THE GREEN FREIGHTER PROJECT – OBJECTIVES AND FIRST RESULTS

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Keywords: *aircraft design, freighter, hydrogen, propulsion system, conversion*

Abstract

This paper introduces the Green Freighter project – a joint aircraft design research project with focus on the design and investigation of environmentally friendly and cost effective freighter aircraft. The project partners are the Hamburg University of Applied Sciences (HAW), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technische Universität Braunschweig, Airbus' Future Projects Office and Bishop GmbH. During the project, unconventional configurations – first and foremost the blended wing body (BWB) – and the use of alternative fuels will be investigated in comparison to conventional kerosene-powered aircraft.

As a first step, theoretical jet versions of the regional aircraft ATR 72 were re-designed and investigated. The preliminary sizing of an initial kerosene version was done using the HAW's Preliminary Sizing Tool (PreSTo) assuming a completely new design. In comparison, two jet-powered derivatives of the real aircraft were set up and investigated as both a kerosene- and a hydrogen-powered version using the IFL's Preliminary Aircraft Design and Optimization program (PrADO).

The results show that for a conversion from kerosene to liquid hydrogen as fuel a lot of cargo volume has to be sacrificed for internal tank volume if external tanks shall be avoided. Assuming today's fuel prices, the direct operating costs (DOC) of the hydrogen version are significantly higher. In the future, however, with changing availability and prices for different fuels, the numbers are expected to change significantly and make the hydrogen version more favorable.

1 Introduction

1.1 Objectives of the Green Freighter Project

The Green Freighter project was launched in December 2006 and has a duration of three years. Its aim is to design and investigate unconventional cargo aircraft configurations and to compare these to conventional ones on the basis of a technology level of the year 2025. In doing so, the main focus is on environmentally friendly and economic aircraft operation which includes the following technical aspects:

- Low fuel consumption,
- Use of future fuels (liquid hydrogen (LH_2), synthetic fuels, biofuel),
- Low noise level for nighttime operation,
- Low emissions and climate impact (CO_2, NO_x, cloud formation, etc.),
- Low operating costs due to zero-pilot operation and no or a reduced environmental control system (ECS).

As the air cargo chain includes different types and sizes of freighter aircraft, the investigations include freighter aircraft from small regional so-called feeders to large long-range freighters. The ATR[1] 72 full freighter version was chosen as the regional and the Boeing B777F as the large reference aircraft. The investigation of unconventional, namely the blended wing body (BWB) configuration, will concentrate on the large aircraft as only aircraft above a certain minimum size are feasible as BWB aircraft (see Unconventional Configurations).

[1] Avions de Transport Régional

1.2 Tools

The central tool in the Green Freighter project is the Preliminary Aircraft Design and Optimization program PrADO, a multidisciplinary aircraft design tool, which has been developed by the IFL [1]. PrADO is split up into several design modules that cover all aspects of the preliminary aircraft design process. Database files include independent and dependent data on the current design problem, and a data management system (DMS) performs the data exchange between the design modules and the database files (see Figure 1). Independent data are given by the user and include e.g. the definition of the transport task (payload, range), a basic parametric description of the configuration layout (e.g. cabin arrangement, wing aspect ratio, reference area, etc.) and further relevant design constraints like maximum allowable take-off and landing distances. Dependent design data result from the calculations of the particular design modules (e.g. aerodynamic coefficients, engine thrust and specific fuel consumption (SFC), mission data, component masses, take-off mass, etc.).

PrADO has three modes of operation. The first one, "Single Design Analysis", starts with the initial user input and iteratively executes the sequence of design modules until convergence of important dependent design parameters is reached. The design modules comprise the following aspects:

- Aircraft geometry,
- Engine design including off-design behavior,
- Aerodynamics,
- Performance,
- Structure analysis including weight and center of gravity (CG) prediction,
- Stability and control,
- Direct operating costs (DOC) and
- Check with design constraints.

The second mode, "Parameter Variation", performs an automatic variation of user-chosen independent parameters, meaning that for each set of variables a complete single design analysis (mode 1) is executed. This allows illustrating the complete design space and its constraints and eases the understanding of the design problem along with its possible solutions.

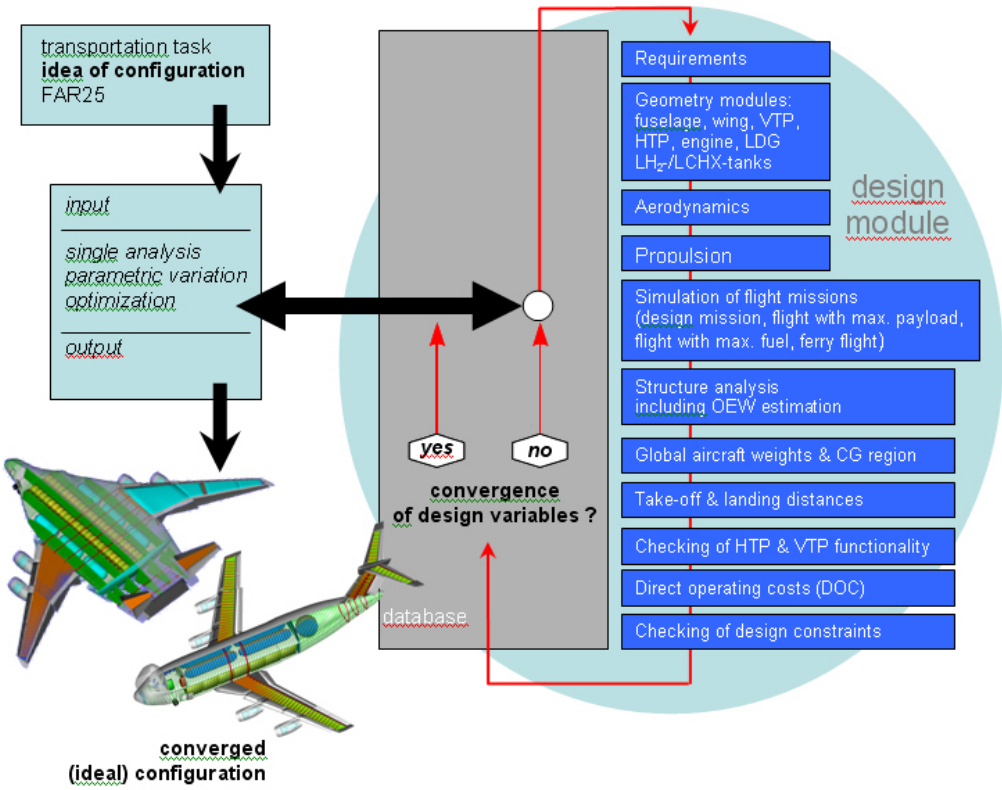

Fig. 1. The work flow of the Preliminary Aircraft Design and Optimization program PrADO

The third mode, “Optimization”, starts an optimization algorithm that searches for a final parameter combination that delivers a best result for a defined target function, e.g. the lowest DOC or minimum fuel consumption for a defined mission.

So far, the activities in the Green Freighter project concerning the adaptation of PrADO have been concentrated on the use of alternative fuels (hydrogen purely or in combination with kerosene) and new engine concepts. In detail, the following work has been done:

- Description of the 3D cryogenic fuel tank geometry including defueling simulation, aircraft center of gravity determination, positioning of the cryogenic fuel tank in/on the aircraft and weight estimation including insulation,
- Enhancement of the thermodynamic engine model including the characteristics of hydrogen and mixed fuels,
- Development of a turboprop engine model including predication of propeller efficiency,
- Geometry modeling of arbitrary engine arrangements in/on the aircraft (e.g. two different engines in one nacelle),
- Modification of flight simulation concerning use of fuel and engine types on the different flight legs (e.g. use of hydrogen during take-off and climb, change to kerosene in the cruise),
- Enhancement of the structure sizing method SAM[2] [2], [3] based on the finite elements method to analyze blended wing body configurations with cryogenic fuel tanks in the fuselage.

In addition to PrADO, the Preliminary Sizing Tool PreSTo, which has been developed by the HAW, is used for the preliminary sizing of the conventional aircraft [4]. PreSTo, which is partly based on the NASA Reference Publication 1060 [5], delivers an initial aircraft description that could e.g. be used as the basis for the user input entered into PrADO for further optimization (see Section 2.1). The tool is available for download in German and English language under http://fe.ProfScholz.de.

[2] Structural, Aerodynamic and Aeroelastic Sizing Module

1.3 Freighter Aircraft

Nowadays, most freighter aircraft are former passenger aircraft that were converted after they were decommissioned as passenger aircraft. Such a conversion typically includes removing of passenger-related cabin systems, installation of a large cargo door and a cargo loading system, structural reinforcement of the floor structure and the installation of freighter specific aircraft systems (e.g. smoke detection and fire extinguishing systems).

Due to the worldwide economic growth, air traffic in general and air cargo traffic in particular are increasing rapidly. Both Airbus and Boeing expect the worldwide air cargo traffic to grow by about six percent per year and the size of the world freighter aircraft fleet to double to about 4000 aircraft by 2025 [6], [7]. That demand for additional freighter aircraft makes them an increasingly interesting market segment, of which 22 % is expected to be satisfied with new factory-built freighters [6].

Freighter aircraft are affected by the same global circumstances like depleting crude oil resources, rising fuel prices, the need to reduce emissions of CO_2 and other pollutants and coming emission-related taxes as every other kind of aircraft. Therefore, they need to become more efficient as well, but additionally, freighter aircraft face some even more stringent future requirements especially concerning noise as they are mostly operated during nighttime. Many airports already have set up noise related landing fees and/or restrictions for nighttime operation [8]. As an answer to those challenges, new factory-built freighter aircraft like the Boeing B777F and B747-8F or the Airbus A380F and A330-200F are already entering the market, but nevertheless those freighter aircraft are still derivates of the respective passenger version.

1.4 Unconventional Configurations

Practically all of today’s transport aircraft show the conventional tail-aft configuration, which is characterized by three main features: a fuselage which accommodates the payload, a wing attached to the fuselage that produces the lift, and surfaces for stability and control at the aft end of the fuselage. Any aircraft configuration that differs from that in one or more features is unconventional. Examples ([9], [10]) are the canard, three-surface, joined wing, multi-fuselage, flying wing and the blended wing body (BWB) configuration whose fuselage and wing merge smoothly into each other. The main potential benefits of the BWB compared to the conventional configuration are a lighter airframe structure and improved aerodynamics ([11], [12]), but only for aircraft of a certain minimum size. As the fuselage is shaped like an airfoil, it extends significantly over the length of the cargo (or passenger) compartment to the front and especially to the rear. Hence, the height of the compartment defines the fuselage length and – if a certain aspect ratio shall be achieved – also the span. Previous investigations of the IFL showed a minimum payload of *at least* 50 t to make the BWB configuration feasible for aircraft having passenger or cargo compartments of the same height as today's aircraft [13]. Regarding hydrogen-powered aircraft, the BWB configuration offers further advantages as such aircraft can provide the required very large storage volume (see Unconventional Fuels).

The BWB reveals great prospects for economic and ecologic future aircraft operation, but nonetheless, there are still challenges, especially for passenger versions, that need to be solved before such an aircraft may enter into service [12], [14]:

- Stability and control,
- Emergency passenger evacuation,
- No outside-view for many/all passengers,
- Maneuver accelerations on outboard seats,
- Cabin pressurization of a non-cylindrical pressure vessel,
- Airport infrastructure,
- Certification.

Some of these aspects play little or no role for freighter aircraft. Consequently, the Green Freighter is being regarded as a means to develop a knowledge base on blended wing body aircraft without those 'show-stoppers'.

1.5 Unconventional Fuels

In the Green Freighter project, fuels that are synthetically derived from biological feedstocks (bio to liquid, BTL), coal (CTL) or natural gas (GTL) by means of the so-called Fischer-Tropsch process, are in the first steps treated as conventional kerosene. Later on, when aircraft emissions are being investigated in more detail, one will have to differentiate as these fuels can e.g. be completely free from sulfur and, consequently, the combustion of those fuels does not create sulfur oxides (SO_x) [15]. That leads to an improvement of especially local air quality.

Hydrogen is not a fuel in the definition of an energy *source*; in fact, it is an energy *carrier* comparable to a battery. Energy must be employed first to obtain hydrogen in a pure state, and only parts of that energy can be retrieved afterwards. Nowadays, hydrogen is most often separated from natural gas because this process is much cheaper than electrolysis (splitting water into hydrogen and oxygen by means of electricity) [15]. If environmentally friendly produced – meaning by means of electrolysis and 'green' electricity – hydrogen offers the potential of extremely low CO_2 and other emissions over the whole 'well-to-wing' chain. However, the large amounts of produced water during combustion lead under certain atmospheric conditions to an increased formation of contrails and cirrus clouds which are assumed to also contribute to global warming [16]. Such effects on the climate shall be taken into account in a final emissions assessment, though the quantification is very difficult [17].

In contrast to kerosene, hydrogen must be cooled down to -253 °C (-423 °F) to be stored as liquid (LH_2). That requires thermal tank insulation and special fuel system components which are able to operate under such temperature conditions. Based on the same energy content, LH_2 has only one third of the mass of kerosene but a four times greater volume, which consequently requires a large storage volume. Safety analyses have shown that hydrogen is at least as safe as conventional hydrocarbon fuels [18]. One of its biggest advantages is its gaseous state at ambient pressure: In the event of a leakage and/or fire, it evaporates and rises away quickly and, therefore, does not form a (burning) carpet.

Other unconventional energy sources like electricity or Silane (chemical compounds of silicon and hydrogen) will not be investigated in the Green Freighter project.

2 Investigation of a Regional Freighter Aircraft using Kerosene and Hydrogen Propulsion

The basis for the work presented in this paper is a theoretical jet-driven derivative of the full freighter version of the turboprop aircraft ATR 72. The ATR 72 is typically used as a feeder aircraft to transport cargo between regional airports and to and from hubs. The ATR 72 is 27 m long, 7.5 m high, and has a wingspan of 27 m. It is built in high wing/T-tail configuration with an unswept double-trapezoid wing with an aspect ratio of 12 and a rectangular center section. Most of the secondary 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 [19]. 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 can accommodate up to seven LD3 containers and has a range at maximum payload (8,093 kg) of 963 km (520 NM) under typical operational conditions (45 min continued cruise + 161 km (87 NM) to alternate airport) [20]. This work’s reference aircraft is equipped with two jet engines instead of the original Pratt & Whitney PW306 turboprop engines (see Figure 2), while the geometry of the airframe and the operational requirements were kept widely the same.

From a flight mechanics point-of-view, a conversion of an aircraft’s propulsion system from propeller to jet is a larger change to its flight performance than obvious at first glance. Propeller and jet engines behave differently over flight speed. Principally, the thrust of a jet engine is independent from flight speed, whereas the thrust of a propeller engine decreases with rising speed, but its thrust-power (i.e. thrust times velocity) stays constant. Consequently, if jet aircraft shall be optimized *for minimum fuel consumption*, they fly faster than propeller aircraft, and a propeller and a jet version of geometrically the same aircraft are operated at different flight speeds: the jet aircraft with respect to minimizing the required thrust, the propeller aircraft with respect to minimizing the power. In numbers that means that the minimum thrust speed V_{min_thrust} is about 1.3 times as large as the minimum power speed V_{min_power} [21]:

$$V_{min\_thrust} = \sqrt[4]{3} \cdot V_{min\_power} \approx 1.3 \cdot V_{min\_power} \quad (1)$$

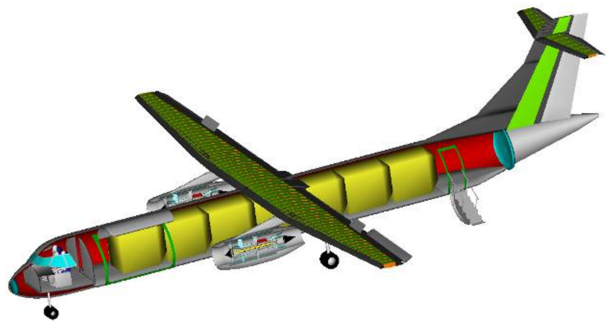

Fig. 2. PrADO-model of the ATR 72 kerosene jet version

In contrast, if jet aircraft shall be optimized *for minimum operating empty and take-off mass*, the cruise speed is typically lower than the optimum cruise speed for minimum fuel consumption.

2.1 Aircraft Preliminary Sizing with PreSTo

PreSTo is used to determine first estimates for the aircraft mass and thrust requirement of a jet-driven ATR 72 *if newly-developed*. The results are used for the assessment of the PrADO-analyses of the *converted* aircraft.

The first step in the preliminary sizing process is to express the five design requirements posed to the aircraft concerning

- The landing distance,
- The take-off distance,
- The cruise Mach number,
- The climb gradient after take-off (2nd segment) with one engine inoperative and

- The missed approach climb gradient with one engine inoperative

as either thrust-to-weight ratio, wing loading or a relation of the two. The results are put together in one matching chart, and the design point is read from that (see Figure 3).

Prior to the preliminary design of the ATR 72 jet version, the results of the real aircraft conversion of the Dornier Do 328 from turboprop to jet propulsion were studied and taken into account for the setup of the mission requirements (e.g. longer take-off distance) and the initial assumptions made during the redesign process. The engines, for example, were estimated that way to lie in the range of the General Electric CF34 turbofan family, and the required value for the engine bypass ratio was chosen to be 6.2, which is the value of the CF34-3. Table 1 holds the requirements posed to the theoretical jet version of the ATR 72.

Parameter	Value
Max. payload	8,093 kg
Range	520 NM = 963 km
Take-off field length	1550 m
Landing field length	1450 m
Engine bypass ratio (CF34-3)	6.2

Table 1. Requirements posed to the ATR 72 jet version

The initial assumptions, which are needed for the preliminary sizing process in addition to the general aircraft requirements, are based on previous investigations of several real aircraft. Table 2 lists the assumptions made during the sizing process.

Parameter	Value
Max. landing lift-coefficient	2.4
Max. t-o lift coefficient	1.9
Specific fuel consumption	18.4 mg/(Ns)
Ratio of cruise speed to min. drag speed	1.316
Max. landing to max. t-o mass	0.97
Operating empty to max. t-o mass	0.55

Table 2. Assumptions made for the preliminary sizing of the ATR 72 jet version

After the determination of the design point, that point is used in combination with

- The design range,
- The payload,
- The reserve distance to an alternate airport,
- The loiter time and
- Statistical data

to estimate several aircraft parameters for the specified reference mission, such as

- The cruise altitude and cruise speed,
- The maximum take-off, landing and operating empty mass,
- The wing area,
- The engine thrust and
- The required fuel mass and volume.

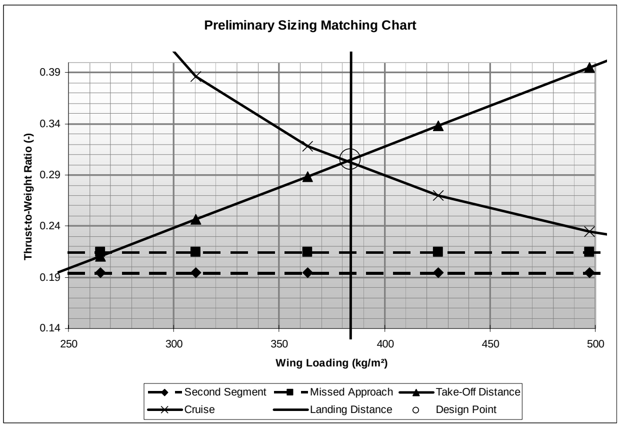

Fig. 3. Matching chart for preliminary sizing of the ATR 72 jet version

Table 3 contains the results of the preliminary sizing process in comparison to the results of the PrADO analyses. PreSTo delivers a large cruise altitude of more than 11 km and a cruise Mach number of 0.76 compared to 8 km and 0.45 of the real turboprop aircraft. The reason for that is the completely new design of the aircraft, meaning that design steps like the choice of an airfoil section and wing geometry are assumed to be free. In case of the prop-jet-conversion of the ATR 72, however, the geometry and airfoil are predetermined by the real aircraft and have been optimized for a low cruise Mach number. The real airfoil of the ATR 72 is based on a NACA-5 series airfoil with 18 % thickness at the wing root and 13 % thickness at the wing tip, and a wing having such airfoils would cause very high drag at high Mach numbers. The following investigation of the ATR 72 using PrADO and the real airfoil and geometry will therefore deliver smaller numbers for cruise Mach number and altitude.

2.2 Investigation of the ATR 72 Kerosene Version with PrADO

The detailed analysis of the different flight missions is performed using PrADO's second operational mode "Parameter Variation". This means that a set of complete single point analyses of the ATR 72 is run, in which the engine thrust and mass are not predefined but determined during the analysis process as dependent variables. The reference mission, however, stays the same: it is required to transport a payload of 8050 kg (1150 kg per container) over a distance of 520 NM (963 km). Each single analysis has a different combination of initial cruise altitude and cruise Mach number; the values vary between cruise Mach numbers of 0.4 to 0.7 and cruise altitudes of 8 to 12 km; flight missions outside that region are regarded as not feasible.

The remaining relevant parameters for an aircraft analysis, such as

- The complete aircraft geometry,
- The cargo arrangement (seven LD3 containers),
- The engine model,
- The allowable take-off and landing distances, etc.,

have to be defined once and are kept as constant and independent constraints of the analysis process.

2.2.1 Minimum Mass and Minimum Fuel Consumption

The minimum value for the maximum take-off mass is calculated for an initial cruise altitude of 8 km and a cruise Mach number of 0.42 (see Figure 4), which are almost the same numbers as for the initial propeller version. Figure 4 is also representative for the development of the operating empty mass and the necessary engine thrust over cruise Mach number.

The calculated values for engine thrust, maximum take-off mass and operating empty mass are calculated as 43.8 kN (9,800 lbf), 23,150 kg and 13,000 kg; the wing loading of 380 kg/m² is higher than that of the original turboprop version but lies in the region of the jet aircraft version, when sized using PreSTo (see Table 3). However, it is noticeable that the required take-off engine thrust is calculated larger than previously estimated with PreSTo (+26 %).

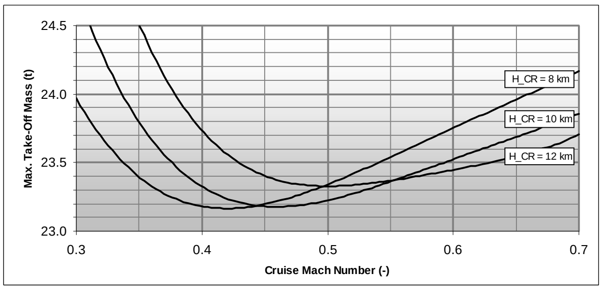

Fig. 4. Max. take-off mass of the ATR 72 kerosene version over cruise Mach number

When looking at the development of the fuel consumption, the optimum operational conditions change in the expected direction: a minimum value is reached for a cruise Mach number of about 0.62 at an altitude of 12 km (see Figure 5). The reference combination of cruise Mach number and initial cruise altitude is 0.5 and 10 km (hence: Fuel Consumption of ($M_{CR} = 0.5$ and $h_{CR} = 10$ km) = 1).

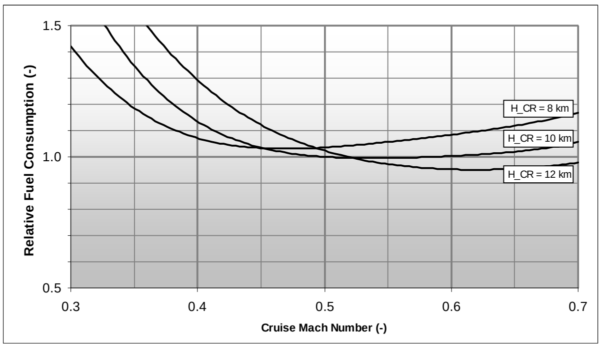

Fig. 5. Relative fuel consumption of the ATR 72 kerosene version over cruise Mach number

2.2.2 Payload-Range Diagram

The dashed line in the payload-range diagram (Figure 6) marks the payload-range diagram of the original turboprop ATR 72, which correlates well with the minimum mass/minimum thrust solution.

2.2.3 Direct Operating Costs (DOC)

The comparison of the direct operating costs of different cruise Mach numbers and cruise altitudes in terms of ton-mile-costs ($\text{US\$}/(\text{NM} \cdot \text{t})$) is performed for the '8,050 kg payload/520 NM range'-mission using a PrADO specific determination method. The reference combination of cruise Mach number and altitude is again $M_{CR} = 0.5$ and $h_{CR} = 10$ km. The results pre-

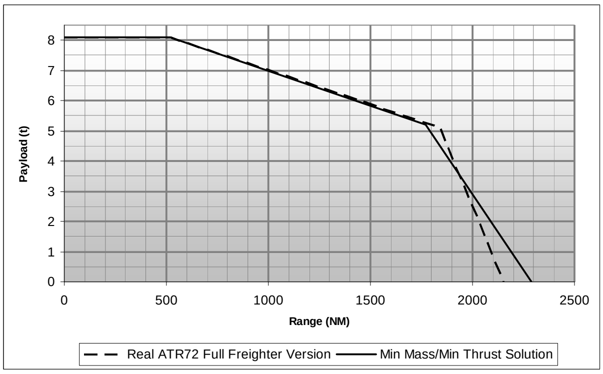

Fig. 6. PL-R diagram of the ATR 72 kerosene version

sented here are based on today's cost structure and prices (e.g. 1.13 US$/kg kerosene).

A comparative analysis shows diminishing values with rising cruise Mach number (see Figure 7). The line of 4 km cruise altitude was added to Figure 7 to show the principle development of the DOC over cruise Mach number: up to a certain value they keep decreasing with rising Mach number and start rising, but much slower, above that value. In particular, up to a cruise Mach number of 0.45 the minimum values are reached at a cruise altitude of about 4 km; above 0.45, cruise altitudes of 8 – 10 km deliver the best values. The reference mission for fuel consumption and DOC analysis of the hydrogen version was again chosen to be the combination of a cruise Mach number of 0.5 and a cruise altitude of 10 km.

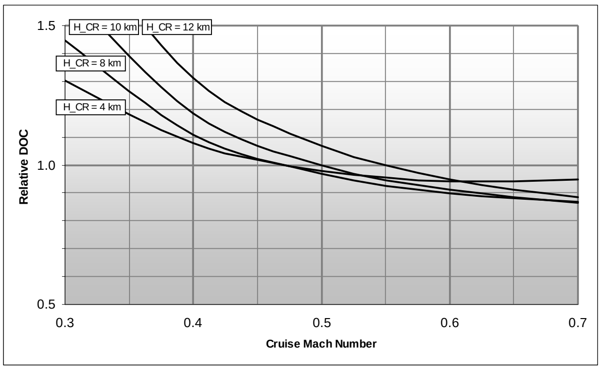

Fig. 7. Relative direct operating costs of the ATR 72 kerosene version over cruise Mach number

The principal reason for decreasing costs with rising cruise Mach number – thus despite rising aircraft mass, engine size and fuel consumption – is that a higher cruise Mach number leads to shorter flight times and therefore an increase in transport capacity (more flights per day). This correlation is especially important for passenger aircraft and generally less important for cargo aircraft as those aircraft are operated less often per day, respectively night. Future DOC analyses will account for that fact from a more 'freighter point-of-view' (see Future Steps), and lead to changes in the development of the DOC over cruise Mach number.

2.3 Investigation of the ATR 72 Hydrogen Version with PrADO

The hydrogen version of the ATR 72 freighter aircraft is, in a first step, intended to be kept as a "minimum change solution". Although the snowball-effects due to the change of the fuel system would probably be too many to perform a conversion from kerosene to hydrogen on an already manufactured aircraft, it should be at least possible to re-use as many components of the kerosene version as possible for the manufacturing of a new aircraft. That would reduce the development effort and simplify the certification of the aircraft.

The largest visible change from the kerosene to the hydrogen version is the installation of two cylindrical liquid hydrogen tanks: one in the forward fuselage between the flight deck/entrance area and the cargo compartment, and one in the aft fuselage between the cargo compartment and the rear pressure bulkhead (see Figure 8). The wings are not used to store fuel tanks as several small cylindrical tanks inside the wing would be very heavy.

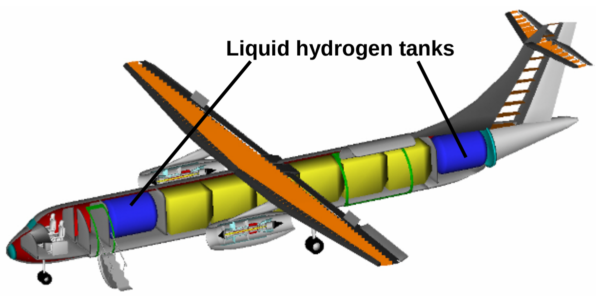

Fig.8. PrADO-model of the ATR 72 hydrogen version

Due to the installation of the forward LH_2-tank, the available volume of the cargo compartment is reduced from seven to six LD3 containers. Another effect of the tank installation inside the fuselage is that the door positions have to be switched: the large cargo door is moved to the aft and vice versa since the large cargo door in its initial position would be obstructed by the forward LH_2 tank. The dimensions of the LH_2-tanks are kept restricted to the opening size of the cargo door so that a removal or replacement would be possible on a real aircraft. The total volume of both tanks is 10.1 m^3, which corresponds to a total fuel mass of about 720 kg.

Alongside the forward LH_2-tank compartment, a channel connects the entrance area with the cargo compartment (see Figure 9). The channel is drawn on the port side of the fuselage for visibility reasons; in a real aircraft it would be obstructed by the door steps and therefore the channel would be on the starboard side.

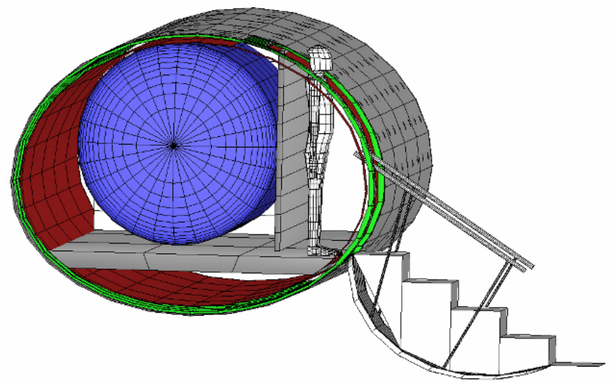

Fig. 9. Cross section of the forward LH_2-tank installation in the ATR 72 hydrogen version

In a first attempt, the payload is assumed to be diminished by the same factor as the number of containers to 6,900 kg; in case of a real aircraft that value would depend on the strength of the floor structure, of course. The alternative to the installation of LH_2-tanks inside the fuselage and the sacrifice of valuable cargo volume would be the installation of LH_2-tanks in external tanks – e.g. in pods under the wings or on top of the fuselage. Those solutions, however, would increase both the mass and the drag of the aircraft, and especially the installation of tanks on top the fuselage could no longer be called a minimum change solution. A fuselage stretch would lead to a larger tank or cargo volume and, consequently, longer range or larger payload but would cause new problems due to the further reduction of pitch angle during take-off and landing.

2.3.1 Minimum Mass and Minimum Fuel Consumption

The development of the maximum take-off mass of the ATR 72 hydrogen version shows a minimum value at a cruise Mach number of 0.36 at initial cruise altitudes between 4 – 6 km. As only flight regimes of at least 8 km and Mach 0.4 shall be considered, the lowest maximum take-off mass results as 21,250 kg at a cruise Mach number of 0.4 and an altitude of 8 km (see Figure 10).

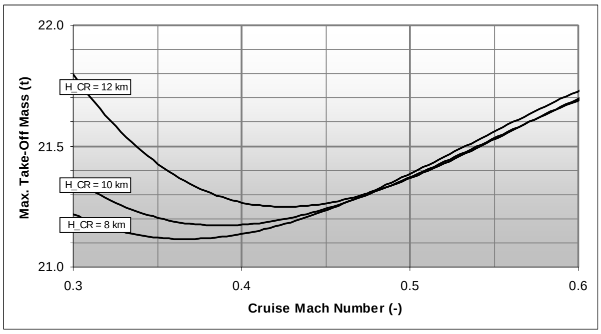

Fig. 10. Max. take-off mass of the ATR 72 hydrogen version over cruise Mach number

The calculated values for engine thrust, maximum take-off mass and operating empty mass are calculated as 40.1 kN (9,000 lbf), 21,250 kg and 13,600 kg. Those values lie in realistic orders of magnitude: the operating empty mass has, of course, to be higher than the one of the kerosene version due to the extra installation of the hydrogen tanks, whereas the maximum take-off mass is reduced due to the very low fuel density. As a result, the required engine thrust is diminished as well.

The maximum take-off wing loading changed to 348 kg/m^2, while the thrust-to-weight ratio stayed the same of 0.385. See Table 3 for the detailed comparison with the previous design steps.

With respect to minimum fuel consumption, the optimum cruise Mach number and cruise altitude result, as expected, as a larger values: 0.54 at a cruise altitude of 10 km (see Figure 11). The reference combination of cruise Mach number and cruise altitude is again 0.5 and 10 km.

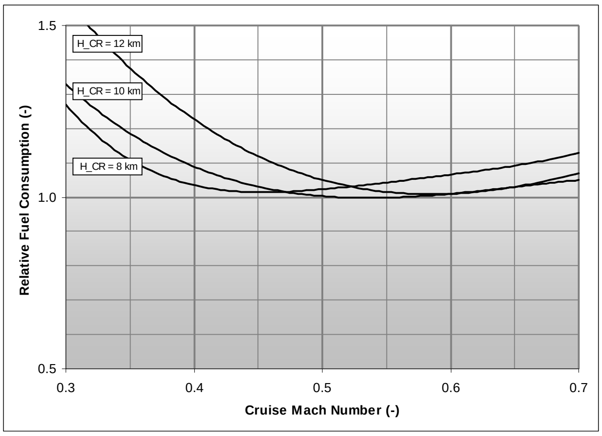

Fig. 11. Relative fuel consumption of the ATR 72 hydrogen version over cruise Mach number

2.3.2 Payload-Range Diagram

Figure 12 shows the payload-range diagram of the ATR 72 hydrogen version in contrast to the payload-range diagram of the original turboprop aircraft. The hydrogen version of the ATR 72, with a reduced payload, is almost able to reach the design range at maximum payload of the original turboprop version and the kerosene version (510 NM instead of 520 NM). The ranges at maximum payload and with maximum fuel reduce to one single spot. The ferry range results as about 670 NM (1240 km).

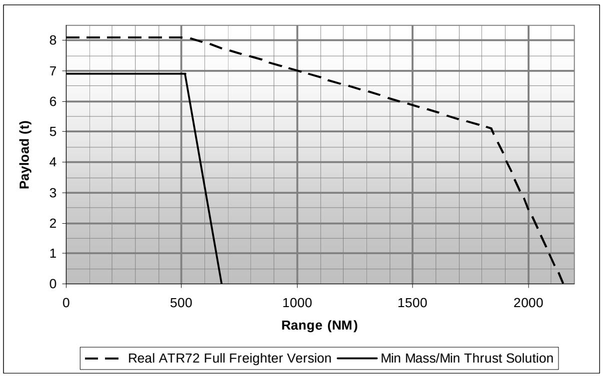

Fig. 12. PL-R diagram of the ATR 72 hydrogen version

2.3.3 Direct Operating Costs (DOC)

Figure 13 shows the relative development of the direct operating costs in terms of ton-mile-costs ($US\$/(NM \cdot t)$) of the ATR 72 hydrogen version for a mission of 6,900 kg payload and 510 NM range.

As in the case of the kerosene version, the values keep decreasing with a rising cruise Mach number, but all values of the hydrogen version lie significantly above those of the kerosene version. The main reason for such large direct operating costs is the still much higher price for 'green' hydrogen than for kerosene (assumption: 3.75 US$/kg hydrogen). Future assessments will deliver results accounting for different scenarios for the developments of fuel and system prices.

Parameter	Unit	Original ATR 72 Full Freighter Version [20] [22]	PreSTo	PrADO Kerosene Version	PrADO Hydrogen Version
Payload	kg	8,093	8,093*	8,050*	6,900*
Range	NM km	520 960	520* 960	520* 960	510 950
Cruise Mach number	-	0.41	0.76	0.42	0.4
Optimum cruise altitude	m ft	7000 23000	11,750 38,600	8,000 26,000	8,000 26,000
Cruise speed	kt	248	440	250	240
Max. take-off mass	kg	22,000	23,250	23,150	21,250
Operating empty mass	kg	11,900	12,800	13,000	13,600
Wing area	m^2	61	61	61*	61*
Max. take-off wing loading	kg/m^2	361	384	380	348
Take-off thrust-to-weight ratio	-	(0.25 shp/kg)	0.305	0.385	0.385
Single engine thrust	kN lbf	(2,750 shp)	34.8 7,800	43.8 9,800	40.1 9,000

* Input Parameter

Table 3. Results of the preliminary sizing and PrADO-analysis of the ATR 72 jet version

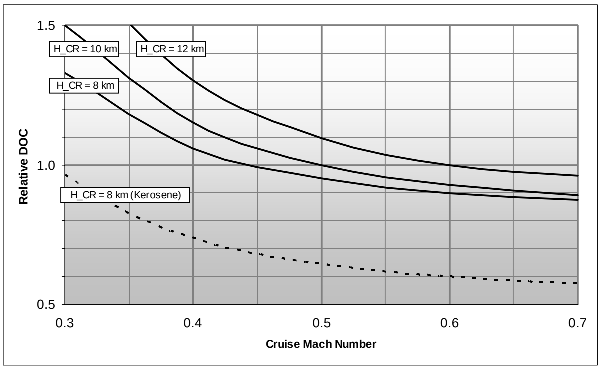

Fig. 13. Relative direct operating costs of the ATR 72 hydrogen version over cruise Mach number

3 Conclusions and Discussion

The Green Freighter project partners possess PrADO-models of a kerosene and a hydrogen version of the ATR 72 full freighter version, which form the basis for future improvements and extensions on the models themselves and on the analysis methods used. PreSTo delivers realistic results of a newly-designed kerosene-powered comparative jet aircraft.

The presented results are preliminary in value but show directions, effects and orders of magnitude for changes to the aircraft model.

For a conversion from kerosene to liquid hydrogen, a lot of cargo volume has to be sacrificed for internal tank volume if external tanks shall be avoided, and the direct operating costs of a 2008 scenario are significantly higher. This is especially due to the much higher price for 'green' hydrogen than for kerosene. In the future, however, with changing availability and prices for different fuels, the numbers are expected to change significantly and make the hydrogen version more favorable.

In case of the ATR 72 as the reference aircraft a 'minimum change solution' for the conversion from kerosene to hydrogen propulsion leads to an unfavorable compromise due to the ATR 72's thick airfoil and its unswept wings of high aspect ratio. Allowing for larger changes to the aircraft geometry – like wing sweep; see Figure 14 – is expected to show positive effects on the flight performance.

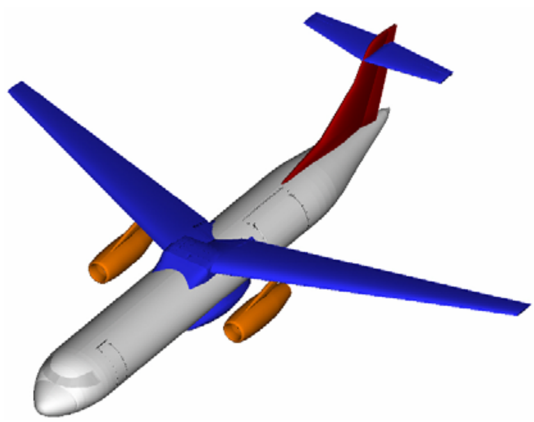

Fig. 14. PrADO-model of the ATR 72 hydrogen version including fairings and wing sweep

4 Future Steps

The most important future steps to be undertaken in the Green Freighter project are the adaptation of the ATR 72 model to the new jet propulsion system (e.g. wing sweep and fairings, see Figure 14), the preparation of a propeller engine module (see Figure 15), the investigation of a larger conventional reference freighter aircraft (Boeing B777F) and investigations of kerosene-, hydrogen- and hybrid-powered blended wing body freighter aircraft.

The DOC estimation and assessment method will be expanded and adapted to freighter aircraft. The main aspects are

- Freighter aircraft specific input data,
- Scenarios for the development of the prices for kerosene, hydrogen and other synthetic and biofuels,
- The influence of future emissions- and noise-related taxes and fees
- The influence of nighttime noise restrictions,
- The challenges and possible benefits of zero-pilot operation.

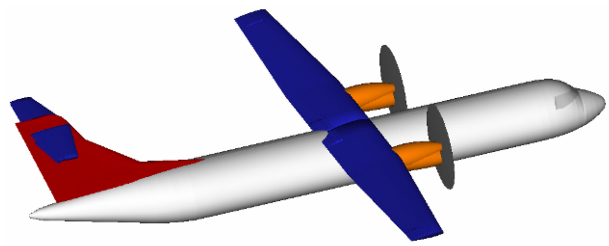

Fig. 15. PrADO-model of the ATR 72 including (geometry-) model of turboprop engines

5 Further Information

Further information on the Green Freighter project can be found under the following link:

- **http://GF.ProfScholz.de**

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