JET VERSUS PROP, HYDROGEN VERSUS KEROSENE FOR A REGIONAL FREIGHTER AIRCRAFT

K. Seeckt, D. Scholz
Hamburg University of Applied Sciences
Aircraft Design and Systems Group (Aero)
Berliner Tor 9, 20099 Hamburg, Germany

Abstract

This paper describes the design and analysis of four different variants of a regional freighter aircraft on the basis of the ATR72 full freighter version. The variants differ in their type of propulsion system (jet/turboprop) as well as in the fuel they use (kerosene/hydrogen). The presented work has been performed within the scope of the joint aircraft design project "Green Freighter" (GF). The setup of the aircraft models inside the Preliminary Aircraft Design and Optimization program PrADO is shown with special respect to the propulsion systems and the integration of the hydrogen tanks. Afterwards, the resulting aircraft parameters, such as the aircraft masses and the payload-range diagrams, are presented, and the aircraft variants are compared according to their Direct Operating Costs (DOC) and their emissions. In order to integrate two large hydrogen tanks inside the aircraft fuselage it is necessary to stretch the original fuselage. This stretch plus the masses of the hydrogen tanks increase the empty masses of the hydrogen-powered aircraft compared to the kerosene variants by about 8 %. From a purely economic point of view, the use of hydrogen as fuel is not favorable at today's kerosene and an energy equivalent hydrogen price. However, its combustion produces only water vapor and about 10 % of the amounts of nitrogen oxides of the kerosene variants as emission. This makes hydrogen favorable from an ecologic point of view, and in the future, these low emissions are expected to become economic benefits as well.

1. INTRODUCTION

1.1. Motivation

Freighter aircraft are becoming an increasingly interesting aircraft market segment. The worldwide air traffic of passengers and cargo has grown significantly over the last decades, and each of the major transport aircraft manufacturers (Airbus, Boeing, ATR, Bombardier and Embraer) expects this growth to continue [1] – [5]. Even today, in the light of the world economic crisis, Embraer states in its Market Outlook 2009–2028 from February 2009 that "Air Travel Demand Will Grow Despite Current Economic Crisis" [5]. The expected annual growth rates over the next two decades lie around 4.9 % for passenger transport [1], [3], [5] and even 5.8 % for cargo transport [1], [3]. This increasing demand for cargo transport also leads to an increased demand for freighter aircraft. In consequence, "… over the next 20 years, world air cargo traffic will triple compared to current levels, and the number of airplanes in the freighter fleet will double" [6].

"Today, freighters carry an estimated 60% of the world's revenue cargo…" [6]; the rest is transported in the lower deck compartments of passenger aircraft. Among the freighters, most aircraft are former passenger aircraft that were converted to a freighter after they were decommissioned as passenger aircraft. The rest are new-built aircraft derivates of passenger aircraft programs like the Airbus A330F or the Boeing B777F. Consequently, all these aircraft were not designed as dedicated freighter aircraft, and the special demands of a freighter were not fully taken into account during their design phase. The results are e.g. the unfavorable usual position of the cargo loading door at the side of the forward fuselage and the fact that cargo containers are shaped in accordance to aircraft fuselage cross sections and not vice versa.

However, it will not be enough to just ramp up production rates of the already available freighter aircraft to tackle future demands. Besides the pure need for more cargo capacity and more freighter aircraft, aviation in general faces increasing challenges of various kinds: economic, ecologic, social and political:

- Airline business and the competition between airlines are getting increasingly intense. "Over the past two decades, freight yields have declined at an average rate of 3.0 % per year" [6].
- The global climate is warming, and there is "…very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming…" [7]. In 1999 the Intergovernmental Panel on Climate Change (IPCC) stated in its special report "Aviation and the Global Atmosphere" [8] that "the best estimate of the radiative forcing in 1992 by aircraft is … about 3.5 % of the total radiative forcing by all anthropogenic activities… Aircraft contribute to global change approximately in proportion to their contribution to radiative forcing."
- The growing public awareness of the climate change and a growing general environmental consciousness are drastically changing the public perception of aviation. Statements like those of the bishop of London, Richard Chartres, from 2006 that "making selfish choices such as flying on holiday … [is] a symptom of sin" [9] and the German non-governmental organization (NGO) Germanwatch from 2003 that "flying is – relating to expenditure of time – the most climate-

damaging legal activity a person can perform during peacetime" [10] are indicators as well as reinforcers of an aviation-critical public attitude.

- Noise abatement procedures are being applied at an increasing number of airports [11]. Especially night-time operational restrictions have large influence on the logistics companies as 66 % of all flights of freighter aircraft (in Germany) take place between 22:00 h and 06:00 h in order to deliver e.g. express freight during the office hours [12].
- In July 2008, the European parliament decided to include aviation into the emissions trading scheme of the European Union for CO_2 from 2012 on [13].
- The world's crude oil resources are limited. Nevertheless, in the course of the growing world economy, the worldwide energy demand is growing, and among the consequences are rising energy and fuel prices. Consequently, "… in the foreseeable future, crude oil will no longer be able to accommodate demand. Therefore, in the light of the long time period needed for a conversion of the energy sector, it is already necessary today to search for alternatives for crude oil" [14].

In summary, "in the longer term, the continuing growth of civil aviation is unsustainable given current technologies and operating systems" [15].

In view of the enormous challenges posed to the aviation industry at the beginning of the 21st century, the Advisory Council for Aeronautics Research in Europe (ACARE) set up the "Vision 2020"-called "agenda for the European Aeronautics' ambition" [16] in 2001. This agenda defines the two European top-level goals of "meeting society's needs and winning global leadership" [16]. Examples of direct aims of the Vision 2020 are reductions of the number of accidents in air transport by 80 % and of the air transport costs by 30%. On the environmental side, among the aims are reductions of noise emissions by 50 %, CO_2 of 50 % and NO_x of 80 %.

Freighter aircraft could be an appropriate means to validate and introduce the required new technologies to usher in "The Age of Sustainable Growth" [17] in aviation. They could e.g. act as demonstrators for technologies like unmanned operation of transport aircraft, the use of hydrogen as fuel or for new unconventional aircraft configurations like the Blended Wing Body (BWB). The X-48B for example, a model of a BWB aircraft which is currently being flight tested by Boeing, the NASA and the US Air Force Research Laboratory (AFRL), is also intended as a step towards a BWB freighter aircraft [18].

1.2. The Green Freighter Project

The three-year joint research project "Green Freighter" was launched in December 2006 and is partly funded by the German Federal Ministry of Education and Research (BMBF). Its project partners are the Hamburg University of Applied Sciences (HAW Hamburg), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig, the Airbus Future Projects Office (FPO) and the SME (Small and Medium Enterprises) Bishop GmbH – an engineering office. The main project objective is to investigate unconventional short- and long-range freighter aircraft with special respect to environmentally friendly and economic aircraft operation [19]. In this context, 'unconventional' means unconventional regarding the aircraft's overall configuration (BWB) and/or regarding the fuel it uses: liquid hydrogen (LH_2) or bi-fuel (kerosene and liquid hydrogen).

The short-range reference aircraft is based on the ATR 72 full freighter version (see FIG 1), whereas the Boeing B777F was chosen as the long-range reference for the comparison of a conventional to a BWB aircraft [20]. The Figures 2 and 3 show the models of the Boeing B777F and the comparative BWB aircraft, which have been developed by the IFL. Subject matter of this paper is the comparison of four different short-range aircraft variants (see FIG 4) based on the ATR 72.

The central tool in the Green Freighter project is the IFL's Preliminary Aircraft Design and Optimization program PrADO [21]. This multidisciplinary program consists of several design modules of which each represents one discipline within the preliminary aircraft design process. These are e.g. geometry and structure, aerodynamics, mass and CG prediction, engine and aircraft performance, stability and control, flight simulation, Direct Operating Costs, etc. The relevant design process and aircraft data are stored in separate database files and handled by a central Data Management System (DMS).

FIG 1. PrADO Model of the ATR 72 (Propeller-Driven, Kerosene-Powered)

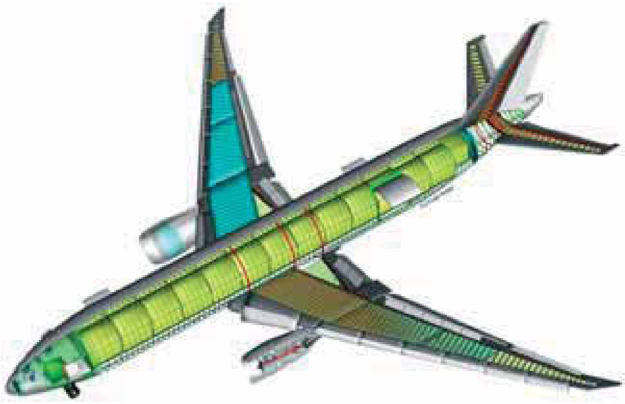

FIG 2. PrADO Model of the Boeing B777F (Kerosene-Powered)

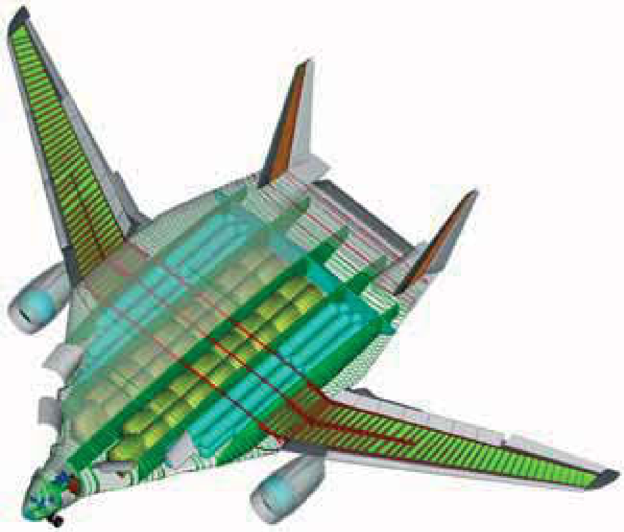

FIG 3. PrADO Model of the BWB Aircraft (Hydrogen-Powered)

Besides PrADO the HAW Hamburg's Aircraft Preliminary Sizing Tool PreSTo is used for the comparative preliminary sizing of the conventional reference aircraft. PreSTo is based on the aircraft design lecture of Prof. Dr. Dieter Scholz at the Hamburg University of Applied Sciences [22] and consists of a set of Microsoft Excel spreadsheets. A simplified version for the use within the aircraft design lecture is available for download in German and English language under http://fe.ProfScholz.de.

For more information on the Green Freighter project see http://GF.ProfScholz.de.

1.3. Fuels

1.3.1. Hydrocarbons

Today's aviation fuels, usually referred to by the umbrella term 'kerosene', are based on petroleum and therefore crude oil. Current developments towards alternative fuels most often aim at drop-in replacements, which means that they can be used as blends or purely in existing engines. The most important ones are GTL (gas-to-liquid), CTL (coal-to-liquid) and BTL (bio-to-liquid). Those fuels have in common that they are synthetically derived liquid fuels from a different feedstock than crude oil – usually by means of the so-called Fischer-Tropsch process. Thus, they are also referred to as 'FT-fuels'. Though alternatives to conventional kerosene in the sense that they do not depend on crude oil as the sole raw material, GTL- and CTL-fuels are still fossil fuels. Only BTL fuels represent a possibility to be an alternative in the sense of being 'climate neutral' if environmentally friendly *produced* [23]. Within the scope of the Green Freighter project, FT-fuels are not investigated as separate fuel options. They are included in the fuel option 'kerosene' as potential environmental benefits would be caused by the production process and not by their application as fuel in an aircraft.

A typical energy content for kerosene is 42.8 MJ/kg¸ its density lies between 775 kg/m^3 and 840 kg/m^3 at 15 °C [24]. The combustion of 1 kg of kerosene uses 3.4 kg of aerial oxygen and produces 3.15 kg of carbon dioxide (CO_2), 1.25 kg of water vapor (H_2O) plus several other substances of lower – but not negligible – quantity:

- Nitrogen oxides (NO_x): about 14 g,
- Sulfur oxides (SO_x): about 1 g,
- Carbon monoxide (CO): about 3.7 g,
- Unburned hydrocarbons (UHC): about 1.3 g and
- Soot: about 0.04 g [25].

The exact amounts of these reaction by-products depend highly on the type and technology level of the engine and on the specific fuel used (e.g. sulfur content).

1.3.2. Hydrogen

The application of hydrogen as aviation fuel has been the subject of previous studies like e.g. the European "Cryoplane" project under Airbus leadership [26]. Hydrogen has an energy content of 122.8 MJ/kg and a density of 70.8 kg/m^3 in liquid state [27]. The combustion of 1 kg of hydrogen produces 9 kg of water vapor and – dependant on the engine – about 4.3 g of NO_x [28]. Hence, compared to the energy content of 1 kg of kerosene, the combustion of an energy-equivalent amount of hydrogen generates only 3.24 kg of water vapor and about 1.5 g of nitrogen oxides. The mass of liquid hydrogen is only about one third the one of kerosene. On the other hand, the storage of liquid hydrogen requires an about four times greater volume, and the hydrogen has to be cooled down to -253 ºC (-423 °F) to be available in liquid state (LH_2). Of course, such a low temperature poses high demands on the thermal tank insulation and requires special fuel system components that are able to operate under such thermal conditions.

When dealing with hydrogen as fuel it is important to be aware that hydrogen is not a fuel in the sense of an energy *source* like e.g. crude oil. In fact it is an energy *carrier*, rather comparable to a battery. Hydrogen does not exist in pure state in nature but has to be separated under the expense of energy first, and only parts of this energy can be retrieved during its use afterwards. "More than ninety percent of hydrogen produced today is generated by reforming natural gas […] into hydrogen and carbon dioxide. While meeting today's industrial hydrogen demands, the overall efficiency of this process for the production of transportation fuels should be questioned as it basically converts one fuel into another and generates carbon dioxide, a greenhouse gas" [29]. Another method to produce pure hydrogen is the so-called electrolysis. Here, water is split up into hydrogen and oxygen by means of electricity. The hydrogen produced in this way offers the potential of extremely low emissions over the whole 'well-to-wing' chain – if the electricity is generated from renewable energy.

At first glance, having almost only water as combustion emission of an aircraft appears perfect. However, there is a difference between the climate impact of the emissions of terrestrial applications like cars and those of aircraft. The emission of water vapor may lead under certain atmospheric conditions to the formation of contrails and in their further development to cirrus clouds. The influences of contrails and cirrus clouds on the global climate change are not fully understood yet, but the general tendency is that they enforce global warming [30]. In this context, the combustion of hydrogen has, compared to kerosene, the beneficial property that no soot particles are being produced that could act as condensation nuclei. Moreover, in the special case of the here regarded regional aircraft, the water vapor emissions have a smaller climate impact than those of longer range aircraft due to the relatively low cruise altitude of less than 8 km. Contrails usually only form above this altitude [31].

“Safe handling of hydrogen is no longer a problem in the industrial and commercial area” [27]. Especially the gaseous state at ambient atmospheric conditions is advantageous: in the event of a leakage and/or fire, it evaporates and rises away quickly and does not form a (burning) carpet like kerosene. Nevertheless, many people raise safety concerns over the use of hydrogen. These concerns are e.g. caused by pictures of the disaster of the airship “Hindenburg” in 1937 in which 36 people died. This public fear or, at least, skepticism towards the use of hydrogen as fuel represents an important psychological factor that has to be taken into account when assessing an introduction of hydrogen as aviation fuel. Here, freighter aircraft may act as demonstrators to develop confidence.

2. DESCRIPTION OF THE SHORT-RANGE AIRCRAFT VARIANTS

The investigation of four different aircraft variants is being presented in this report. The baseline aircraft is the ATR 72 full freighter version. The variants differ in their type of propulsion system (jet- versus propeller-driven) and in the fuel they use (kerosene- versus hydrogen-powered). FIG 4 shows the resulting aircraft variants matrix.

2.1. Original ATR 72 Full Freighter Version

The ATR 72 is typically used as a feeder aircraft to transport cargo between regional airports and to and from hubs. It is 27.2 m long, 7.5 m high, and has a wingspan of 27 m. It is built in high wing/T-tail configuration. Its wing is unswept, has a double-trapezoid planform with rectangular center section and an aspect ratio of 12. Most of the secondary aircraft structure plus the outer wings, the fin and the tailplane structure are manufactured from composite materials, summing up to 19 % of the overall structural mass [32]. The freighter version has an operating empty mass of 11.9 t, a maximum take-off mass of 22 t and is equipped with a 2.95 m wide and 1.8 m high (116” x 71”) cargo door behind the flight deck. It has a range at maximum payload (8625 kg including seven LD3 containers of 76 kg each) of 963 km (520 NM) under typical operational conditions (see below) [33]. The aircraft is equipped with two Pratt & Whitney Canada PW127F turboprop engines driving Hamilton Sundstrand HS568F six-blade propellers.

2.2. Fuselage Models and Hydrogen Tank Integration

The geometry of the airframe is kept as close to the original ATR 72 as possible. Therefore, in case of the kerosene versions, the geometry is widely the same as the one of the original. In case of the hydrogen versions, however, a lot of cargo volume would have to be sacrificed for internal tank volume if external tanks shall be avoided. The thickness of the hydrogen tank insulation is estimated to be 12 cm; the mass of the hydrogen tank insulation and structure is estimated to be 10 kg/m^2 (following Böhm [34]). A more extensive investigation of the properties of different types of internal and external hydrogen tanks is currently in progress at the HAW Hamburg.

In case of the hydrogen variants, the fuselage is stretched by 3.8 m to accommodate two large cylindrical hydrogen tanks internally (see FIG 5). One tank is installed in front of the cargo compartment and one behind it. The wings are not used to store fuel. The large thickness of the hydrogen tank insulation would either cause one very flat and therefore pressure-unfavorable tank or many very small cylindrical tanks with a very large total area. Both alternatives

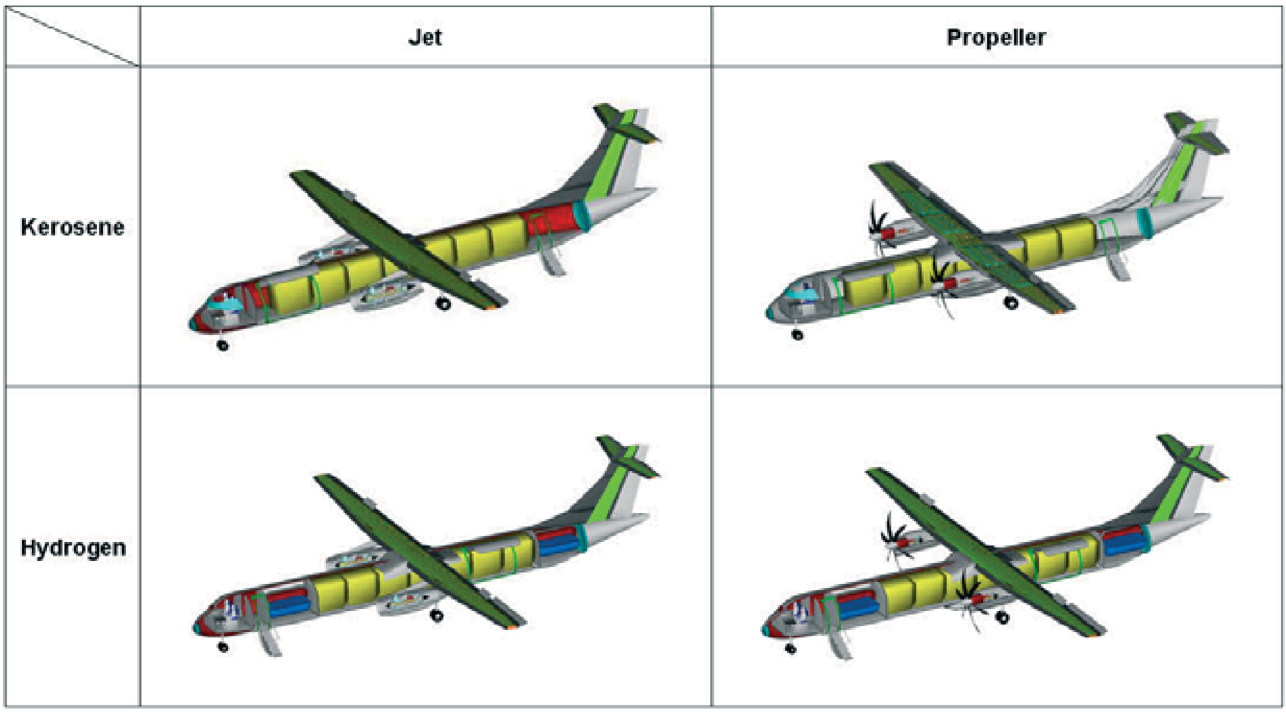

FIG 4. Aircraft Variants Matrix

would bring too little additional fuel capacity to justify the high complexity and mass of such tank installations.

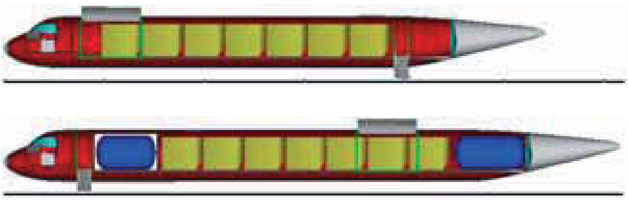

FIG 5. Original Versus Stretched Fuselage

Without any further changes to the aircraft the large cargo door in its initial position in the forward fuselage would be obstructed by the forward hydrogen tank. Therefore, the door positions are switched: the large cargo door is moved to the aft and the small one is installed in the entrance area behind the flight deck. The entrance area and the cargo compartment are connected by a channel alongside the forward hydrogen tank to allow for accessibility of the cargo compartment (see FIG 6).

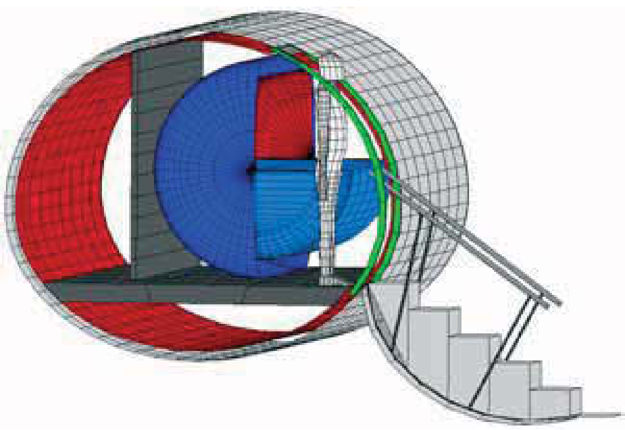

FIG 6. Integration of Forward Hydrogen Tank and Entrance Area

2.3. Jet Propulsion System

The PrADO engine model for the jet variants is based on the General Electric CF34 turbofan family with the CF34-3B1 as the baseline engine. In order to verify the engine model, the CF34-3B1 has been re-modeled and successively refined as a fixed engine. For this purpose, the engine's properties like

- Mass,
- Specific fuel consumption (SFC),
- Geometry (dimensions, no. of compressor and turbine stages, etc),
- Air mass flow, etc.

have been constantly checked against the real engine's data taken from Rolls-Royce [35]. The main characteristics of the CF34-3B1 are listed in TAB 1; FIG 7 depicts a section view of the engine.

After the verification process has been finished, the engine models are treated as so-called 'rubber engines'. This means that the engines are adapted and sized by PrADO according to the resulting thrust requirement and operating condition of each aircraft variant.

TAB 1. CF34-3B1 Engine Data [35] – [37]

Parameter	Value	
	Original	Model
Take-off thrust (ISA, SL)	38.8 kN	38.8 kN
Bypass ratio (BPR)	6.25	6.25
Overall pressure ratio (OPR)	21	21
Stages*	Fan, 14 HPC, 2 HPT, 4 LPT	Fan, 14 HPC, 2 HPT, 4 LPT
Mass	757 kg	751 kg

* Note: The numbers of compressor and turbine stages are not given as input data but are a result of the sizing process!

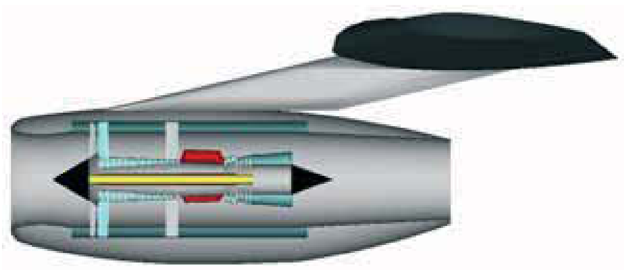

FIG 7. Geometry Model of the GE CF34-3B1 Turbofan Engine

2.4. Propeller Propulsion System

The baseline engine for the turboprop aircraft variants is the original engine of the ATR72, the Pratt & Whitney Canada PW127F. Its main characteristics as well as those of the original Hamilton Sundstrand propeller HS 568F are listed in TAB 2. A picture of the turboprop propulsion system is shown in FIG 8.

TAB 2. PW127F Engine and HS 568F Propeller Data [35], [38], [39]

Parameter	Value	
	Original	Model
Take-off shaft power (ISA, SL)	2750 hp	(38.5 kN)
Stages*	Prop, 1 LPC, 1 HPC, 1 HPT, 2 LPT, 2 PT	Prop, 1 LPC, 1 HPC, 1 HPT, 2 LPT, 2 PT
Mass: Engine Propeller	481 kg 169 kg	516 kg 169 kg**

* Note: The numbers of compressor and turbine stages are not given as input data but are a result of the sizing process!

** Input data

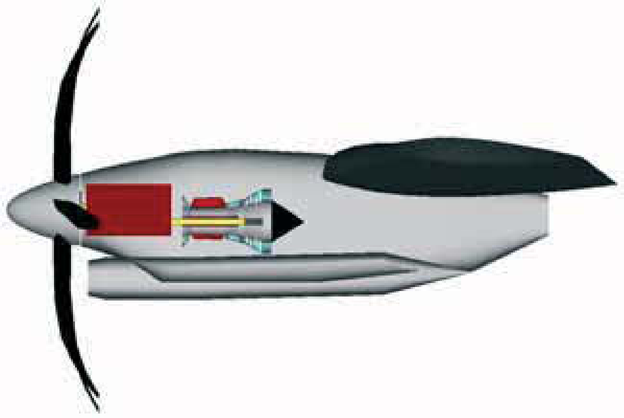

FIG 8. Geometry Model of the PW127F Turboprop Engine with HS568F Six-Blade Propeller

Currently, it is not yet possible to model radial compressors and reverse flow combustion chambers inside PrADO. Therefore, a substitutional engine model is used that features an axial compressor and a normal combustion chamber. This change mostly affects the geometrical model of the engine. The thermodynamical performance, however, can be modeled like that of the reference engine, and the mass properties may be adjusted by means of the number of blades per stage and/or the material densities.

As well as the jet engine models, the propeller engines are treated as 'rubber engines' after the baseline design of the PW127F has been set up and checked with the real engine's properties.

3. AIRCRAFT MODELLING

3.1. Description of the PrADO Propeller Module

At the beginning of the Green Freighter project it was not yet possible to analyze propeller-driven aircraft using PrADO. Therefore, in order to perform the desired investigations of the ATR-based aircraft variants (and later propeller-driven BWB variants) a new engine module had to be developed and integrated into PrADO. This task was performed by the IFL with the assistance of the HAW Hamburg and Bishop GmbH. The design process used within the turboprop engine module follows the method described in "Aircraft Engine Design" by Mattingly et al. [40].

The newly developed PrADO turboprop engine module is based on the jet engine module for a two-shaft turbofan engine with one axial compressor and two turbines. One effect of this approach is that the specific fuel consumption of the engine is not determined and presented per unit of power (as it is commonplace in case of turboprop engines) but per unit of thrust as it is commonplace in case of jet engines and as it is presented in the reference method.

The essential change to the original module is that the low-pressure turbine (LPT) does not drive a fan but the propeller. So, shaft power is delivered from the LPT to the propeller (with losses due to the shaft bearing and the reduction gear) and converted to thrust by the propeller (with additional losses expressed by the propeller efficiency). For that purpose, the propeller geometry, mass and the development of the propeller efficiency over Mach number have first to be defined and stored in a template file. During the following design process, this data is loaded into the program and is kept constant throughout all iteration steps even if the engine size is adapted to the thrust requirements of the present aircraft layout. In case of large changes to the thrust requirement and engine size, this may lead to unrealistic geometric outputs, and a new propeller would have to be chosen and added by hand.

The total thrust of a turboprop engine is not only produced by the propeller, but the core engine adds thrust in the order of about 10 %. It follows:

(1) $$T_{total} = T_{prop} + T_{core\_eng}$$, with

(2) $$T_{prop} = \frac{\eta_{prop}\, P_{prop}}{V_\infty}$$ and

(3) $$P_{prop} = \eta_{shaft}\, \eta_{gear}\, P_{LPT}$$.

3.2. Description of the PrADO DOC Module

For the economic assessment of civil aircraft designs it is commonplace to look at the so-called Direct Operating Costs (DOC). They "… include the total operating costs of the aircraft. … By definition, DOC methods contain only the aircraft-related costs" [41]. Throughout aviation business, there are many DOC methods of different aircraft operators, airline associations and aircraft manufacturers in use that differ slightly in the cost elements they comprise. The calculation method applied inside the DOC module of PrADO [42] has been developed at the IFL and is mostly geared to the calculation methods applied by Lufthansa, the Association of European Airlines (AEA) and the method described in Roskam VIII [43] (based on the method of the Air Transport Association of America (ATA)). It determines the so-called DOC parameter, C_{DOC}, which describes the relation of all costs that are directly related to the operation of the aircraft over its total time in operation $\left(\sum C\right)$ to the totally performed transport work $\left(\sum W_T\right)$. It is expressed in the unit 'Euro per ton-kilometer' $\left[\frac{€}{\text{t km}}\right]$:

(4) $$C_{DOC} = \frac{\text{Costs}}{\text{Transport Work}} = \frac{\sum C}{\sum W_T} \quad \left[\frac{€}{\text{t km}}\right]$$.

In this equation, the costs are made up of the six cost elements for aircraft depreciation, insurance, fuel, maintenance, crew and fees:

(5) $$\sum C = C_{depreciation} + C_{insurance} + C_{fuel} + C_{maintenance} + C_{crew} + C_{fees} \quad [€]$$

For a freighter aircraft, the transport work is calculated as the product of the average amount of cargo per flight $\left(\overline{m}_c\right)$, the number of flights per year $\left(n_{f,y}\right)$, the number of years of the aircraft in operation $\left(n_y\right)$ and the reference flight range (R):

(6) $\sum W_T = \overline{m}_c \cdot n_{f,y} \cdot n_y \cdot R \quad [\text{t km}]$

3.3. Input Data

During the design investigations all aircraft and cost parameters are kept the same for all four variants. Consequently, all later differences in aircraft properties as well as their economic and environmental performances result from the different fuels used. The standard input values for DOC calculation using PrADO are listed in TAB 3.

TAB 3. Standard DOC-Calculation Input Values [42], [44]

Parameter	Value/Selection
Annual aircraft availability	4198 h/a
Turnaround time	0.75 h
Number of years in operation	14 a
Specific Component costs: Airframe and systems Engine	 757.223 €/kg 24.3374 €/N
Spare parts costs	15 % of a/c price
Annual insurance costs	1 % of a/c price
Interest rate	8%
Residual value	15 % of a/c price
Fuel price: Kerosene Hydrogen	 0.5 €/kg 1.5 €/kg
Number of pilots per crew	2
Number of crews per aircraft	6
Crew costs (pilots)*	30.667 €/flight h
Maintenance costs: Airframe and systems Engines	 255.65 €/flight hour 102.26 €/flight hour and engine
Landing fees	8.69 €/t (MTOW)
Ground handling fees	40.903 €/t cargo

* Crew costs for each pilot of all crews per flight hour

The prices for kerosene and hydrogen are chosen to be equivalent to their specific content of energy. Consequently, the price for 1 kg of hydrogen (122.8 MJ/kg) is three times the price of 1 kg of kerosene (42.8 MJ/kg). The kerosene price is taken as 0.5 €/kg, which corresponds to the average value at the end of 2008 [44].

The reference mission for the presented investigations is the mission 'flight at maximum payload' of the original ATR 72 full freighter version. It is defined by the following mission requirements listed in TAB 4.

TAB 4. Reference Mission Input Data (Flight with Maximum Payload) [33]

Parameter	Value/Selection
Net payload	8093 kg
Range at max. payload	963 km (520 NM)
Cruise Mach number	0.4
Cruise altitude (beginning of cruise)	6 km (FL 200)
Distance to alternate airport	161 km (87 NM)
Loiter time	045 min
Engine size	not fixed, 'rubber engine'

4. RESULTS

The most obvious visible result of a conversion of the reference kerosene aircraft variants to hydrogen is the 14 % longer fuselage. Moreover, the door positions have to be switched, and two large hydrogen tanks have to be integrated inside the fuselage. The installation of these large tanks decreases the available cargo volume by the bulk cargo volume of 11.7 m^3 from 75.5 m^3 to 63.8 m^3 [33], which is disadvantageous for cargo of less density like e.g. parcels. However, the minimum average cargo density to achieve the maximum payload of 8093 kg results as 127 kg/m^3, which is still well below the average cargo density of 160 kg/m^3 [41].

4.1. Aircraft Masses and Required Thrust

The total dimensions and mass properties of the liquid hydrogen tanks are collected in TAB 5.

TAB 5. Liquid Hydrogen Tank Data

Parameter	Value
Fuel volume	11.7 m^3
Fuel mass	833 kg
Tank surface	34.8 m^2
Tank mass	348 kg

The additional installation of hydrogen tanks in combination with the required fuselage stretch increases the operating empty mass of the hydrogen variants significantly. Both hydrogen variants are in the order of 8 % heavier, of which only about 3 % are caused by the tanks themselves. In contrast, the maximum take-off masses of the hydrogen variants are about 2 % smaller than those of the kerosene variants. The reason for that is the much lower density of the liquid hydrogen. For the current reference mission the required amount of hydrogen weighs only about 35 % of the amount of required kerosene. TAB 6 shows the results of the various aircraft masses and the consequential aircraft thrust requirements.

TAB 6. Mass and Thrust Comparison of ATR 72 Kerosene/Hydrogen and Jet/Propeller Variants

Parameter	Value			
	Kerosene Jet	Kerosene Prop	LH_2 Jet	Lh_2 Prop
Operating empty mass [t]	12.7	12.1	13.7	13.1
Maximum take-off mass [t]	23.2	22.2	22.7	21.8
Engine mass [kg]	805	510	791	552
Maximum take-off thrust [kN]	40.9	(38.3)*	41.3	(38.4)*
Specific fuel consumption (cruise) [mg/(Ns)]	17.8	(13.7)*	6.2	(4.7)*

* See Section 3.1 for explanation

Strikingly, the engine thrust of the hydrogen variants is larger than that of the respective kerosene variants, although the hydrogen variants have a lower maximum take-off mass. The explanation for this is the higher operating empty mass, and consequently, landing mass of the hydrogen aircraft. The higher mass significantly increases the necessary thrust to fulfill the certification requirement for a minimum climb gradient after a missed approach.

Payload-Range Diagrams

FIG 9 shows the payload-range diagrams of all four aircraft variants as well as the one of the original ATR 72.

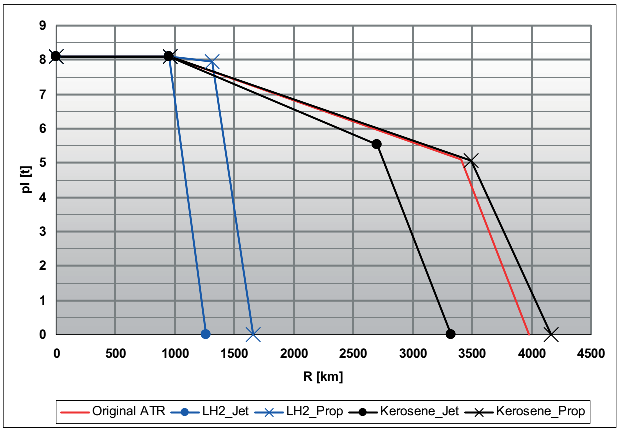

FIG 9. Comparison of Payload-Range Diagrams of ATR 72 Kerosene/Hydrogen and Jet/Propeller Variants

It becomes apparent that both hydrogen variants have significantly smaller ranges beyond the point ‘flight at maximum payload’. The ‘range at maximum fuel’ of the hydrogen-powered jet variant is furthermore the same as the ‘range at maximum payload’. In case of the hydrogen-powered propeller variant it is noteworthy that a very small reduction of payload leads to a considerable increase of the possible range. Moreover, both jet-driven variants reach only about 80 % of the propeller variants’ ferry range.

4.2. Direct Operating Costs

TAB 7 holds the calculated DOC parameters of the different aircraft variants. It becomes obvious that the direct operating costs of the propeller variants lie significantly below those of the jet versions. The differences are in the region of about 10 %. The Direct Operating Costs of the hydrogen variants are about 2 % to 3% higher as those of the kerosene-powered aircraft. Thus, from a purely economic point of view, it is not favorable to use liquid hydrogen as fuel under the given circumstances – especially energy costs.

TAB 7. Comparison of Direct Operating Costs at Reference Mission (Flight at maximum Payload)

Parameter	Value			
	Kerosene Jet	Kerosene Prop	LH_2 Jet	LH_2 Prop
C_{DOC} [€/tkm]	0.540	0.486	0.556	0.493

4.3. Emissions

The numbers for energy consumption and generated emissions of the four aircraft variants are given in TAB 8.

Most noticeable, the jet variants consume about 30 % more energy than the propeller variants and, in consequence, generate more emissions in the same order of magnitude. Furthermore, the energy consumption of the hydrogen-powered jet variant is calculated as about 3 % larger than the one of the kerosene variant. In case of the propeller variants, it is the opposite: the kerosene aircraft uses about 5 % more energy.

Of course, the hydrogen variants do not produce any carbon dioxide. Moreover, their amounts of generated NO_x account for only about 10 % of those of the kerosene variants. Their amounts of emitted water vapor are about 2.5 times larger than those of the kerosene variants. However, at this cruise altitude of 6 km contrails or cirrus clouds do not form.

TAB 8. Comparison of Energy Consumptions and Emissions at Reference Mission (Flight at maximum Payload)

Parameter	Value			
	Kerosene Jet	Kerosene Prop	LH_2 Jet	LH_2 Prop
Total fuel consumption [t]	2.43	1.97	0.88	0.65
Total energy consumption [GJ]	104	84	107	80
Generated CO_2 [t]	7.7	6.2	0.0	0.0
Generated water vapor [t]	3.0	2.5	7.9	5.9
Generated NO_x [kg]	34.0	27.6	3.8	2.8

5. DISCUSSION

The presented results mark a solid base for the comparison of conventional and hydrogen-powered freighter aircraft. The PrADO-analyses show well the general trends of the operation of such aircraft. However, the current propeller engine models are substitutes for the real engines with radial compressors and reverse-flow combustion chambers. Furthermore, these propeller engine models are two of the very first ones to be modeled inside PrADO at all. Hence, it is still desirable to increase the model accuracy especially concerning thermodynamics and propeller efficiency estimation to increase confidence.

It becomes apparent that the jet variants are disadvantaged compared to their competitive propeller variants. Their energy consumptions are larger, and their Direct Operating Costs are higher as well. The reason for that is the comparison of the four variants under exactly the original ATR 72's operational conditions, which are at relatively low cruise Mach number of 0.4 and low cruise altitude of 6 km. This favors the propeller variants due to the different performances of jet and propeller engines over Mach number. As a future step, it is therefore advisable to vary the mission requirements 'Mach number' and 'cruise altitude' for each aircraft variant and conduct a set of parameter variations to find the optimum solution for each variant.

FIG 10 shows the general development of the Direct Operating Costs of a jet aircraft over cruise Mach number at different altitudes. In comparison, FIG 11 shows the development of the total fuel consumption (fuel mass) of the same aircraft as in FIG 10. Both Figures have been created by means of a parameter variation of a kerosene-powered, jet-driven ATR 72 variant.

It can be seen that the minimum value of the Direct Operating Costs is reached at significantly higher cruise Mach number than 0.4. The explanation for this development is the higher utilization of the aircraft, which means that if the aircraft flies faster, more flights can be conducted and more cargo may be transported. Consequently, cost elements like depreciation and insurance are being distributed over more flights, which reduces the Direct Operating Costs per ton-kilometer.

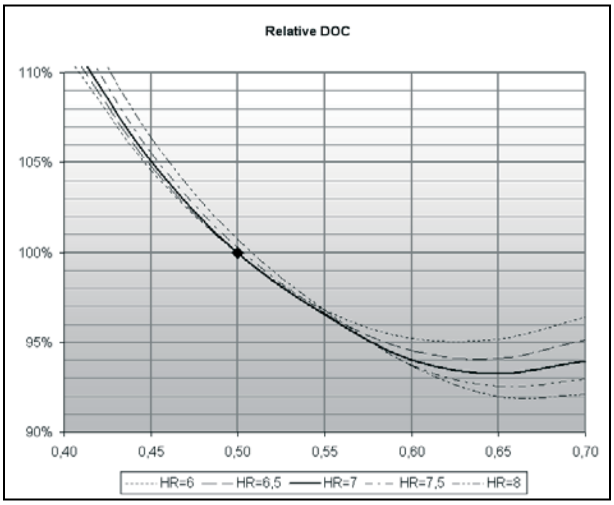

FIG 10. Development of the Direct Operating Costs of the ATR 72 Kerosene/Jet Variant over Mach Number and Altitude

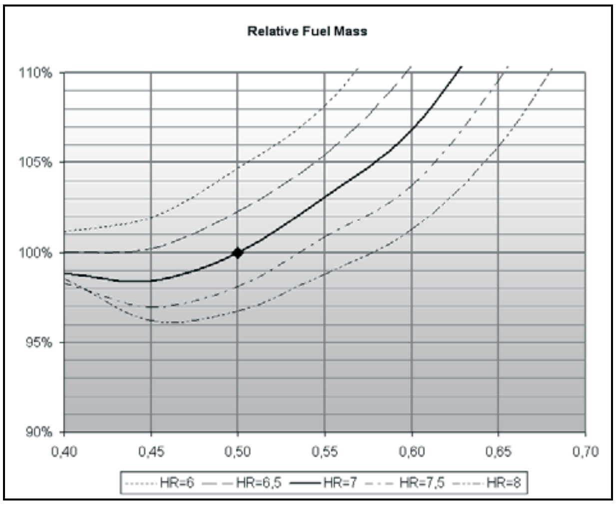

FIG 11. Development of the Fuel Consumption of the ATR 72 Kerosene/Jet Variant over Mach Number and Altitude

In contrast to the DOC, the fuel consumption – and emissions in consequence – increase with rising Mach number. These two oppositional trends in Figures 10 and 11 show clearly the basic discrepancy between the requirements for low costs and low emissions. Low emissions require a lower cruise speed and cause higher costs.

For future aircraft this means that if low emissions shall be beneficial in terms of costs as well, the economic circumstances have to change considerably. Examples to achieve such circumstances are a significant increase in the price for fuel and energy in general or to penalize large fuel consumption in a different way (e.g. by an emissions trading scheme). However, if rising energy prices lead to higher cargo (and ticket) fares the affordability of air cargo and traffic might be limited to rich people and countries again, like decades ago. Besides the social effects, such development could harm the development of worldwide aviation.

In the case of a hydrogen-powered aircraft a trade-off between payload and range as in the case of kerosene-powered aircraft is no longer reasonable. Due to the low density of the liquid hydrogen, the line between the points 'range at maximum payload' and 'range at maximum fuel' in the payload-range diagram runs very flat. So, looking at the point 'range at maximum fuel' a move towards maximum payload would only bring a very small increase in payload while scarifying much range and carrying all the necessary tank (and fuselage) structure for the integration of the large hydrogen volume. For hydrogen aircraft it is therefore more advisable to define one maximum range and one maximum payload and to design an aircraft that is able to fulfill those requirements at minimum mass and aerodynamic penalty.

6. CONCLUSIONS

Jet versus Prop

In the regarded Mach number region of around 0.4 propeller aircraft are more fuel-efficient than jet-driven aircraft. They are more environmentally friendly, and, in addition, they produce less Direct Operating Costs. Jet aircraft become more economically favorable at higher cruise Mach numbers (due to a better utilization of the aircraft) but under the expense of an increasing fuel consumption. In those regions saving costs means burning more fuel. Thus, propeller aircraft are clearly the more favorable 'feeder' freighters

Hydrogen versus Kerosene

The hydrogen propeller variant consumes less energy than the kerosene aircraft in an order of 5 %, and it is more environmentally friendly due to its significantly lower emissions (no carbon dioxide, 90 % less nitrogen oxides, more water but no contrails). Of course, an overall environmental benefit is highly depending on the way the hydrogen is produced. The Direct Operating Costs of the hydrogen propeller variant are about 1 % to 2 % higher. Consequently, from a purely economic point of view, the use of hydrogen is not favorable at today's kerosene and an energy equivalent hydrogen price and under the current circumstances, particularly at today's kerosene and energy equivalent hydrogen prices.Future steps

In the course of the Green Freighter project it has become possible to model and analyze unconventional fuels, fuel combinations and turboprop engines using the Preliminary Aircraft Design and Optimization program PrADO. The new modules for unconventional fuels, turboprop engines analysis etc. and the other tools of the project partners (like PreSTo of the HAW Hamburg) will be further improved and extended.

The next future steps in the investigation of the short range aircraft are to improve the current models in more detail and to perform parameter variations to determine the best operational conditions for each aircraft variant. Moreover, there are unmanned versions of the regarded aircraft variants in preparation, in which the former cockpit region is used as installation region of the forward hydrogen tank. This avoids the necessity to stretch the fuselage as in case of the manned versions and is therefore expected to save empty and take-off mass as well as energy and costs.

Furthermore, a DOC method for freighter aircraft is in preparation at the HAW Hamburg that especially takes into account environmental aspects like an emissions trading scheme etc. The development of this method is going along with a research of freighter specific data on their utilization like number of flights per day/night, stage lengths, handling times and charges.

ACKNOWLEDGEMENT

The project underlying this report was funded by the German Federal Ministry for Education and Research (support code (FKZ) 1710X06). The author is responsible for the content of this publication.

NOMENCLATURE AND ABBREVIATIONS

ACARE	Advisory Council for Aeronautics Research in Europe
AEA	Association of European Airlines
AFRL	Air Force Research Laboratory
ATA	Air Transport Association of America
ATR	Avions de Transport Régional
BMBF	Bundesministerium für Bildung und Forschung (German Federal Ministry of Education and Research)
BTL	Bio-To-Liquid
BWB	Blended Wing Body
C	Costs
CO	Carbon monoxide
CTL	Coal-To-Liquid
CO_2	Carbon dioxide
DMS	Data Management System
DOC	Direct Operating Costs
FL	Flight Level
FPO	Future Projects Office
FT	Fischer-Tropsch
GTL	Gas-To-Liquid
HAW	Hochschule für Angewandte Wissenschaften (University of Applied Sciences)
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine
H_2	Hydrogen
IFL	Institut für Flugzeugbau und Leichtbau (Institute of Aircraft Design and Lightweight Structures)
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LH_2	Liquid Hydrogen
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
MTOW	Maximum Take-Off Weight
$\overline{m_c}$	Average amount of cargo mass per flight
NASA	National Aeronautics and Space Administration
NM	Nautical Mile(s)
NO_x	Nitrogen Oxides
$n_{f,y}$	Number of flights per year

n_y	Number of years in operation
OPR	Overall Pressure Ratio
P	Power
pax	Passenger(s)
PL	Payload
PrADO	Preliminary Aircraft Design and Optimization program
PreSTo	(Aircraft) Preliminary Sizing Tool
PT	Power Turbine
R	Range
SFC	Specific Fuel Consumption
SL	Sea Level
SME	Small and Medium Enterprises
SO_x	Sulfur Oxides
T	Thrust
UHC	Unburned Hydrocarbons
US	United States
W_T	Transport work
η	Efficiency

REFERENCES

[1] AIRBUS: Global market forecast 2007-2026. Corporate Information, 2007. – URL: http://www.airbus.com/en/corporate/gmf/ (2009-03-03)

[2] AVIONS DE TRANSPORT REGIONAL: Regional Market Outlook 2008-2027. Corporate Information, 2008. – URL: http://www.atr.fr/public/atr/html/media/downloadcenter.php (2009-03-03)

[3] BOEING: Current market outlook 2008-2027. Corporate Information, 2008. – URL: http://www.boeing.com/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2008_to_2027.pdf (2009-03-03)

[4] BOMBARDIER AEROSPACE: Commercial Aircraft Market Forecast 2008-2027. Corporate Information, 2008. – URL: http://www2.bombardier.com/en/3_0/3_1/pdf/Market_forecast_Regional.pdf (2009-03-03)

[5] EMBRAER: Market Outlook 2009-2028. Corporate Information, 2009. – URL: http://www.embraercommercialjets.com/hotsites/market-outlook-2008/english/content/home/default.asp (2009-03-03)

[6] BOEING: World Air Cargo Forecast 2008-2009. Corporate Information, 2008. – URL: http://www.boeing.com/commercial/cargo/wacf.pdf (2009-03-09)

[7] ALLEY, Richard; BERNTSEN, Terje; BINDOFF, Nathaniel L. et. al.; Intergovernmental Panel on Climate Change: Climate Change 2007: The Physical Science Basis – Summary for Policy Makers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva : International Panel on Climate Change, 2007.

[8] PENNER, Joyce E.; LISTER, David H.; GRIGGS, David J. et. al. (eds.); Intergovernmental Panel on Climate Change: Aviation and the Global Atmosphere – Summary for Policy Makers. Geneva : International Panel on Climate Change, 1999. – URL: http://www.ipcc.ch/ipccreports/sres/aviation/index.htm, ISBN: 92-9169-

[9] LEAKE, Jonathan: It's a sin to fly, says church. In: *The Sunday Times*, 2006-07-23 – URL: http://www.timesonline.co.uk/tol/news/uk/article691423.ece (2009-03-09)

[10] TREBER, Manfred; KIRCHMAIR, Andrea; KIER, Gerold; Germanwatch e. V.: Die Subventionierung des Flugverkehrs. Bonn/Berlin : Germanwatch e. V., 2003. – URL: http://www.germanwatch.org/rio/bpflug03.pdf (2009-03-13)

[11] BOEING: *Growth in Airport Noise Restrictions* 2009. – URL: http://www.boeing.com/commercial/noise/restrictions.pdf (2009-03-11)

[12] ARBEITSGEMEINSCHAFT DEUTSCHER VERKEHRSFLUGHÄFEN: Fakten zum Thema: Nachtflugbetrieb. Berlin : Arbeitsgemeinschaft Deutscher Verkehrsflughäfen, 2009. – URL: http://www.adv.aero/fileadmin/pdf/Wirtschaft_u_Recht/ADV-Pras_Nachtflug_2009__Kompatibilitaetsmodu.pdf (2009-03-11)

[13] EUROPÄISCHES PARLAMENT: Emissionshandel im Luftverkehr ab 2012. – URL: http://www.europarl.de/presse/pressemitteilungen/quartal2008_3/PM_080708_1a (2009-03-11)

[14] BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE: Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2007. Hannover : Bundesanstalt für Geowissenschaften und Rohstoffe, 2007. – URL: http://www.bgr.bund.de/cln_101/nn_331182/DE/Themen/Energie/Downloads/Energiestudie__Kurzf__2007,templateId=raw,property=publicationFile.pdf/Energiestudie_Kurzf_2007.pdf (2009-03-11)

[15] UPHAM, Paul; MAUGHAN, Janet, RAPER, David, et. al. (eds.): *Towards sustainable aviation*. London : Earthscan, 2003 – ISBN: 1-85383-818-7

[16] ADVISORY COUNCIL FOR AERONAUTICS RESEARCH IN EUROPE: *A Vision for 2020 - meeting society's needs and winning global leadership*. Luxembourg : Office for Official Publications of the European Communities, 2001 – URL: http://www.acare4europe.com/docs/Vision%202020.pdf (2009-03-11), ISBN: 92-894-0559-7

[17] ADVISORY COUNCIL FOR AERONAUTICS RESEARCH IN EUROPE: *Strategic Research Agenda Volume 1*, 2002. – URL: http://www.acare4europe.com/docs/es-volume1-2/volume1.pdf (2009-03-11)

[18] WILSON, J. R.: The blended wing takes flight. In: *Aerospace America*, Aug 2008, p. 26-31

[19] SEECKT, Kolja; HEINZE, Wolfgang, SCHOLZ, Dieter: *The Green Freighter Project – Objectives and First Results*. In: *CD Proceedings : ICAS 2008 - 26th Congress of the International Council of the Aeronautical Sciences including the 8th AIAA Aviation Technoloy, Integration, and Operations (ATIO) Conference* (Anchorage, Alaska, USA, 14-19 September 2008). Edinburgh, UK : Optimage Ltd, 2008. - Paper: ICAS 2008-4.10.3 (056.pdf), ISBN: 0-9533991-9-2

[20] SEECKT, Kolja; SCHOLZ, Dieter: *Green freighter – requirements and selection of design concepts to be investigated*. Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Aircraft Design and Systems Group (Aero), Technical Note, 2007 – URL: http://reports_at_aero.profscholz.de

[21] HEINZE, W.; ÖSTERHELD, C. M.; HORST, P.: *Multidisziplinäres Flugzeugentwurfsverfahren PrADO – Programmentwurf und Anwendung im Rahmen von Flugzeug-Konzeptstudien*. DGLR Jahrestagung, Hamburg, DGLR-Jahrbuch 2001 Band III, 2001.

[22] SCHOLZ, Dieter (ed.): *Aircraft design*. Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Aircraft Design and Systems Group (Aero), Short Course Notes, 2008. – URL: http://www.flugzeugentwurf.de

[23] TURNER, Aimee: Green Journey. In: *Flight International*, 2008-06-17, p. 39-40

[24] EXXONMOBIL AVIATION: World Jet Fuel Specifications with Avgas Supplement. Machelen : ExxonMobil Aviation, 2008. – URL: http://www.exxonmobil.com /AviationGlobal/Files/WorldJetFuelSpec2008_1.pdf (2009-03-10)

[25] GREWE, Volker; Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre: Climate impact of aviation : Presentation. ERA-Net AirTN (Air-Transport-Net) - Forum on Green ATS, Bonn, 2007-10-31.

[26] WESTENBERGER, Andreas; Airbus; Future Projects Office: Cryoplane – Hydrogen Aircraft : Presentation. H2 Expo, Hamburg, 2003-10-11 – URL: http://www.h2hh.de/downloads/ Westenberger.pdf (2007-07-26)

[27] LTH KOORDINIERUNGSSTELLE: *Luftfahrttechnisches Handbuch.* Volume: *Triebwerkstechnologie – Wasserstofftechnologie*. Ottobrunn : IABG, 2008 (AT 01 900-00).

[28] BREWER, G. Daniel: *Hydrogen Aircraft Technology*. Boca Raton : CRC Press, 1991 - ISBN 0-8493-5838-8

[29] HEMIGHAUS, Greg; BOVAL, Tracy; BOSLEY, Carol; et. al., Chevron Corporation: Alternative jet fuels. Chevron Corporation, Corporate Information, 2006. – URL: http://www.chevronglobalaviation.com/docs/5719_Aviation_Addendum._webpdf.pdf (2007-08-02)

[30] SCHUMANN, Ulrich; Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre: Globale Verkehrsemissionen in der freien Troposphäre und unteren Stratosphäre und ihre Klimawirkung. In: Metz, Norbert (publ.): Im Spannungsfeld zwischen CO2-Einsparung und Abgasemissionsabsenkung, Haus der Technik Fachbuch, 92 (2008), Expert Verlag, Renningen, p. 247-263 – ISBN 978-3-8169-2806-5

[31] CHAMBERS, Lin H.; FISCHER, Joyce D., National Aeronautics and Space Administration, Langley Research Center: *Contrail Education – Frequently Asked Questions*, 2008. – URL: http://asd-www.larc.nasa.gov/GLOBE/faq.html (2009-03-25)

[32] AVIONS DE TRANSPORT RÉGIONAL: ATR 42-300/320 and ATR 72-200/210 - The regional way to profitability. Corporate Information, 2005. – URL: http://www.atraircraft.com/public/atr/html/media/medias.php?aid=757 (2008-06-05)

[33] AVIONS DE TRANSPORT RÉGIONAL: ATR large cargo door. Corporate Information, 2003. – URL: http://www.atraircraft.com/public/atr/html/media/medias.php?aid=757 (2008-05-27)

[34] BÖHM, Martin: *Gesamtentwurf eines ökonomischen und ökologischen Lufttransportsystems unter Ausnutzung von Synergieeffekten*. Universität der Bundeswehr München, Fakultät für Luft- und Raumfahrttechnik, Doctoral Thesis, 2006

[35] ROLLS-ROYCE : Aero data. Derby : Rolls-Royce plc, 2006 (VCOM11141 Issue 3). – Corporate Information

[36] ROUX, Elodie: *Turbofan and Turbojet Engines*. Blagnac : Editions Elodie Roux, 2007 – ISBN: 978-2-9529380-1-3

[37] GENERAL ELECTRIC COMPANY: *Comparison Chart: Turbofans*, 2008. – URL: http://www.geae.com/engines/commercial/comparison_turbofan.html

[38] PRATT & WHITNEY CANADA INC: Engine Specification – Model: PW127F, Spec No: 1095. Longueuil : Pratt & Whitney Canada Inc, 1996 (P&WC 8000 (06-93)). – Corporate Information.

[39] HAMILTON SUNDSTRAND, Publications Department: Component Maintenance Manual 815500, 820522 – Chapter 61-13-12. Windsor Locks : Hamilton Sundstrand Corporation, 2003. Corporate Information

[40] MATTINGLY, Jack; Heiser, William H.; Daley, Daniel H.: Aircraft engine design. New York : American Institute of Aeronautics and Astronautics, 1987 – ISBN: 0-930403-23-1

[41] SCHOLZ, Dieter: *Flugzeugentwurf*. Hochschule für Angewandte Wissenschaften Hamburg, Department Fahrzeugtechnik und Flugzeugbau, Aircraft Design and Systems Group (Aero), Lecture Notes, 2005

[42] HEINZE, Wolfgang: *Beschreibung der im Entwurfsprogramm PrADO verwendeten DOC-Berechnungsmethode als Diskussionsgrundlage für die Bewertung eines modularen Flugzeugkonzeptes*. Technische Universität Braunschweig, Institut für Flugzeugbau und Leichtbau, Work Package Description "LuFo III-Verbundvorhaben K2020, Arbeitspaket „kosteneffizientes Verkehrsflugzeug", 2004

[43] ROSKAM, Jan: *Airplane Design*. Bd. 8 : *Airplane Cost Estimation*: *Design, Development, Manufacturing and Operation*, Ottawa, Kansas, 1990

[44] INTERNATIONAL AIR TRANSPORT ASSOCIATION: Jet Fuel Price Currency Comparison, 2009. – URL: http://www.iata.org/whatwedo/economics/fuel_monitor/price_development.htm (2009-04-03)