentially the subject of a multi-objective optimisation, and therefore Pareto fronts need typically be constructed to visualize the region of optimal designs within the design space. A simplified example of utilizing the tool for design space exploration, with active constraints, is illustrated in Fig. 8. In principle, nacelle drag should also be added as a third dimension when plotting design space exploration results that consider varying levels of specific thrust, but this has been omitted here in order to simplify the plot. The aircraft exchange rates for the baseline design were used for plotting a constant block fuel line (ignoring nacelle drag effects and nonlinearities) and this iso-line therefore defines, in a simple manner, the boundaries of trading specific fuel consumption for weight. During a block fuel optimization, the optimizer continuously evaluates different engine designs as it searches for the optimal solution. Designs that fail to meet constraints set by the user are discarded and have been labeled as infeasible in the plot.

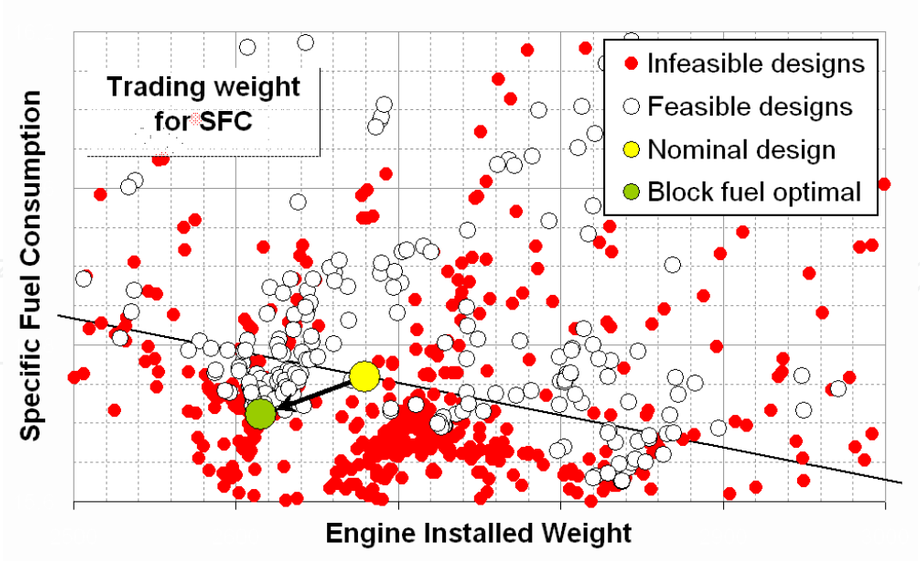


Fig. 8. Visualization example of constrained design space exploration.

4.3 Economic considerations

Safety considerations aside, civil aero engine design has been driven primarily by economic considerations even from its fairly early days. A testament to this has been the advent of the world's first commercial jet-airliner, the de Havilland Comet, powered by 4 Rolls-Royce Avon turbojet engines. Although it burned nearly four times as much fuel compared to piston-driven engines, it's business case was very strong since it permitted significantly higher flight speeds resulting in reduced flight times (i.e. a better airline product) and increased aircraft annual utilization. Furthermore, the excellent power to weight ratio of the turbojet engine meant that it could be used to power aircrafts with significantly higher passenger capacities than what was feasible before. The evolution of aircraft transport efficiency since the late 30's is summarised in Fig. 9 based on data from Avellán (2008).

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 alone. The market competitiveness of these fuel optimal designs however is highly dependent on the development of jet fuel prices in the years to come until 2020. The volatility of jet fuel price over the last 10 years is illustrated in Fig. 10. A further economic 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$/US gallon. It is worth noting that at the time of writing the average jet fuel price was 320 [c$/US gallon] (International Air Transport Association, 2011; Platts, 2011). 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.

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 Direct Operating Costs (DOC) by 2.5% and 4.5% for short and long range applications, respectively.

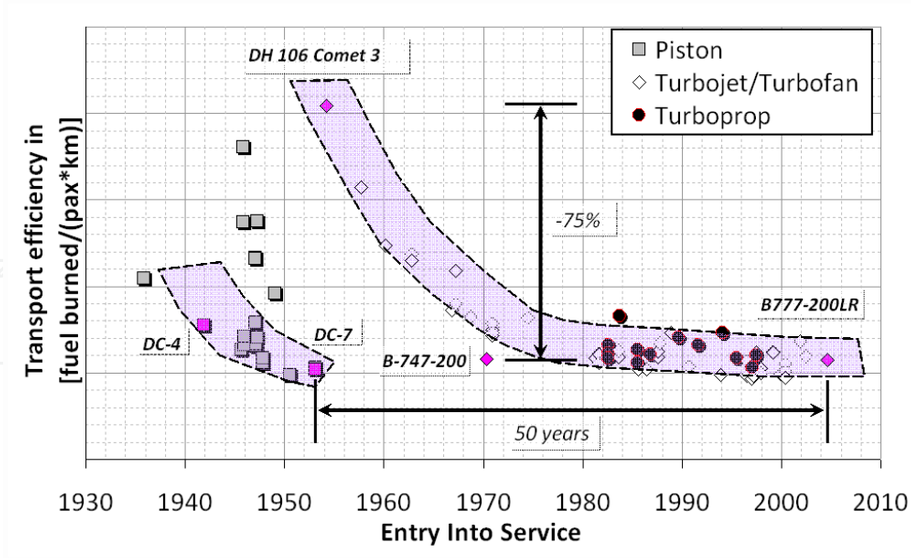


Fig. 9. Evolution of aircraft transport efficiency (based on data from Avellán (2008)).

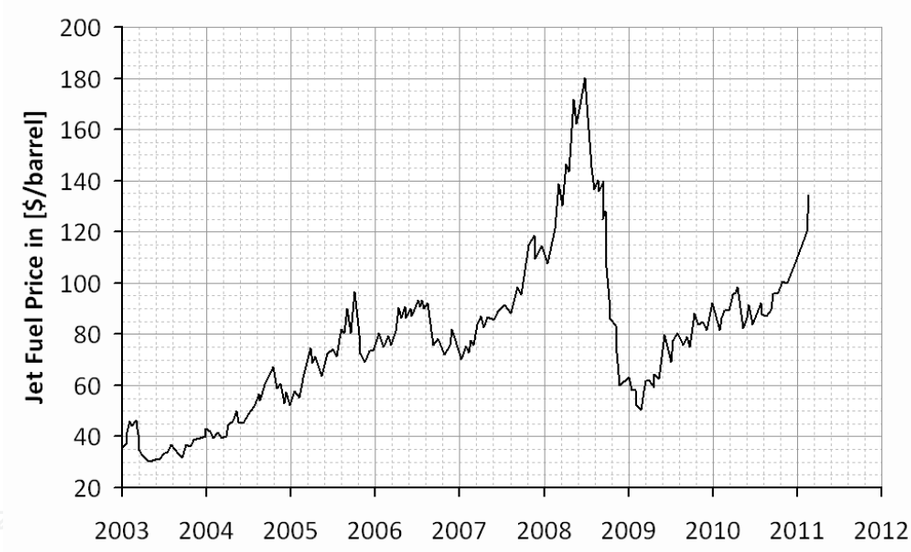


Fig. 10. Long term perspective of jet fuel price movements (based on data from International Air Transport Association (2011) and Platts (2011)).

The cost of fuel as a fraction of the total DOC was predicted to be 13% and 19% for short and long range applications, respectively. An increase in block fuel by 1% translates in an increase of 0.13% and 0.19% in DOC, respectively, 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 32%, respectively, and would also result in 13% and 19% higher DOC levels, respectively.

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 70's and through large part of the 80's. The introduction of carbon taxes could also have a similar effect.

5. Summary of design space exploration results

A summary of three different design space exploration case studies using the tools and algorithm described is presented here. This work has looked at the potential block fuel benefits resulting from the introduction of:

- An intercooled core in a direct drive UHBR turbofan configuration.
- An intercooled recuperated core in a geared UHBR turbofan configuration.
- An open rotor propulsor in a geared pusher configuration.

The thrust requirements for the first two concepts are for an engine designed to power the long range aircraft model while the latter concept is centered around powering the short range aircraft model. More details on these studies can be found in Kyprianidis et al. (2011) and Larsson et al. (2011).

For the intercooled core assessment, a year 2020 Entry Into Service (EIS) turbofan engine with a conventional core was set up as the baseline. The intercooled core engine is an ultra high OPR design with also year 2020 EIS level of technology, and features a tubular heat-exchanger, while the fan for both engines has the same diameter and flow per unit of area. Business case block fuel benefits of approximately 3.2% are predicted for the intercooled engine, mainly due to the reduced engine weight and the core's higher thermal efficiency which results in a better SFC. **These intercooling benefits are highly dependent on achieving technology targets such as low intercooler weight and pressure losses**; the predicted lower dry weight, compared to the conventional core engine, can be attributed to various reasons. The intercooler weight penalty is largely compensated by the higher core specific output allowing a smaller core size and hence a higher BPR at a fixed thrust and fan diameter. The high OPR provides an additional sizing benefit, for components downstream of the HPC, by reducing further the corrected mass flow and hence flow areas. The intercooled core Low Pressure Turbine (LPT) was designed in this study with one less stage which reduced both engine weight and length, despite the high cycle OPR requiring a greater number of HPC stages. These observations are summarised in Table 2 with the added components weight group considering the intercooler and its installation standard; this group is not considered in the core weight group which also does not consider the core nozzle or the LPT and its casing.

For the intercooled recuperated core assessment, a year 2000 EIS turbofan engine with a conventional core was set up as the baseline. The intercooled recuperated core configuration is an UHBR design with a year 2020 level of technology. Significant business case block fuel benefits of nearly 22% are predicted for the geared intercooled recuperated core engine due to its higher thermal and propulsive efficiency. The use of HPT cooling air bled from the recuperator exit (Boggia & Rud, 2005; Walsh & Fletcher, 1998) results in a 1.3% SFC improvement due to more energy being recuperated from the exhausts, at a fixed effectiveness level - and despite the considerable increase in cooling air requirements (+3.5% of core mass flow). The predicted dry weight for the intercooled recuperated configuration is higher compared to the conventional core engine. There is a weight benefit from the use of EIS

	Conventional core	Intercooled core
	DDTF LR EIS 2020	DDIC LR EIS 2020
Engine dry weight	Ref.	-5.9%
LPT weight	Ref.	-27.1%
Core weight	Ref.	-32.5%
Added components weight (as % of engine dry weight)	-	7.7%
Block fuel weight	Ref.	-3.2%
Mid-cruise SFC	Ref.	-1.5%
Thermal efficiency	Ref.	+0.007
Propulsive efficiency	Ref.	+0.000

Table 2. Comparison of an intercooled engine with a conventional core turbofan engine at aircraft system level.

	Conventional core	Intercooled recuperated core
	BASE LR EIS 2000	IRA LR EIS 2020
Thrust/weight	Ref.	-12%
Engine dry weight	Ref.	+16.5%
Nacelle weight	Ref.	+29.7%
Fan weight	Ref.	+36.6%
LPT weight	Ref.	-17.1%
Added components weight (as % of engine dry weight)	-	25.4%
Block fuel weight	Ref.	-21.6%
Mid-cruise SFC	Ref.	-18.3%
Thermal efficiency	Ref.	+0.024
Propulsive efficiency	Ref.	+0.120

Table 3. Comparison of an intercooled recuperated engine with a conventional core turbofan engine at aircraft system level.

2020 light-weight materials in most major engine components, as well as from the high speed LPT - due to the reduced stage count. Also, the relatively low engine OPR and the use of an intercooler increases core specific output, resulting in a smaller core. The introduction however of the gearbox, intercooler and recuperator components inevitably results in a significant weight penalty. It should be noted that a lower level of specific thrust, and hence a larger fan diameter, has been assumed for the intercooled recuperated core engine; this results in both a heavier fan and a heavier nacelle. These observations are summarised in Table 3 with the added components weight group considering the intercooler and recuperator and their installation standard, as well as the gearbox.

For the geared open rotor assessment, a year 2020 EIS geared turbofan engine with a conventional core was set up as the baseline. The geared open rotor concept design also assumes year 2020 EIS level of technology, and features two counter-rotating propellers in a pusher configuration powered by a geared low pressure turbine. Significant business case

	Geared turbofan	Geared open rotor
	GTF SR EIS 2020	GOR SR EIS 2020
Engine installed weight	Ref.	+11%
Nacelle weight	Ref.	-88%
Fan/propeller weight	Ref.	+73%
LPT weight	Ref.	+20%
Core weight	Ref.	-31%
Block fuel weight	Ref.	-15%
Mid-cruise SFC	Ref.	-14%
Thermal efficiency	Ref.	-0.013
Propulsive efficiency	Ref.	+0.16

Table 4. Comparison of a geared open rotor engine with a geared turbofan engine at aircraft system level.

block fuel benefits of nearly 15% are predicted for the geared open rotor engine primarily due to its higher propulsive efficiency. Although, the geared turbofan engine benefits from a better thrust to weight ratio it suffers from significantly higher nacelle drag losses, compared to the open rotor design. These observations are summarised in Table 3.

A NO_x emissions assessment of the presented engine configurations has been performed and is illustrated in Fig. 11. The same combustor concept has been considered for both designs i.e., conventional Rich-burn/Quick-quench/Lean-burn (RQL) combustion technology. The results obtained are compared against ICAO Annex 16 Volume II legislative limits (ICAO, 1993), as well as the Medium Term (MT) and Long Term (LT) technology goals set by CAEP (Newton et al., 2007). 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

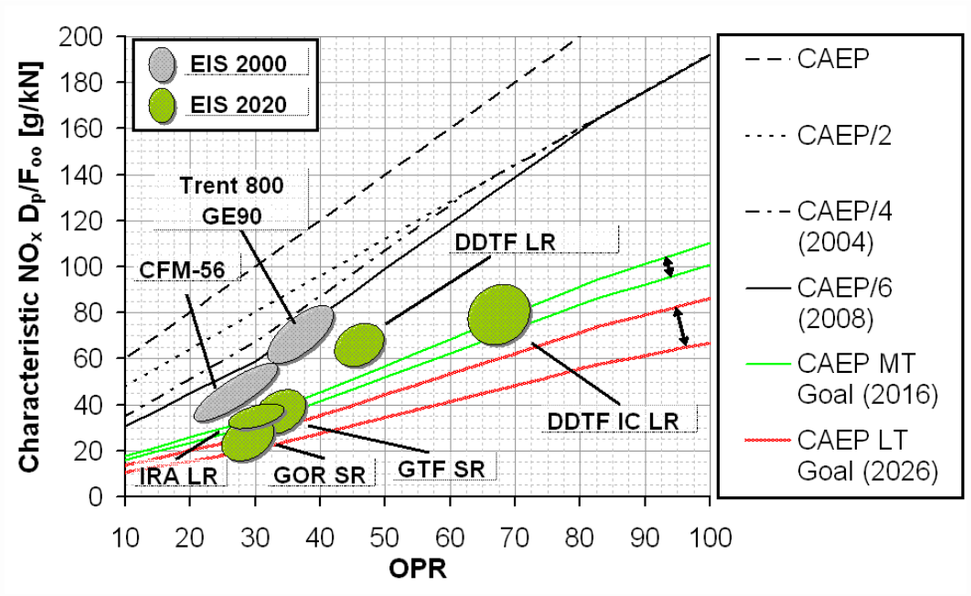


Fig. 11. NO_x emissions assessment for different future aero engine design concepts.

such combustor designs in the proposed future cycles. A sufficient margin against the ICAO CAEP/6 LTO cycle NO_x certification limit may be achieved for all the configurations that have been assessed assuming year 2020 EIS.

6. Conclusions

The research work presented started by reviewing the evolution of the aero engine industry's vision for the aero engine design of the future. Appropriate research questions were set that can influence how this vision may further involve in the years to come. Design constraints, material technology, customer requirements, noise and emissions legislation, technology risk and economic considerations and their effect on optimal concept selection were also discussed in detail.

With respect to addressing these questions, several novel engine cycles and technologies - currently under research - were identified. It was shown that there is a great potential to reduce fuel consumption for the different concepts identified, and consequently decrease the CO_2 emissions. Furthermore, this can be achieved with a sufficient margin from the ICAO NO_x certification limits, and in line with the medium term and long term goals set by CAEP. It must be noted however that aero engine design is primarily driven by economic considerations. As fuel prices increase, the impact of fuel consumption on direct operating costs also increases. The question therefore rises:

> **Can the potential reduction in fuel consumption and direct operating costs outweigh the technological risks involved in introducing novel concepts into the market?**

The answer is left to be given by the choices the aero engine industry makes in the years to come.

7. Acknowledgements

The author is grateful to Richard Avellán (Volvo Aero) for providing the transport efficiency data used in Fig. 9. Stimulating discussions with A.M. Rolt (Rolls-Royce), J.A. Borradaile, S. Donnerhack (MTU Aero Engines), P. Pilidis, (Cranfield University), R. Singh, (Cranfield University), S.O.T. Ogaji, (Cranfield University), P. Giannakakis (Cranfield University), T. Grönstedt (Chalmers University), A. Lundbladh (Volvo Aero) and L. Larsson (Volvo Aero) on advanced concepts and aero engine design are gratefully acknowledged. Finally, the author would like to thank the reviewers of this work for their constructive suggestions to improve the overall quality and clarity of the article.

8. Nomenclature

OPR	Engine overall pressure ratio
SFC	Engine specific fuel consumption
T_4	Combustor outlet temperature

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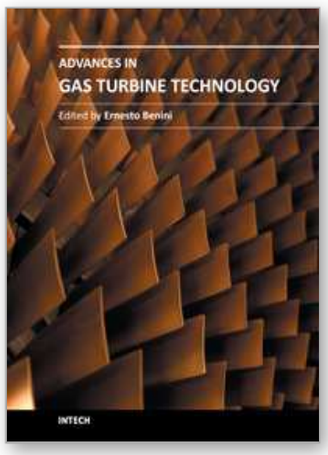
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Edited by Dr. Ernesto Benini

ISBN 978-953-307-611-9
Hard cover, 526 pages
Publisher InTech
Published online 04, November, 2011
Published in print edition November, 2011

Gas turbine engines will still represent a key technology in the next 20-year energy scenarios, either in stand-alone applications or in combination with other power generation equipment. This book intends in fact to provide an updated picture as well as a perspective vision of some of the major improvements that characterize the gas turbine technology in different applications, from marine and aircraft propulsion to industrial and stationary power generation. Therefore, the target audience for it involves design, analyst, materials and maintenance engineers. Also manufacturers, researchers and scientists will benefit from the timely and accurate information provided in this volume. The book is organized into five main sections including 21 chapters overall: (I) Aero and Marine Gas Turbines, (II) Gas Turbine Systems, (III) Heat Transfer, (IV) Combustion and (V) Materials and Fabrication.

How to reference

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