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Conceptual Design and Investigation of Hydrogen-Fueled Regional Freighter Aircraft

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Abstract

This thesis presents the conceptual design and comparison of five versions of regional freighter aircraft based on the ATR 72. The versions comprise four baseline designs differing in their propulsion systems (jet/turboprop) and the fuel they use (kerosene/hydrogen). The fifth version is an improved further development of the hydrogen-fueled turboprop aircraft. For aircraft modeling the aircraft design software PrADO is applied. The criteria for the overall assessment of the individual aircraft versions are energy use, climate impact in terms of global warming potential (GWP) and direct operating costs (DOC).

The results indicate that, from an aircraft design perspective, hydrogen is feasible as fuel for regional freighter aircraft and environmentally promising: The hydrogen versions consume less energy to perform a reference mission of 926 km (500 NM) with a payload of 8.1 t of cargo. The climate impact caused by the emissions of hydrogen-fueled regional freighter aircraft is less than 1 % of that of kerosene-fueled aircraft. Given the circumstance that sustainably produced hydrogen can be purchased at a price that is equivalent to kerosene with respect to energy content, hydrogen-fueled regional freighter aircraft are also economically competitive to current kerosene-fueled freighters. In consequence, regional freighters appear especially favorable as first demonstrators of hydrogen as aviation fuel, and cargo airlines and logistics companies may act as technology drivers for more sustainable air traffic.

The potential of regional freighter aircraft alone to mitigate climate change is marginal. The share of national and regional air cargo traffic in global manmade climate impact lies in the region of 0.016 % to 0.064 %, which also represents the maximum reduction potential.

The presented work was to a large extend performed during the joint research project "The Green Freighter" under the lead of Hamburg University of Applied Sciences (HAW Hamburg).

Acknowledgements

Large parts of the work presented in this thesis I carried out during my time as Research Associate at the Hamburg University of Applied Sciences (HAW Hamburg), Germany. During this time I very much benefited from the support of numerous persons whom I'd like to thank here.

I very much thank my supervisors Prof. Arthur Rizzi from KTH and Prof. Dieter Scholz from HAW Hamburg for their time and effort along the way. Working on one's personal studies involving two 'home'-universities from different countries as well as additional research partners from industry and academia is often very challenging and only possible with the necessary support. Moreover, I'd like to express my special gratitude to Dr. Wolfgang Heinze from the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technische Universität Braunschweig for his many advices and the numerous occasions he helped me especially with the application of PrADO. Thanks also to Prof. Petter Krus from Linköping University and Prof. Jesper Oppelstrup from KTH for acting as external and internal reviewers.

The results presented in this thesis couldn't have been achieved without the assistance of many students from HAW Hamburg and international partner universities who added valuable contributions. My thanks go to all of them. Furthermore, I very much thank my former colleagues from the Aircraft Design and Systems Group (Aero) at HAW Hamburg for the several discussions, hints and the pleasant working atmosphere.

My final and greatest thanks go to my wife Dörte for her constant support and the freedom she has been giving me to perform this work. Mnja

Contents

List of Figures

List of Tables

Nomenclature

C	Calculation position
	Coefficient
d	Diameter
DC	Step size
E	Warming effect
F	Calculation result
GWP	Global warming potential
h	Altitude
i	Trace gas i
j	Flight segment j
M	Mach number
	Search task
m	Mass
n	Number
P	Power
r	Radius
S	Area
T	Thrust
	Time horizon
V	Speed
V_∞	Flight speed

Greek

η	Efficiency

Indices

CORE	Core engine
CO2	Carbon dioxide
F	Fuel
GEAR	Gear
H2O	Water vapor
INSU	Insulation
L	Landing
MTO	Maximum take-off
NOx	Nitrogen oxides
O	Outer
OFF	Engine shutdown
ON	Engine start up
P	Propeller
PT	Power turbine
SHAFT	Shaft
STRUCT	Structure
TANK	Tank
TO	Take-off
TOTAL	Total

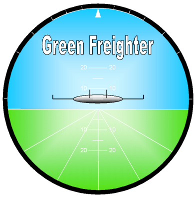
List of Abbreviations

ACARE	Advisory Council for Aeronautics Research in Europe
ACI	Airports Council International
ATAG	Air Transport Action Group
ATR	Avions de Transport Régional
BPB	Bundeszentrale für politische Bildung (German Federal Agency for Civic Education)
BtL	Bio to Liquid
BWB	Blended-Wing-Body
C	Carbon
CG	Center of Gravity
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CS	Certification Specifications
CtL	Coal to Liquid
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DMS	Data Management System
eq.	Equivalent
EU ETS	European Union Greenhouse Gas Emission Trading System
EU-27	European Union (27 Member States)
FAR	Federal Aviation Regulations
FT	Fischer-Tropsch
FTK	Freight Ton Kilometer
GDP	Gross Domestic Product
GE	General Electric
GEFF	Green Environmentally Friendly Freighter
GF	Green Freighter
GtL	Gas to Liquid
GWP	Global Warming Potential
HAW	University of Applied Sciences (German: Hochschule für Angewandte Wissenschaften)
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine

H_2	Hydrogen
H_2O	Water
IATA	International Air Transport Association
ICAS	International Council of the Aeronautical Sciences
IFL	Institute of Aircraft Design and Lightweight Structures (German: Institut für Flugzeugbau und Leichtbau)
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LH2	Liquid Hydrogen
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
NO_x	Nitrogen Oxides
O_2	Oxygen
O_3	Ozone
OEI	One Engine Inoperative
OPR	(Engine) Overall Pressure Ratio
PrADO	Preliminary Aircraft Design and Optimization program
PreSTo	Preliminary Sizing Tool
PT	Power Turbine
PWC	Pratt & Whitney Canada
RPK	Revenue Passenger Kilometer
SL	Sea Level
SOx	Sulfur Oxides
TET	Turbine Entry Temperature
TLARs	Top-Level Aircraft Requirements
TU	Technische Universität
UHC	Unburned Hydrocarbons
ULD	Unit Load Device

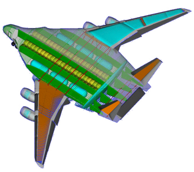
Terms and Definitions

The Green Freighter Project



Large parts of the work presented in this thesis have been performed within the scope of the aircraft design research project "The Green Freighter - Design Evaluation of Environmentally Friendly and Cost Effective Freighters with Unconventional Configuration". The Green Freighter (GF) project ran from December 2006 to April 2010. Its project partners were the Hamburg University of Applied Sciences (HAW Hamburg) acting as project leader, the Institute of Aircraft Design and Lightweight Structures (IFL) of the TU Braunschweig, Airbus Operations GmbH and the engineering office Bishop GmbH. The GF project marked the centerpiece of the Airbus research area "Green Environmentally Friendly Freighter" – GEFF. The aspects of the GF project were the investigation of hydrogen-fueled freighter aircraft using PrADO and the development and application of a quick preliminary sizing tool called PreSTo (Preliminary Sizing Tool). The investigated aircraft comprised conventional designs based on the ATR 72 regional aircraft as well as blended-wing-body (BWB) designs in comparison to the conventional Boeing B777 long-range freighter aircraft. More information on the GF project can be found in Seeckt and Scholz 2007, Seeckt and Scholz 2008 as well as on the GF project website Scholz 2010 that also offers several further publications in relation to the project.

PrADO



The Preliminary Aircraft Design and Optimization program PrADO is a multidisciplinary aircraft design program which has been developed by the Institute of Aircraft Design and Lightweight Structures (IFL) of the TU Braunschweig under the lead of Dr. Wolfgang Heinze. PrADO is a comprehensive aircraft design tool that covers all major aspects of aircraft design and analysis such as aircraft geometry, engine design, aerodynamics and performance, structure analysis, stability and control and direct operating costs among others. A brief description of the program is presented in Section 3.1 of this thesis.

Chapter 1

Introduction

1.1 Motivation

Aviation at the beginning of the 21st century faces great challenges. Two of these are the depleting crude oil resources and the contribution of air traffic to the worldwide climate change. In combination with continuously rising fuel prices and predictions of a large growth of air traffic over the next decades these challenges lead to the need to search for alternatives to today's aviation fuel kerosene. Among the possible alternative fuels there is hydrogen that features several promising properties. Its combustion produces only water vapor and small amounts of nitrogen oxides, it has a very high gravimetric energy density, and it is practically indefinitely available. On the other hand, hydrogen does not exist in pure state in nature but has to be separated from water or another feedstock first. Moreover, its storage is a lot more complicated than that of kerosene, and the current airport and aviation fuel infrastructures would have to be changed significantly if hydrogen should be introduced as aviation fuel. These issues have previously led to conceptual and even practical studies of hydrogen-fueled aircraft at different aircraft manufacturers and research institutions. Nevertheless, reviews of the available knowledge and data on hydrogen in civil air traffic have shown that it is still reasonable and necessary today to further investigate the application of hydrogen as fuel for civil transport aircraft.

For the coming decades, air cargo traffic is forecasted to grow even faster than passenger air traffic. This leads to a large need for new freighter aircraft and makes them an increasingly interesting market segment for the aircraft manufacturers in general. With respect to the practical examination and introduction of hydrogen as aviation fuel, in particular regional freighter aircraft lend themselves as first demonstrator aircraft. They are comparatively cheap in aircraft price, their typical turboprop propulsion systems are much more efficient than jets, and they offer a great flexibility for the integration of hydrogen tank and fuel systems. Throughout the mentioned previous studies on hydrogen-fueled transport aircraft, this favorable type of aircraft has not been investigated comprehensively.

1.2 Aim of the Work

The aim of this thesis is the investigation of hydrogen-fueled regional freighter aircraft regarding their energy consumption, climate impact and economic competitiveness to nowadays kerosene-fueled designs.

For a final assessment of the chances for hydrogen to become a future alternative to kerosene this thesis aims at answering the following questions:

- Is hydrogen generally feasible as fuel for regional freighter aircraft or does its large storage volume lead to incompatible aircraft designs?
- What are the benefits or disadvantages of operating hydrogen-fueled regional aircraft regarding energy use, climate impact and costs?
- What are the circumstances and future trends for air traffic in general, freighter aircraft operation and the implementation of alternative fuels?
- What are the necessary circumstances for the competitiveness or an advantage of hydrogen regarding costs?

For the answers to these questions the user is provided with the necessary background information on the situation today and the foreseeable future trends. Moreover, an aircraft conceptual design study is performed applying the comprehensive aircraft design program PrADO.

1.3 Thesis Structure

This thesis is split up into four main chapters treating the individual aspects of the conducted study.

Chapter 2 gives the most important background information on the current circumstances and future trends for air traffic, freighter aircraft operation and aviation fuels.

Chapter 3 describes the aircraft design program PrADO and contains the input data used for the reference aircraft and reference mission, fuel properties and for the estimation of costs and global warming potential.

Chapter 4 shows the conducted design and investigation of kerosene- and hydrogen-fueled regional freighter aircraft versions using PrADO. The designs are compared and assessed with respect to their individual energy use, relative climate impact in terms of global warming potential and direct operating costs.

Chapter 5 deals with the improvement of the hydrogen-fueled turboprop aircraft version and shows a final comparison of the turboprop aircraft versions with respect to energy use, global warming potential and direct operating costs.

1.4 Publications

The following list comprises the most important papers on individual aspects and preliminary results of the present study that have been prepared by the author of this thesis as the main author and have been published previously.

- Seeckt *et al.* 2008, "The Green Freighter Project - Objectives and First Results", introduces the aircraft design research project "The Green Freighter" and the results of the initial activities of the project partners. The paper was published on the ICAS-Congress in Anchorage, Alaska, USA in September 2008.

- Seeckt and Scholz 2009, "Jet Versus Prop, Hydrogen Versus Kerosene for a Regional Freighter Aircraft", presents the activities and intermediate results of the Green Freighter project partner HAW Hamburg on the investigation of hydrogen-fueled regional freighter aircraft. This paper was peer-reviewed and presented on the German Aerospace Congress in Aachen, Germany in September 2009.

- Seeckt *et al.* 2009, "Mitigating the Climate Impact of Aviation - What Does Hydrogen Hold in Prospect?" deals with the overall aspects of alternative aviation fuels and the current trends in aviation industry to mitigate its environmental impacts. The paper was peer-reviewed and published on the online climate conference "Klima 2009" in November 2009 and became a section of the book "The Economic, Social and Political Elements of Climate Change" (Leal Filho 2011) by Springer Verlag (publication in November 2010).

- Seeckt *et al.* 2010, "Hydrogen Powered Freighter Aircraft - The Final Results of the Green Freighter Project", comprises the overall results of all project partners of the Green Freighter research project. The paper was peer-reviewed and presented on the ICAS-Congress in Nice, France in September 2010.

1.5 Literature Survey

The following list of documents holds the most important references to input data and comparative aircraft design studies of transport aircraft that have been using during the course of this study.

- Brewer 1991, "Hydrogen Aircraft Technology", comprises the knowledge of the Lockheed Corporation on hydrogen aircraft technology gained during several hydrogen aircraft studies in cooperation with NASA during the 1970s. The studies comprise different aircraft design investigations reaching from conventional civil transport jets to military and supersonic designs. Despite the old age of the conducted studies the basic findings and conclusions are still valid and valuable today. It is shown that hydrogen as aviation fuel is feasible and competitive to kerosene propulsion under certain circumstances such as especially fuel price. Moreover, the design investigations show that external tank installations are clearly inferior to internal tanks even for short-range aircraft. Hydrogen system issues, such as insulation and tank structure materials and masses, are treated and system layouts are presented. These information have been used as example hydrogen systems and input data for the work on hydrogen tank mass estimation presented in Chapters 4 and 5 of this thesis.

- Böhm 2007, "Gesamtentwurf eines ökonomischen und ökologischen Lufttransportsystems unter Ausnutzung von Synergieeffekten" ("Overall design of an economic and ecologic air transport system using synergy effects"), is a doctoral thesis on an overall hydrogen aircraft design study at the German Universität der Bundeswehr München. The investigated hydrogen aircraft is a civil passenger transport jet of about Airbus A380 size. The document is helpful as a general introduction to the topic of hydrogen aircraft design, and especially the data given on hydrogen tank structure and insulation masses are valuable. They comprise concrete numbers on area-specific masses of hydrogen tanks and have been used during the work on hydrogen tank mass estimation presented in Chapters 4 and 5 of this thesis.

- Svensson 2005 "Potential of Reducing the Environmental Impact of Civil Subsonic Aviation by Using Liquid Hydrogen", is a doctoral thesis at Cranfield University. It concentrates on the aspects of cruise flight altitude of civil transport jets with respect to climate change and the impacts on engine design of hydrogen-fueled aircraft. Especially the concrete numbers on the Global Warming Potential (GWP) of the aircraft emissions carbon dioxide, water vapor and nitrogen oxides with respect to altitude represent valuable information for the assessment of the climate impact of different hydrogen and kerosene aircraft designs. They are used as input data for GWP quantification of the individual aircraft versions in Chapters 4 and 5 of this thesis.

Chapter 2

Background

This section contains background information on the current circumstances and future trends for air traffic, freighter aircraft operation and aviation fuels. Furthermore, the reference aircraft and mission for the design investigations presented in Chapter 4 are introduced.

2.1 The Economic Meaning of Air Traffic

Air traffic is of great importance for today's global and nearly all national societies and economies around the world. Not only the airlines and aviation sectors profit from the availability of a cheap, safe and fast mode of transport but also those branches that rely on a dense global network. Air traffic enables the fast and safe transport of time-sensitive and high-value wares as well as business and holiday trips. In consequence, one economy branch that is especially closely related to air traffic is tourism.

ATAG (Air Transport Action Group), a global coalition of organizations and business companies from all over the air transport sector, gives the following data on the meaning of air transport to worldwide employment in 2006 (ATAG 2009):

- Worldwide, 32 million jobs are created by the air transport industry.
- 17 % of these jobs are directly linked to air transport at e.g. airlines, airports, aircraft manufacturers.
- 20 % are indirect jobs through purchases of goods and services at e.g. logistics companies.
- 9 % are induced jobs through the spending of air transport industry employees.
- Remarkable 54 % or 17 million jobs worldwide are created through air transport's catalytic impact on tourism.

In total, ATAG states that air transport's direct, indirect, induced and catalytic impact on the global Gross Domestic Product (GDP) was 7.5 % in 2006 (ATAG 2009). In Europe (EU-27), the 3,500 enterprises of the air transport sector employed 400,000 persons and directly contributed 110 billion Euro or nearly 10 % to the overall economic turnaround in 2005 (Huggins 2009). These numbers illustrate the large meaning of aviation in general to the global and European societies and economies already today. For the future, the annual amount of air traffic and its global importance is forecasted to even further increase (see Section 2.3). For more information on the general meaning of aviation to society and economy and a discussion of future trends see (Seeckt *et al.* 2009).

2.2 Air Cargo

Air transport is the fastest, safest and most reliable means of transport. Therefore, it is especially used for high-value, time-sensitive and perishable wares for which short transportation durations are crucial or at least mark a significant economic benefit. In consequence, about 40 % of the global international transport with respect to value is carried out by air transport, although its fraction with respect to mass is less than 1 % (BPB 2009). Examples of typical air cargo are

- Time-sensitive wares such as
  - Air mail
  - Express freight that was guaranteed to be delivered 'just-in-time'
  - High-value where fast transport means only short capital lockup
  - High-tech of fashion products that need to enter the market quickly and prior to competitive products
  - Perishable or living cargo such as fresh fruits, flowers or animals
  - Important technical spare parts and supplies to prevent or stop production delays
  - Media (newspapers, music, etc.)
  - Medicine and blood
- Safety-sensitive wares such as
  - Artwork
  - Hazardous materials that may not be transported via road

Large cargo airlines are e.g. Korean Air, Lufthansa Cargo, Cathay Pacific and Cargolux. In addition to the classical cargo airlines logistics companies that integrate the whole cargo chain from sender to addressee, such as FedEx, DHL, UPS or TNT, are of large importance for global air cargo transport. These companies transport especially express freight with a guaranteed delivery time - usually during the office hours of the addressee.

Regarding regional air cargo, in 2003, 25 billion FTK (Freight Ton Kilometer) were transported intra-nationally and eight billion FTK within nations of one region (e.g. Europe, North America, etc.). These values together correspond to a share of 24 % of the total air cargo volume of 140 billion FTK (BPB 2009, see Figure 2.1) and mark the market niche of interest for the aircraft investigated in this study. The biggest national air cargo markets are the USA followed by Asia. Europe's share in national and regional air transport was 1.3 billion FTK or less than 1 % of the global air cargo transport.

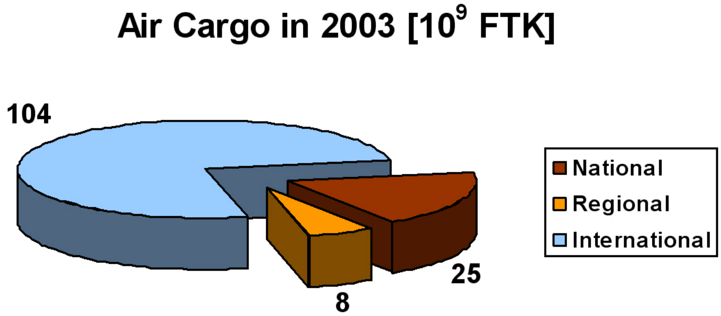


Figure 2.1: World Annual Air Cargo Traffic in 2003

Air cargo is very much focused on a small number of airports and airlines. According to ACI (Airports Council International), 56 % of the worldwide air cargo traffic in 2008 concentrated on the 30 largest cargo airports (BPB 2009). With special respect to intra-national air cargo transport, only ten airlines carried out about 75 % of the total traffic. FedEx and UPS alone held a share 56 % of the total intra-national air cargo transport (BPB 2009).

Air cargo is often transported in containers - so-called Unit Load Devices (ULDs) The most often used one is the LD3 container; its dimensions are shown in Figure 2.2. This container type is also used during the aircraft design investigations presented in Chapters 4 and 5.

2.3 Air Traffic Forecast

Since the very beginning of powered flight air traffic and the overall aviation industry have shown significant growth. In 2008, world annual air traffic reached more than 4.5 trillion airline RPK (Revenue Passenger Kilometer), which is a 38 % increase to 1998, and more than 150 billion FTK (Airbus 2009). Furthermore, despite the significant downturn in 2009 due to the world financial crisis, the aircraft manufacturers expect the general growth trend over the past decades to

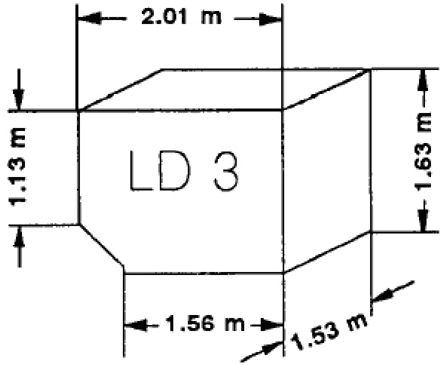


Figure 2.2: LD3 Container Dimensions (Scholz 2005)

continue. Embraer states in its "Embraer Market Outlook 2009-2028" that "Air Travel Demand Will Grow Despite Current Economic Crisis" (Embraer 2009).

For the next twenty years, the annual growth rates are forecasted as 4.7 % for passenger transport and 5.2 % for cargo transport by Airbus (Airbus 2009, see Figures 2.3 and 2.4). Boeing predicts 4.9 % for airline passenger traffic and 5.4 % for cargo traffic (Boeing 2009). Such growth rates roughly mean that air traffic doubles in 15 years and air freight traffic even triples in 20 years.

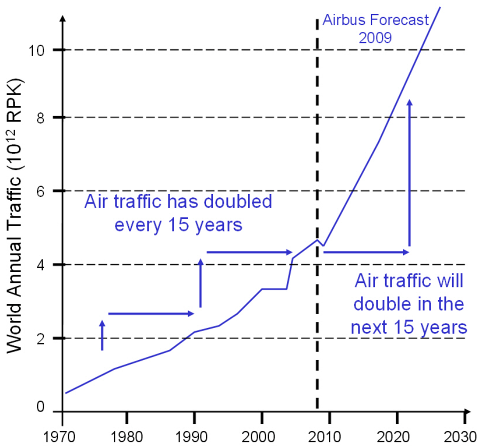


Figure 2.3: World Annual Air Traffic Development and Forecast (based on Airbus 2009)

These growth rates intensify the issues of fuel and energy demand of air traffic and, consequently, its dependency on oil exporting countries. In the light of the

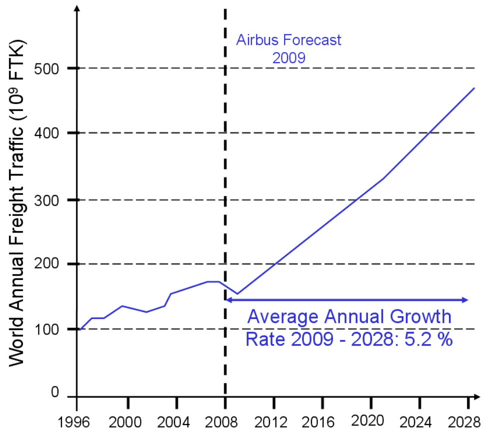


Figure 2.4: World Annual Air Cargo Traffic Development and Forecast (based on Airbus 2009)

worldwide depletion of crude oil resources such growth rates mean that "...in the foreseeable future, crude oil will no longer be able to accommodate demand. Therefore, ...it is already necessary today to search for alternatives to crude oil" (Rempel *et al.* 2007). Section 2.5 deals with the aspect of aviation fuels and alternatives to conventional kerosene in more detail.

2.4 Freighter Aircraft

"Today, freighters carry an estimated 60 % of the world's revenue cargo" (Crabtree *et al.* 2008); the rest is transported in the cargo compartments of normal passenger aircraft. Typical freighter aircraft are former passenger aircraft that were decommissioned and converted into freighter aircraft. Such a conversion includes

- The removal of no longer used passenger related equipment such as cabin monuments,
- The installation of a largo cargo door, usually located at the left side of the forward fuselage section,
- The installation of a cargo loading system,
- The enforcement of the main deck floor structure and
- The installation of additional systems required for cargo transport such as a new fire protection system.

Airbus "...assumes that freighter aircraft on average are operated until they reach the age of 35, whether being new or converted. Small freighters are typically retired after 37 years of operation, while ...aircraft converted to freighters are converted at around 20 years of age meaning that they are operated as freighters for about 15 years." (Airbus 2009). Such older and cheaper aircraft are used as freighter aircraft as the low aircraft price reduces capital lockup, depreciation costs, insurance costs and, in consequence, the total direct operating costs (DOC). The relatively higher fuel costs of such older aircraft are of minor importance to the operators as freighter aircraft are very often used for only two flights per 24 hours within the cargo airline's 'hub-and-spoke' network (see Figure 2.5): one flight from the home airport to a cargo hub and one flight back. In consequence, freighter aircraft are very often operated during the night hours in order to enable delivery of express freight during the office hours and to avoid hard-fought landing and take-off slots at the cargo hub airports during daytime. However, actual developments intensify the pressure on cargo airlines and logistics companies to operate more modern aircraft that are quieter and more fuel efficient. These developments are:

- Rising fuel prices,
- Introduction and tightening of noise abatement regulations and nighttime flight restrictions at an increasing number of airports and
- Further developments such as the inclusion of air traffic in the 'Greenhouse Gas Emission Trading System' of the European Union (EU ETS) (see Section 2.6).

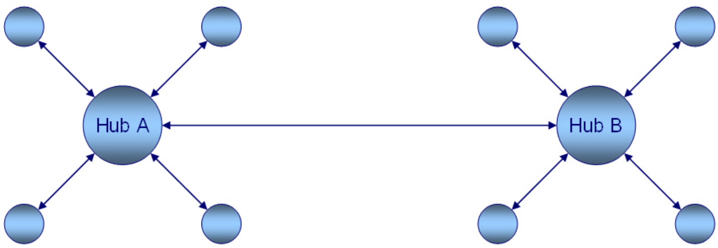


Figure 2.5: Hub-and-Spoke Network

As a consequence of the worldwide growth of air cargo, the global freighter aircraft fleet is expected to double over the next two decades (Crabtree *et al.* 2008). Airbus expects 22 % of the fleet growth to be satisfied with new factory-build freighter aircraft (Airbus 2006). This makes freighter aircraft an increasingly interesting market segment in general, and besides the converted former passenger aircraft there are already new-built freighter aircraft of different sizes available on the market. Examples are the regional turboprop freighter 'ATR 72 Full Freighter

Version' (see Section 3.2) and the large long range Boeing 'B777 Freighter'. Further models are about to soon enter the market such as the Airbus 'A330 200F' or the Boeing 'B747-8 Freighter'. Regional freighter aircraft such as the ATR 72 are operated as so-called 'feeder' aircraft between the smaller and more remote secondary airports and the main cargo hubs, while the larger models such as the B777 Freighter connect the main cargo hubs. Typical flight distances of regional freighters are less than 1,000 km.

With respect to the examination and introduction of hydrogen as aviation fuel particularly regional freighter aircraft lend themselves as first demonstrator aircraft. They are comparatively cheap in aircraft price, and furthermore, freighter aircraft are operated from a significantly smaller number of airports than passenger aircraft. Therefore, in case of a demonstration phase or the introduction of hydrogen the number of affected airports that need to extend or change their infrastructure is significantly smaller.

2.5 Aviation Fuels and Emissions

The direct implications on the environment that go along with the operation of aircraft are engine emissions and noise. Both these issues have always been important technology drivers in civil aircraft design, and "The last 40 years have seen aviation fuel burn and emissions reduced by 70% and noise by 75% ..." (Airbus 2009). The study presented in this thesis concentrates on the aspect of engine emissions.

Kerosene, Synfuel, Biofuel

Nowadays transport aircraft use kerosene as fuel, which is produced from crude oil. Kerosene is not only one particular product but available in different grades, of which the most important one is called 'Jet A-1'. Its most important characteristic is a gravimetric energy density of at least 42.8 MJ/kg. Detailed information on Jet A-1 in comparison to hydrogen is given in Table 2.1.

Figure 2.6 shows the composition of an aircraft engine's exhaust gas that burns kerosene. The main and unavoidable combustion products that are produced during the combustion of kerosene or any other hydrocarbon and air are carbon dioxide (CO_2) and water vapor (H_2O). Moreover, due to the content of sulfur in kerosene sulfur oxides (SO_x) are formed. In addition, further by-products occur that stem from an imperfect combustion. These are nitrogen oxides (NO_x), carbon monoxide (CO), Soot (C_{Soot}) and unburned fuel (Unburned Hydrocarbons, UHC).

The combustion of 1 kg of kerosene uses 3.4 kg of aerial oxygen and produces

- 3.15 kg of carbon dioxide,
- 1.25 kg of water vapor and
- About 0.8 g to 1 g of sulfur oxides (Grewe 2007, Antoine 2004)

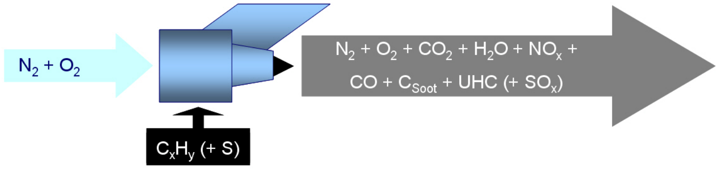


Figure 2.6: Combustion Products of Conventional and Synthetic Kerosene

plus the following reaction by-product whose amount vary highly with engine technology (Grewe 2007):

- Nitrogen oxides: about 14 g,
- Carbon monoxide: about 3.7 g,
- UHC: about 1.3 g,
- Soot: about 0.04 g.

The individual combustion products have the following environmental implications:

- Carbon Dioxide (CO_2) is a natural trace component of the atmosphere of about 0.4 %. "The effect of CO_2 on climate change is direct and depends simply on its atmospheric concentration. CO_2 molecules absorb outgoing infrared radiation emitted by the Earth's surface and lower atmosphere. The observed 25-30% increase in atmospheric CO_2 concentrations over the past 200 years has caused a warming of the troposphere and a cooling of the stratosphere." (Penner *et al.* 1999). Carbon dioxide accumulates in the atmosphere and stays climate-active for several decades or even centuries.

- Water (H_2O): "Water vapor and clouds have large radiative effects on climate and directly influence tropospheric chemistry." (Penner *et al.* 1999). Emissions of water vapor into the higher troposphere and the stratosphere cause the formation of contrails and cirrus clouds under certain conditions which are estimated to have a large impact on climate change.

- Nitrogen Oxides (NO_x) have contradictory indirect influences on climate change. They support the formation of ozone (O_3) in the atmosphere which means an influence of warming, and they enforce the destruction of methane (CH_4) which causes cooling. These effects are highly complex and differ with altitude. Concerning local air quality, nitrogen oxides cause acid rain and are harmful to health. Nitrogen oxides form at high temperatures through the chemical reaction of the natural air components nitrogen and oxygen. High combustion temperatures and long combustion durations support the formation of nitrogen oxides.

- Carbon Monoxide (CO) is a highly toxic gas.
- Sulfur Oxides (SO_x) have different complex implications on the atmospheric chemistry. They tend to support cloud formation which leads to an effect of climate warming. Sulfur oxides (mainly sulfur dioxide (SO_2)) are toxic gases and support the formation of acid rain.
- Soot (C_{Soot}): Soot particles act as condensation nuclei for contrails and cloud formation and have a warming climate impact. Soot is harmful to health and may cause cancer.
- Unburned Hydrocarbons (UHC) are harmful to health and the environment.

Kerosene cannot only be derived from crude oil but also be synthetically produced from various other feedstocks. Such synthetic fuels (Synfuels) mitigate the dependency on crude oil as sole feedstock for kerosene. On the political level, this consequently also mitigates the dependency on oil exporting countries. Moreover, such synthetic fuels could be used with the current aircraft technology, engines and airport infrastructure. That is why these fuels are called 'drop-in' replacements of kerosene.

For the production of Synfuels the so-called Fischer-Tropsch (FT) process is applied among others. In this process the feedstock is gasified and split up into its carbon and hydrogen components ('Syngas'). From the Syngas the carbon and hydrogen molecules can be reassembled in various ways and as various fuels. Possible feedstocks for the production of Synfuels, also referred to as FT fuels, are coal (Coal to Liquid, CtL), natural gas (Gas to Liquid, GtL) but also biological feedstocks such as plants or algae (Bio to Liquid, BtL or Biofuel). The synthetic production of fuel also allows for the composition of Synfuels or Biofuels that are free from sulfur and would consequently not produce sulfur oxides during combustion. However, all of the other described combustion products of kerosene do also occur when using Synfuel and even Biofuel in an aircraft engine.

Any fuel produced from fossil feedstocks increases the amount of carbon dioxide in the atmosphere. Though synthetic fuels from other feedstocks than crude oil could reduce the dependency of air traffic on crude oil-exporting countries only biological feedstocks have the chance of being (nearly) sustainable drop-in replacements of kerosene. Only they provide a carbon source where the emitted carbon dioxide has previously been subtracted from the atmosphere by the feedstock plants or algae (see Figure 2.7). In fact, synthetic fuels derived from fossil feedstocks such as coal or natural gas may even have several times higher climate impacts than conventional crude oil-based kerosene (see Figure 2.10).

Hydrogen

Kerosene is not the only fuel that can be used to run a turbo-machine such as an aircraft jet or turboprop engine. In fact, the first German jet engine, the Heinkel

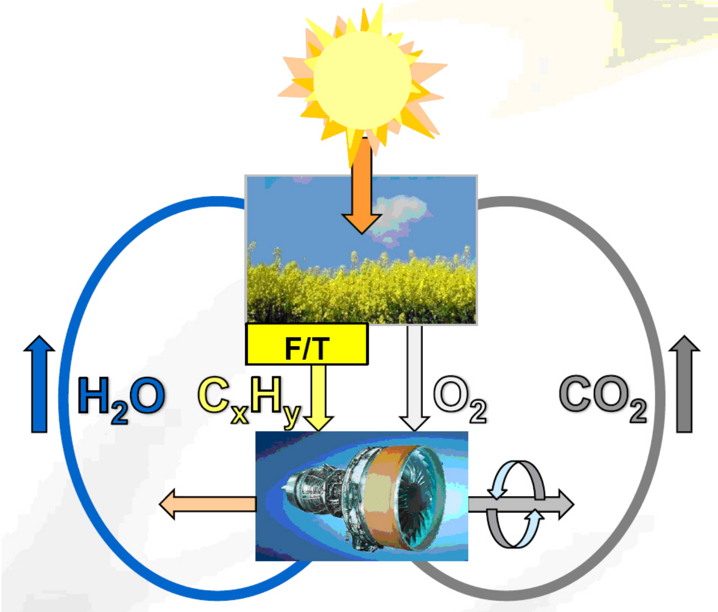


Figure 2.7: Atmospheric Cycles of Hydrogen and Carbon (With Permission of Bauhaus Luftfahrt, Sizmann 2009)

HeS 1 used hydrogen as fuel. Hydrogen is advantageous to kerosene in different aspects:

- Hydrogen has an about three-time higher gravimetric energy density than kerosene of 122.8 MJ/kg (see Table 2.1 and Figure 2.9). Consequently, the mass of a certain amount of energy stored as hydrogen would be only about a third of what it would be if stored as kerosene. This reduces an aircraft's fuel mass fraction (m_F/m_{MTO}), and leads to less energy consumption and noise.
- The combustion of hydrogen produces only water vapor and small amounts of nitrogen oxides (see Figure 2.8).
  - Hydrogen could be used as heat sink for hot engine parts such as turbine blades. This could (especially in jet engines)
  - Reduce bleed-air extraction from the compressor and improve compressor efficiency,
  - Improve the flow inside the turbine as no cooling air is emitted into the stream,
  - Return heat to the combustion process (fuel pre-heating) and

  – Allow for higher turbine entry temperatures (TET) and overall pressure ratios (OPR) (Brewer 1991).

- Hydrogen is practically unlimitedly available; its usage would reduce the political dependency of air traffic on oil exporting countries.

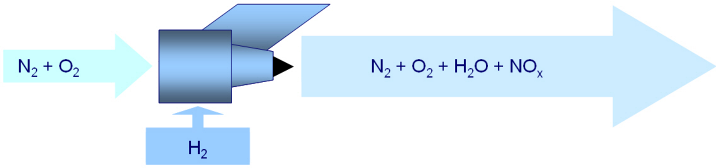


Figure 2.8: Combustion Products of Hydrogen

The combustion of 1 kg of hydrogen uses 8 kg of aerial oxygen and produces 9 kg of water vapor and (highly dependant on engine technology) about 4.3 g of nitrogen oxides (Brewer 1991). Modern combustion chamber designs that use so-called pre-mixing of hydrogen and air even show up to 90 % smaller amounts of nitrogen oxides production (Funke 2009).

Opposite to the mentioned advantages of hydrogen to kerosene hydrogen features several negative characteristics that complicate its handling and have prevented it from being used as aviation fuel:

- Hydrogen is not a fuel in the definition as an energy source (such as crude oil-based kerosene) but an energy carrier rather comparable to a battery. Hydrogen does not exist in pure state in nature put has to be separated first. This can e.g. be done by means of electrolysis, which means that water is split up into its hydrogen and oxygen molecules using electricity. Other modes of production are the separation of hydrogen from natural gas or coal.

- Hydrogen has an extremely low volumetric energy density. Even in liquid state at cryogenic temperatures (liquid hydrogen, LH_2) this value is only 8.7 MJ/dm^3 or only about a quarter of that of kerosene (see Table 2.1 and Figure 2.9). In consequence, the storage of a certain amount of energy in the form of hydrogen requires about four times the volume that would be necessary in case of kerosene. Such large tanks and their snowball effects such as additional structure increase a hydrogen aircraft's empty mass significantly. In gaseous state the required hydrogen tank volume becomes even several times larger depending on tank pressure. Consequently, gaseous hydrogen is regarded as not feasible for transport aircraft designs requiring large amounts of energy.

- To be available in liquid state at ambient pressure hydrogen has to be kept a below 253 °C (20 K), see Table 2.1. This poses high requirements regarding the thermal insulation of a tank and fuel system, which further increases a hydrogen aircraft's empty mass significantly.

- Hydrogen tank and system materials "... must be resistant to hydrogen embrittlement, impermeable (or capable of being sealed) to gaseous hydrogen, and, ... retain satisfactory ductility and fracture resistance at cryogenic temperatures." (Brewer 1991).
- Although hydrogen has been used as fuel in space programs for decades, its use in aircraft poses new requirements regarding long-time strength. "... the system must be designed so that it is capable of withstanding the shocks and stresses of thousands of landings and associated flight loads, and so it will retain its thermodynamic effectiveness through 15- to 20-year useful life of an airplane. During that useful life, it must be accessible for routine inspection, maintenance and/or replacement." (Brewer 1991).

Table 2.1 and Figure 2.9 show a comparison of the main characteristics of kerosene (Jet A-1) and hydrogen.

Table 2.1: Hydrogen and Jet A-1 Main Characteristics (LTH 2008, ExxonMobil Aviation 2008)

Characteristic	Unit	Hydrogen	Jet A-1	Hydrogen/Jet A-1
Density	kg/m^3	70.8 *	775 – 840 **	0.084 – 0.091
Volumetric energy density	MJ/dm^3	8.7 *	33.2 – 36	0.24 – 0.26
Gravimetric energy density	MJ/kg	122.8	Min. 42.8	Max. 2.87
Freezing point	°C	-259	-47.0	x
Boiling point	°C	-253	171 – 267	x
Total sulfur content	-	0 %	Max. 0.3 %	x

* In liquid state
** At 15 °C

Hydrogen, if produced from renewable energy and electrolysis of water, has the chance of being nearly climate neutral and could avoid the mentioned further pollutants that go along with the combustion of hydrocarbons. Here, the total 'well-to-wake' chain including the production process is of importance. "More than ninety percent of hydrogen produced today is generated by reforming natural gas, methane, 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

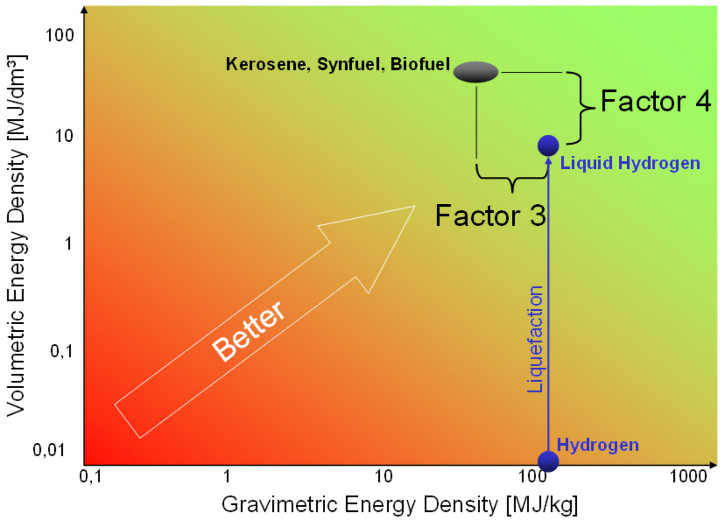


Figure 2.9: Energy Densities of Kerosene and Hydrogen

another and generates carbon dioxide, a greenhouse gas." (Hemighaus *et al.* 2006). Consequently, the climate impact of hydrogen may even be several times larger than that of conventional kerosene (see Figure 2.10).

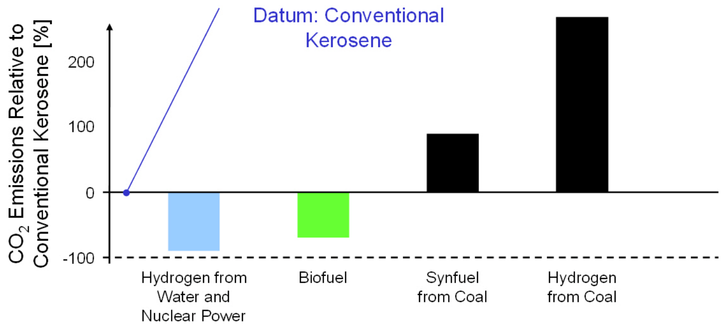


Figure 2.10: Relative CO2 Emissions of Different Fuels (based on IATA 2008)

Regarding safety, previous analyses have shown that the usage of hydrogen is at least as safe as that of kerosene (Brewer 1991). "Safe handling of hydrogen is no longer a problem in the industrial and commercial area." (LTH 1994). Nevertheless, hydrogen is highly inflammable over a wide range of mixing ratios with air, and leakages may easily lead to fires or explosions. However, in the event of a fire, hydrogen does not form a burning carpet such as kerosene but burns and rises away quickly. Moreover, the thermal radiation of a hydrogen flame is significantly less intense as that of a kerosene flame (LTH 1994). Thus, the exposure of an aircraft structure and the people on board is much shorter and less severe than in case of kerosene. Another source of danger to people is hydrogen's storage at cryogenic temperatures. A leakage and contact to skin causes severe injuries.

Over the past decades hydrogen has repeatedly caused interest as an alternative to kerosene as aviation fuel. The most important studies in the direction of using hydrogen as fuel for civil transport aircraft were:

- NASA and Lockheed: In the 1970s, Lockheed performed studies on different liquid hydrogen (LH_2)-fueled subsonic cargo and passenger transport jets for NASA Langley Research Center. The results are presented in the NASA-reports NASA CR-132558 (Brewer *et al.* 1975b), NASA CR-132559 (Brewer *et al.* 1975a) and NASA CR-144935 (Brewer and Morris 1976). The main conclusions from these and furthers studies have been summarized by the main author Daniel G. Brewer in his book "Hydrogen Aircraft Technology" in 1991 (Brewer 1991). The studies showed that hydrogen propulsion is especially beneficial in terms of energy use for long range aircraft with internal hydrogen tanks. "The more energy required to perform the mission, the greater the advantage to be gained by using a high energy fuel The long range LH2 aircraft of this study are lighter; require smaller wing area and shorter span but larger, longer fuselages; use smaller engines; can operate from shorter runways; and use 25 % less energy to perform the mission. Further, the LH_2 airplane would cost less both to develop and to produce." (Brewer and Morris 1976). Figure 2.11 shows an example of one investigated aircraft design (long range LH_2 aircraft).

- Tupolev: In the 1980s Tupolev developed the Tu-155 (see Figure 2.12) that was based on the medium range transport aircraft TU-154B. Moreover, the TU-155 "...was built and successfully tested without any serious incidents." (PSC Tupolev 2010). It first flew burning hydrogen in one of its three engines in April 1988. The modified engine was also able to be run with natural gas. The TU-155 was followed by the TU-156 that could be run with natural gas or kerosene.

- Cryoplane: The Cryoplane Project comprised 36 European research partners from industry, universities and research institutions and ran from 2000 to 2002. During this project several conventional and unconventional overall aircraft design studies (see e.g. Figure 2.13) and detailed investigations of hydrogen fuel systems and components were performed. The investigations showed that there is a "Practical configuration available for all categories of airliners" (Westenberger 2003). However, the obtained results were partially contradictory to previous studies such as those of Lockheed and NASA in the 1970s. For example, the "Specific energy consumption increased by 8–15%"

for all investigated aircraft designs due to "more wetted area, higher mean flight weight" (Westenberger 2003).

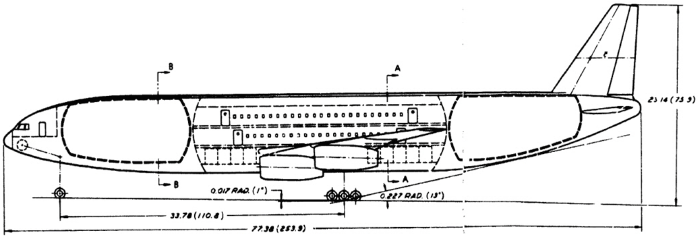


Figure 2.11: Long Range Hydrogen-Fueled Passenger Aircraft (Brewer and Morris 1976)

Figure 2.12: Tupolev TU-155 (PSC Tupolev 2010)

2.6 Current Emission Reduction and Climate Change Mitigation Activities

The global climate is warming, and, according to the International Panel on Climate Change's (IPCC) special report "Aviation and the Global Atmosphere" (Penner *et al.* 1999), there is very high confidence that human activities have been contributing to that. As part of the man made emissions of CO_2 and other greenhouse gases air traffic adds to the anthropogenic impact on climate change. Airbus states in its Global Market Forecast from 2009 that air travel contributes 2 % to man made CO_2 emissions (Airbus S.A.S. 2009). The German Aerospace Center DLR names a 2.2 %

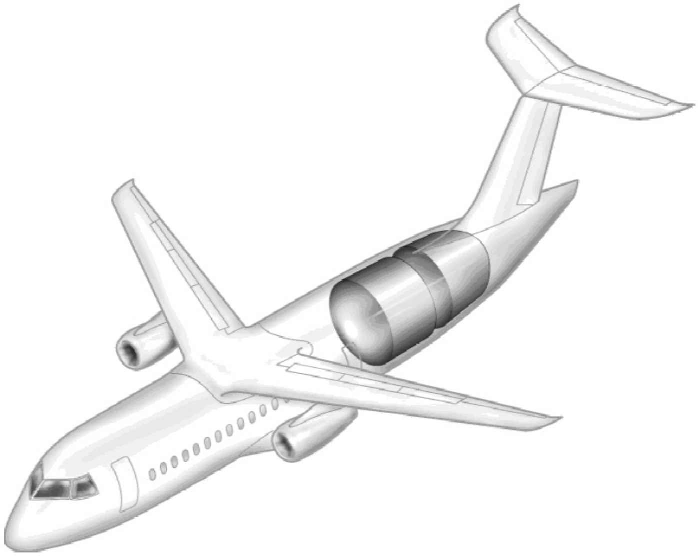


Figure 2.13: Cryoplane Small Regional Aircraft Design (Westenberger 2003)

share of air traffic in its publication "Klimawirkungen des Luftverkehrs" (Climate Impacts of Air Traffic) from 2007 (Bührke and Meyer 2007). Moreover, due to the high altitude at which aircraft emit carbon dioxide, nitrogen oxides etc. the overall share of air traffic to climate change, expressed as so-called radiative forcing, is expected to be even higher. "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 climate change approximately in proportion to their contribution to radiative forcing." (Penner *et al.* 1999). In the more recent mentioned DLR publication a fraction of 3 % is estimated, where the (difficult to quantify) impact of cirrus clouds is not included. "Within the range of known uncertainties the share of air traffic to radiative forcing may be between two and eight percent." (Bührke and Meyer 2007). Furthermore, it is very likely that air traffic's share in man made climate change is growing due to the increasing amount of air traffic and the successful reduction efforts of other economic sectors such as e.g. energy suppliers (Penner *et al.* 1999).

The growing public awareness of climate change and an increasing general environmental consciousness are changing the public perception of air traffic. Two examples are the statement of the bishop of London, Richard Chartres, in 2006 that "making selfish choices such as flying on holiday ... [is] a symptom of sin" (Leake 2006) and that of the German NGO (Non-Governmental Organization) Germanwatch in 2003 that "flying is - relative to expenditure of time - the most climate-damaging legal activity a person can perform during peacetime"

(Treber *et al.* 2003). Climate change and especially the mentioned critical public perception of air traffic have led to several activities and agendas of airlines, logistics companies, airports, research organizations and politics to deal with and mitigate the environmental of air traffic. Three of the most important European approaches are introduced in the following:

- Airlines and logistics companies offer their customers to compensate for the climate impact of the purchased service. For that purpose these companies collaborate with enterprises and NGOs such as 'The CarbonNeutral Company' (e.g. SAS) or 'myclimate' (e.g. Lufthansa) or offer own services. The logistics company DHL, for example, offers a 'climate-neutral parcel' called 'GoGreen'. All these activities have in common that the customers may choose to pays an extra amount of money that is invested in climate protection programs and that the direct climate impact of the purchased service is compensated this way. However, the calculation methods of the various enterprises and NGOs differ and partly only include the carbon dioxide emissions. Consequently, these climate protection activities are facing not only support but also criticism (see e.g. spiegelonline 2010).

- In January 2001, ACARE (Advisory Council for Aeronautics Research in Europe) comprising 'personalities' from "the Member States, the [European] Commission and stakeholders, including manufacturing industry, airlines, airports, service providers, regulators, the research establishments and academia" (ACARE 2010) formulated the Strategic Research Agenda 'European Aeronautics: A Vision for 2020' - usually referred to as 'Vision 2020'. In this agenda ACARE defines the most important goals and research activities for "Meeting society's needs and winning global leadership" (ACARE 2001). Besides the goals regarding safety, operations and others the following main goals on the environmental impact of aircraft are given to be reached by 2020:

  – Reduction of noise by 50 %,
  – Reduction of CO_2 emissions by 50 %,
  – Reduction of NO_x emissions by 80 %.

- In July 2008, the European Parliament decided to include air traffic into the European Union Greenhouse Gas Emission Trading System (EU ETS) from 2012 on. This means that each aircraft operator has to possess the necessary amount of CO_2 emissions certificates for each flight departing or landing on a European airport. In the first year, 79 % of all air traffic emission certificates are allocated to the airlines for free based on the average emissions between 2004 and 2006, another 15 % are sold at auction and 3 % of the emission certificates are kept as reserve for e.g. new airlines. The missing 3 % mark the anticipated reduction of carbon dioxide emissions in air traffic. In the following years the amount of free certificates will be reduced so that airlines are forced to buy more emission certificates. At the time of writing this thesis there are still many uncertainties of e.g. how airlines have to organize and file the required data, how the revenues will be used by the individual states and how new and fast growing airlines such as low-cost airlines will be treated. In total, it is important to notice that this inclusion of air traffic into the EU ETS does not aim at a reduction of air traffic CO_2 emissions in the named orders of magnitude. In fact it is planned to make airlines buy emission certificates at the stock exchange and that the CO_2 emissions are reduced in other branches of economy where reductions are easier and cheaper to realize (Waltering 2010).

Chapter 3

Input Data

This section introduces the aircraft design program PrADO and gives information on the input data used for fuel properties, hydrogen fuel systems, direct operating costs and global warming potential used in for the aircraft design investigations presented in the following sections.

3.1 PrADO

PrADO is a multidisciplinary aircraft design program which has been developed by the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig. It is split up into several design modules that cover all major disciplines of the aircraft design process. 15 database files include independent and dependant data on the actual aircraft design, and a data management system (DMS) performs the data exchange between the design modules and the database files. Independent data are given by the user and include e.g.

- The definition of reference missions in terms of payload and range,
- A widely parametric description of the aircraft design to be investigated (cabin layout, wing aspect ratio, wing area, etc.) and
- Design constraints such as the desired take-off and landing distances.

Dependant data result from the calculations performed by the particular design modules such as

- Fuselage geometry,
- Wing geometry,
- Horizontal and vertical tail geometry,

- Engine geometry,
- Engine performance charts,
- Aerodynamics,
- Aircraft performance data,
- Structure analysis including mass and center of gravity (CG) prediction,
- Stability and control,
- Flight simulation,
- Direct operating costs (DOC),
- etc.

PrADO offers three modes of operation. These are

1. Single point design analysis,
2. Parameter variation and
3. Optimization.

A single point design analysis starts with the initial user input and iteratively executes the sequence of design modules until convergence of the independent design variables is reached. A parameter variation performs an automatic variation of user-selected independent parameters, meaning that for each set of variables a complete single point design analysis is performed. This allows for the illustration of the complete available design space and possible solutions. In the optimization mode the user may apply one of three optimization algorithms to search for optimum results of one selected target variable such take-off mass or DOC by modifying selected free parameters. A detailed description of PrADO is given in Heinze *et al.* 2001. Figure 3.1 shows the general structure and workflow of PrADO. More information on the application of the program and collections of input data and results follow in the next sections.

The geometric aircraft models inside PrADO include all main aircraft components such as fuselage, wing, tails, etc., and all these components are also included as single items in the aircraft mass models and CG determinations. Figure 3.2 shows a principle geometric model of all aircraft versions modeled in PrADO within the scope of this thesis.

At the beginning of the GF project it was not possible to model all relevant types of engines and aircraft missions that were to be investigated throughout the project. Thus, new PrADO modules had to be set up by the IFL with partly assistance of HAW Hamburg. The most important novelties that were first employed during the GF project and are of relevance for this thesis are

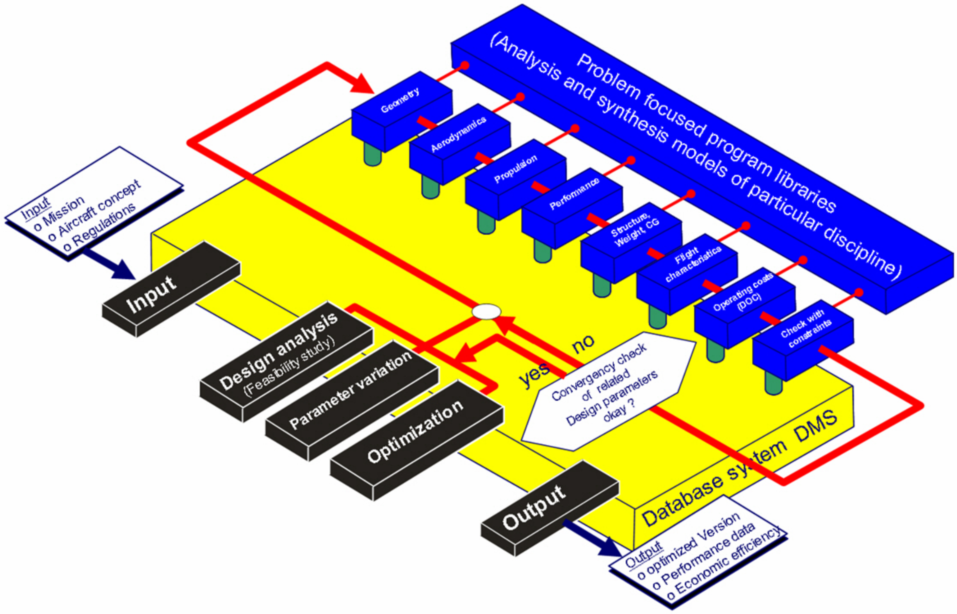


Figure 3.1: PrADO Structure

- The 3D-description of liquid hydrogen tanks including aircraft CG travel due to fuel consumption,
- A module for the investigation of turboprop engine designs,
- The enhancement of the thermodynamic engine model including the combustion characteristics of hydrogen.

3.2 Reference Aircraft and Top-Level Aircraft Requirements

The reference aircraft for the studies presented in the following was selected to be the ATR 72 as full freighter version (see Chapters 4 and 5). It was selected as it marks a typical and successful representative regional aircraft that is not only available as passenger version but also as a dedicated freighter. Moreover, the amount of qualified data on the ATR 72 which is crucial for re-design investigations is comparatively good.

The ATR 72 is a stretched version of the ATR 42. It is built in T-tail configuration and driven by two Pratt & Whitney PW 127F turboprop engines with four- or six-blade propellers dependant on the aircraft version. It features a double-trapezoid wing in high-wing configuration with constant-chord inner and

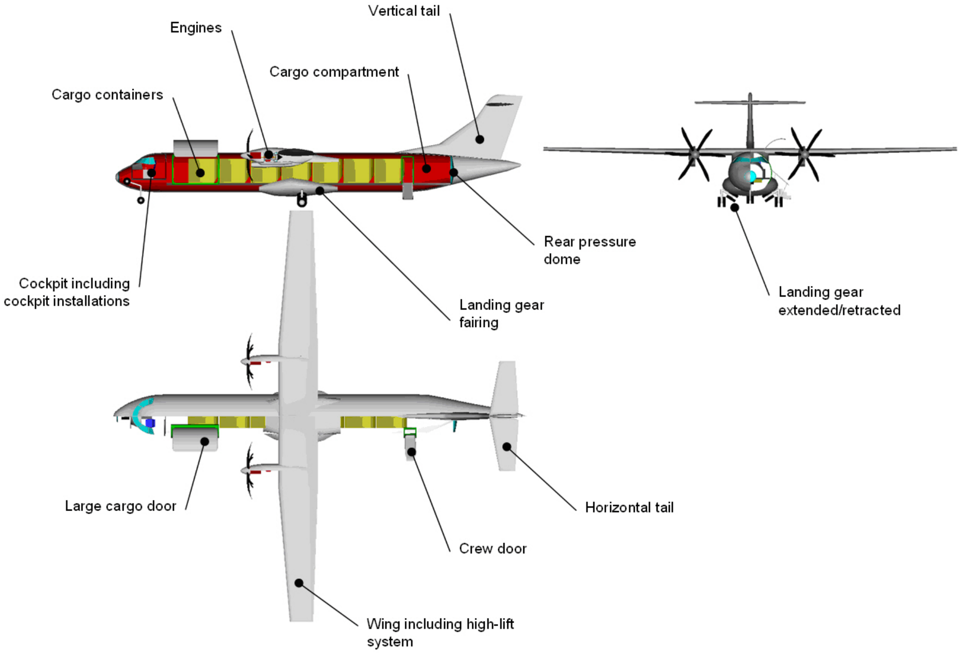


Figure 3.2: Principle PrADO Aircraft Geometry Model

tapered outer sections. As high-lift devices double-slotted flaps are used. Most of the secondary structure is manufactured from composite materials, summing up to 19 % of the overall structural mass (ATR 2005). The aircraft's technical key characteristics are summarized in Table 3.1.

Table 3.2 shows the characteristic payload-range data of the ATR 72 full freighter version. The en-route assumptions used for these data are: ISA-conditions, no wind and reserves for 45 min continued cruise and 87 NM (161 km) to alternate airport. As reference mission for the following design investigations the same mission was selected as the one jointly selected by the project partners for the GF project. This is the mission 'Range at Maximum Payload': 8.1 t of payload over 500 NM (926 km) range.

The following top-level aircraft requirements (TLARs) posed to the following aircraft versions result from the reference aircraft ATR 72 (see Table 3.3).

3.3 Fuel Properties

The fuel properties used for the thermodynamic engine models are collected in Table 3.4. The thermodynamic properties of kerosene vary partly with fuel standard, and/or only minimum values of the gravimetric energy density are

Table 3.1: ATR 72 Key Characteristics (Jackson 2008, ATR 2003)

Characteristic	Unit	Value
Length	m	27.2
Wing span	m	27.1
Wing area	m^2	61
Wing aspect ratio	-	12
Engine take-off power	kW	2,051
Maximum ULD capacity	-	7 LD3 containers
Total cargo volume	m^3	75.5
Operating empty mass	t	11.9
Maximum payload	t	8.1
Maximum zero-fuel mass	t	20
Maximum take-off mass	t	22
Maximum landing mass	t	21.4
Take-off field length	m	1,290 *
Landing field length	m	1,067 *
Cruise speed	kt	248 **
Cruise Mach number	-	0.41 **

* ISA, SL
** In 23,000 ft (7 km)

Table 3.2: ATR 72 Characteristic Missions (ATR 2003)

Mission	Payload	Range
Range at maximum payload	8.1 t	500 NM (926 km)
Range at maximum fuel	5.1 t	1,830 NM (3,390 km)
Ferry range	0 t	2,150 NM (3,980 km)

Table 3.3: Top-Level Aircraft Requirements

TLAR	Unit	Value
Payload	t	8.1
Range (at max. payload)	km (NM)	926 (500)
Container capacity	-	7 LD containers
Cargo Volume	m^3	75

required. Therefore, the presented values were selected in cooperation with the GF project partner IFL in order to use the same fuel properties in all aircraft models.

Table 3.4: Kerosene and Hydrogen Fuel Properties Used for PrADO Engine Models (Partly from Bräunling 2009)

Property	Unit	Kerosene	Hydrogen
Gravimetric energy density	kJ/kg	43,147	119,880
Density	kg/m^3	785	71 *
Specific heat capacity: Air	J/kg/K	1004.13	1004.13
Specific heat capacity: Exhaust gas	J/kg/K	1238.26 **	1287.93 ***
Adiabatic exponent: Air	-	1.4002	1.4002
Adiabatic exponent: Exhaust gas	-	1.301 **	1.3005 ***

* In liquid state
** Fuel-to-air ratio: 0.012 at 1,500 K
*** Fuel-to-air ratio: 0.006 at 1,500 K

The wider ignition spectrum and faster speed of combustion of hydrogen were incorporated into the models of the hydrogen-fueled engines in terms of a higher reaction efficiency inside the combustion chamber of 0.95 instead of 0.925 as in case of kerosene as fuel. This change has decreases slightly the size and mass of the combustion chamber.

The information found in literature regarding turbine entry temperature of hydrogen-fueled engines are contradictory. While some sources tend towards lower combustion temperatures of hydrogen engines (e.g. Svensson 2005) other sources (e.g. Brewer 1991) state that due to the low radiative heat of a hydrogen flame and the high combustion velocity higher combustion temperatures could be implemented without problems regarding e.g. high temperature strength of engine components or the increased formation of nitrogen oxides. In consequence to these differing statements, the turbine entry temperatures during the GF project were decided by the GF project partners to be kept the same as those of kerosene-fueled ones. The exact values for temperatures inside the original reference engines were given by the propulsion system department of the Airbus FPO and come under a non-disclosure agreement.

3.4 Hydrogen Fuel Systems

A hydrogen fuel system consists of the same principle components as a conventional kerosene fuel system. These are tanks, pipes, pumps and valves. However, in difference to kerosene as fuel the extremely low density and temperature of liquid hydrogen as well as possible losses due to hydrogen boil-off require some significant differences, such as

- Very large hydrogen tanks,
- Heat insulation of the hydrogen tanks and pipes,
- Hydrogen boil-off and quick release lines,
- Heat exchangers for pre-heating and controlled gasification of the hydrogen prior to entry into the engines, and
- Specially designed components which are capable to operate under the given thermal conditions and inside liquid or gaseous hydrogen.

The student project Batal 2010 that was conducted in cooperation with the GF project partner Bishop GmbH deals with the layout of a hydrogen fuel system of a hydrogen-fueled aircraft based on the ATR 72. Figure 3.3 shows a principle layout of the fuel system of the investigated hydrogen-fueled ATR 72 of that project (preliminary version RF20-HP that is not treated in particular in this thesis).

The figure shows two large hydrogen tanks in the forward and rear part of the fuselage. Each tank contains three centrifugal pumps that transport the hydrogen from the tanks to the engines. In addition, jet pumps are installed inside the tanks that keep up a minimum fuel level inside the centrifugal pumps compartments. Engine feed lines (violet) transport the hydrogen to the engines, and return lines (light blue) transport excessive hydrogen that is currently not used by the engines back to the hydrogen tanks. A safety line enables supplying each engine by an individual tank which is required by the aircraft certification regulations CS-25 and FAR Part 25 during take-off. One refueling line (brown) connects the refueling coupling with the hydrogen tanks for refueling on ground. Finally, both hydrogen tanks are connected to a hydrogen boil-off and quick release line (green) that leads to a fire-protected hydrogen outlet at the top of the fin. Shut-off valves before and aft of the propeller burst area protect the hydrogen lines to/from the forward tank from leakage in case of disruption due to propeller blade burst. Heat exchangers and boost pumps are located on each engine for pre-heating, gasification and pressure increase of the hydrogen prior to entry into the combustion chamber. A detailed layout of a hydrogen fuel system offers enough technical aspects for several own studies and lies without the scope of this conceptual aircraft design study. Nevertheless, for this thesis adequate estimations of the sizes of the hydrogen tanks and the overall fuel system mass as well as the investigation of fuel tank integration into the aircraft are necessary.

The fuels system components are modeled individually inside PrADO. Instead, their masses are estimated according to literature data (Brewer 1991, LTH 2008) and added to the overall mass and CG models of the respective aircraft versions as increases of the area-specific masses of the hydrogen tanks. Changes in fuel

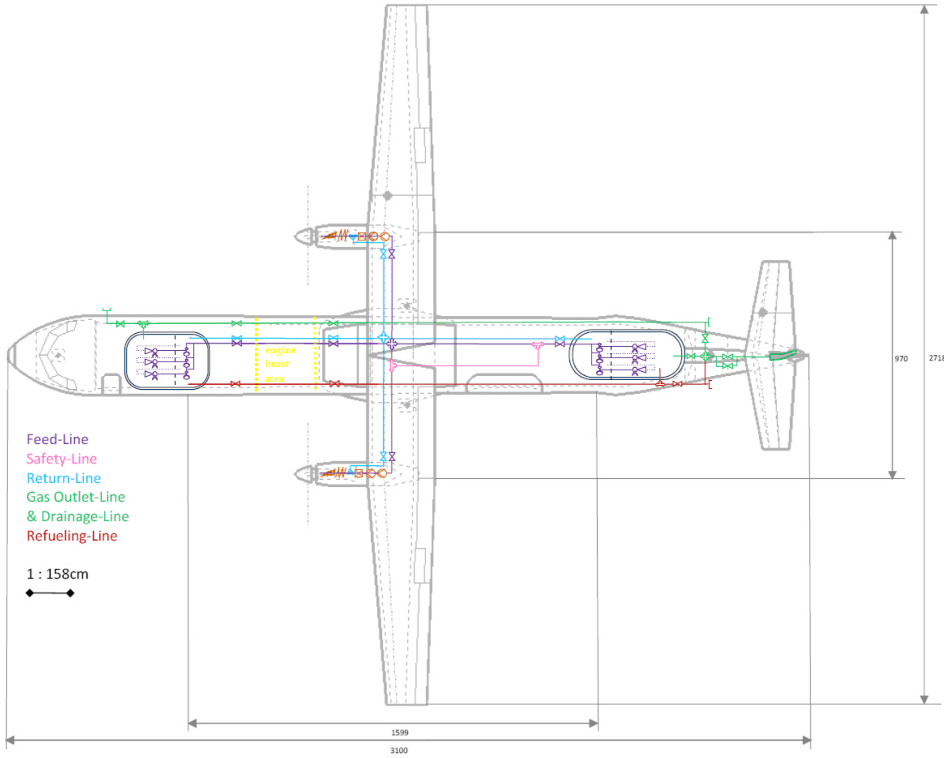


Figure 3.3: Hydrogen Fuel System Layout (Preliminary Version RF20-HP Shown, Batal 2010)

mass and CG travel due to sinking hydrogen levels in the hydrogen tanks, however, are accounted for inside the PrADO mass and CG models for the individual flight phases (see Figure 3.4). Moreover, the hydrogen tanks including their thermal insulation are modeled individually. Figure 3.5 shows the installation of the forward hydrogen tank on the port side of the fuselage. It can be seen that this installation still allows for a connection between the entrance area and the cargo compartment alongside the hydrogen tank compartment.

The masses of the hydrogen tanks including their insulation have been estimated according to the German Aerospace Handbook LTH (LTH 2008), and based on this source a new PrADO module was created within the scope of a student project at HAW Hamburg that incorporates the given method (Bazydlo 2010). The information concerning hydrogen tank masses used in LTH 2008 are based on the work by Böhm 2007 and were prepared by the same author. Remark: At the time of writing this thesis, this document still has 'draft version' status, thus, the

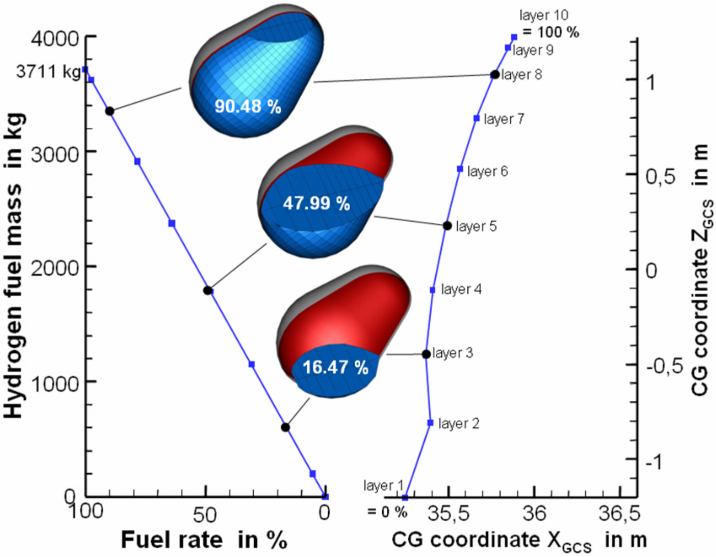


Figure 3.4: PrADO Fuel Mass and Center of Gravity Model (Heinze *et al.* 2008)

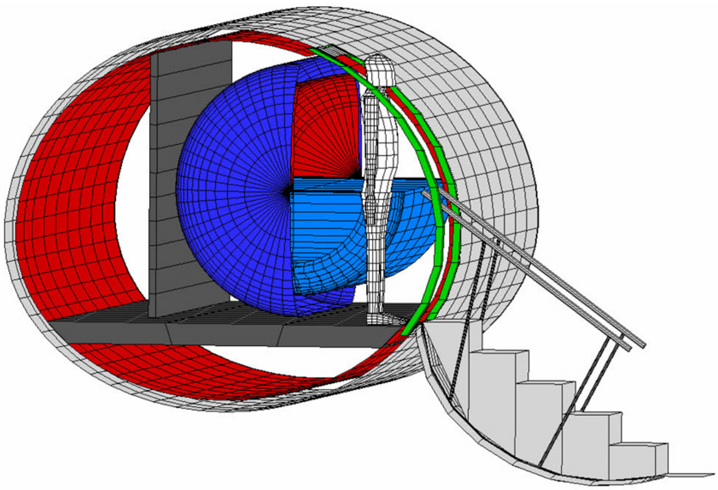


Figure 3.5: Forward Hydrogen Tank Integration (Preliminary Version RF20-HP Shown)

information given are of preliminary character. The information on the structural design of hydrogen tanks are available for the aluminum alloys 2219 and 2024 and hemispherical and volume-optimized so-called vessel dished ends (see Figure 3.6). For mass estimation of the structural and insulation mass graphs are given than depict the relative masses with respect to area or volume for different tank diameters and flight altitudes. The insulation mass is calculated for polyurethane foam in thickness of 5 cm to 30 cm. Moreover, typical masses of feed and boost pumps and heat exchangers are collected.

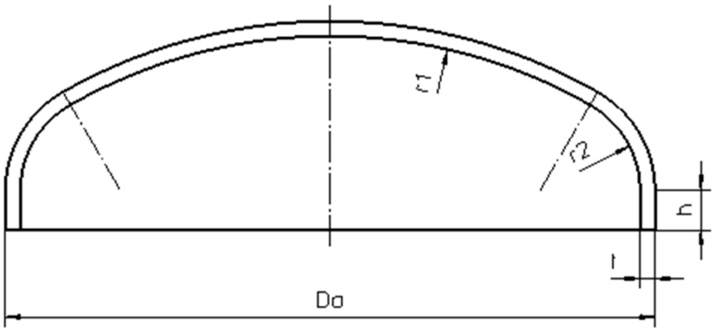


Figure 3.6: Vessel Dished End (wikipedia 2010)

In Figure 3.6 the radii r_1 and r_2 are defined as

$$r_1 = d_O \tag{3.1}$$

and

$$r_2 = 0.1 \cdot d_O \tag{3.2}$$

In order to be able to use the given information in LTH 2008 and Brewer 1991 polyurethane foam was selected as insulation material with an insulation thickness of 15 cm. These selections lead to typical area-specific masses of the tank structure and insulation for a hydrogen tank of about 2 m diameter of

$$\frac{m_{STRUCT}}{S_{TANK}} = 3 \text{ kg/m}^2 \tag{3.3}$$

and

$$\frac{m_{INSU}}{S_{TANK}} = 5 \text{ kg/m}^2 \tag{3.4}$$

In the given charts it is presumed that the tank caps are shaped as hemisphere and that the length of the cylindrical part is the same as the inner tank diameter, which is not the case for the hydrogen tanks used in the following aircraft versions. For this reason and as the system components pipes, pumps and valves also have to be included in the hydrogen tank mass (as these components are not calculated automatically by PrADO) the determined values of area-specific tank mass are increased in the respective aircraft models. The resulting hydrogen tank and system masses are given in the respective sections for each hydrogen aircraft version.

3.5 DOC Input Parameters

For a comparison of the direct operating costs of the different aircraft versions the economic circumstances at the time of operation of the aircraft are of great importance. In this context, especially the prices of the different fuels and energy in general are crucial. In scenarios working with high prices for energy an aircraft optimization leads to a result that is optimized for low fuel and energy consumption which means an aerodynamically optimum design that is relatively heavy. In these cases the higher aircraft price (which is calculated as proportional to aircraft mass) and the higher depreciation costs etc. are of minor importance. In scenarios with cheap fuel prices (which is the case for kerosene today) a low aircraft price and low depreciation costs etc. are of greater importance. Thus, an optimization with respect to minimum DOC leads to a design optimized for minimum mass as the comparatively higher fuel costs are of less importance.

For DOC estimation an IFL in-house method is applied that is based on a method developed by Lufthansa (Heinze 2004). The input data used for DOC estimation are based on Heinze 2004, IATA 2009 and Airbus 2009; they are collected in Table 3.5. These data represent cost levels of aircraft components, kerosene and labor costs of 2008.

The price for hydrogen is estimated as energy-equivalent in order to enable an unprejudiced fuel comparison and leads to a price for 1 kg of hydrogen that is three-times the price of 1 kg of kerosene. For a wider applicability of the operating costs are calculated without the influences of local politics in terms of e.g. emission-specific taxes, so that no extra penalty functions for carbon dioxide emission are added to the established DOC method.

With respect to the investigation of regional freighter aircraft some standard input values usually used for DOC estimation of civil transport passenger jets are changed according to Airbus 2009 (see Section 2.4). These changes are

- 1000 hours of aircraft availability per year,
- 35 years of aircraft operation before decommissioning and
- 0 % residual value at the time of decommissioning.

3.6 Global Warming Potential

The assessment of the environmental impact of the individual aircraft versions of this thesis concentrates on their climate impacts in terms of their global warming

Table 3.5: DOC-Calculation Input Values (Heinze 2004, IATA 2009, Airbus 2009)

Parameter	Unit	Value/Selection
Number of flight crews per aircraft	-	6
Number of years in operation	a	35
Annual aircraft availability	h/a	800
Specific components costs: Airframe and systems	€/kg	757
Specific components costs: Jet engines	€/N	24
Specific components costs: Turboprops	€/kW	700
Spare parts costs	-	15 % of aircraft price
Annual insurance costs	-	1 % of aircraft price
Interest rate	-	8 %
Residual value	-	0 % of aircraft price
Fuel price: Kerosene	€/kg	0.5
Fuel price: Hydrogen	€/kg	1.5
Crew costs *	€/flight h	31
Maintenance costs: Airframe and systems	€/flight h	256
Maintenance costs: Engines	€/flight h	102 (per engine)
Landing fees	€/t **	8.7
Ground handling fees	€/t cargo	41

* Costs for each pilot of all crews
** Maximum take-off mass

potential (GWP). "The global warming potential of a trace gas is the ratio of global warming through emission of one kilogram of the gas to the global warming through emission of one kilogram of CO_2

$$GWP_i(T) = \frac{E_i(T)}{E_{CO_2}(T)} \tag{3.5}$$

where T is the time horizon and E_i is the warming effect of the trace gas, i . . . Generally, the GWP varies with the time horizon chosen." (Svensson 2005). Moreover, the average climate effects of the individual trace gases vary with season and the geographic latitude of the atmospheric model. The typical time horizon and atmospheric model selected for GWP assessments are 100 years in summer atmosphere in mid-latitudes (30° to 60° North). The usually incorporated trace gases are carbon dioxide, water vapor and nitrogen oxides. These general selections have also been adopted for the work presented in this thesis. Table 3.6 collects the input data for the quantification of the relative climate impacts of carbon dioxide, water vapor and nitrogen oxides with respect to altitude.

Table 3.6: Global Warming Potentials of Carbon Dioxide, Water Vapor and Nitrogen Oxides over Altitude (Svensson 2005)

Altitude (km)	$E_{CO_2}(100\ a)$	$E_{H_2O}(100\ a)$	$E_{NO_x}(100\ a)$
0	1	0	-7.1
1	1	0	-7.1
2	1	0	-7.1
3	1	0	-4.3
4	1	0	-1.5
5	1	0	6.5
6	1	0	14.5
7	1	0	37.5
8	1	0	60.5
9	1	0	64.7
10	1	0.24	68.9
11	1	0.34	57.7
12	1	0.43	46.5
13	1	0.53	25.6
14	1	0.62	4.6
15	1	0.72	0.6

It can be seen that the climate impact of CO_2 emissions are treated as independent from altitude, and that water vapor is negligible in altitudes of up to 9 km. Above 9 km the effect of water vapor rises with altitude but stays smaller than that of carbon dioxide. In case of nitrogen oxides emissions the numbers for altitudes of up to 4 km are even negative. Thus, nitrogen oxides emissions in these altitudes are anticipated to have an indirect effect of atmospheric cooling through the destruction of methane. However, this must not be misunderstood as any kind of positive atmospheric effect!

Using such warming effects of different trace gases over altitude allows for the calculation of each aircraft version's total GWP as the sum of all integrated effects from engine start up (ON) to shutdown (OFF) of all trace gases i:

$$GWP = \sum_{i=1}^{n} \int_{ON}^{OFF} \dot{m}_i \cdot E_i(h(t))dt \tag{3.6}$$

In this equation, $\dot{m}_i$ is the individual emission mass flow of each trace gas i and $E_i(h(t))$ is the actual global warming effect of that trace gas at the actual altitude $h(t)$. For the application of the GWP to available PrADO results Equation 3.6 is simplified to

$$GWP = \sum_{i=1}^{3} \sum_{j=TO}^{L} m_{ij} \cdot E_i(h) \tag{3.7}$$

where the individual effects of the three trace gases carbon dioxide, water vapor and nitrogen oxides are calculated as the sum of all flight segments j from take-off (TO) to landing (L). In doing so, the trace gas emissions per flight segment m_{ij} are estimated as proportional to the fuel consumed per flight segment. This estimation is only partly correct. As stated earlier, the emissions of carbon dioxide and water vapor are directly proportional to fuel consumption. However, the amounts of nitrogen oxides emitted into the atmosphere vary highly with engine technology and power setting. In this thesis, the average values of 14 g of nitrogen oxides emissions per kg kerosene (Grewe 2007) and 4.3 g per kg hydrogen (Brewer 1991) are used. This number of nitrogen oxides emissions during the combustion of hydrogen is rather conservative; more recent terrestrial test engines with modern combustion chambers and mixing units (pre-mixing) of hydrogen and air prior to entry into combustion chamber have shown reductions of NO_x-formation of more than 90 % (Funke 2009) compared to kerosene.

Chapter 4

Conceptual Design and Investigation

This section presents the conceptual design and investigation of hydrogen-fueled regional freighter aircraft in comparison to kerosene-fueled designs using the aircraft design software PrADO. The investigated aircraft designs are based on the ATR 72 and comprise turboprop as well as jet aircraft. Parts of the work presented in this section as well as preliminary results have been published previously in Seeckt and Scholz 2009 and Seeckt *et al.* 2010.

4.1 Aircraft Versions Overview

In the course of the GF project several aircraft versions were set up based on the real ATR 72. The version names start with the letters "RF" which stand for "Regional Freighter". It follows a number indicating their evolutionary position and an index for the type of fuel and propulsion system used: "K" for kerosene, "H" for hydrogen, "P" for Propeller and "J" for jet. Moreover, the names of some hydrogen versions end with a further three letter code indicating their characteristic design feature. The versions that are treated in this thesis are listed in the following.

- RF00-KP (Reference version based on the real ATR 72)
- RF10-KJ (Kerosene version with jet propulsion)
- RF23-HP-STR (Hydrogen version with propeller propulsion and stretched fuselage)
- RF25-HJ (Hydrogen version with jet propulsion)
- RF4075 (Hydrogen version with full 75 m^3 cargo compartment volume)

One design requirement throughout the setup of the presented aircraft versions was that all hydrogen- and kerosene-fueled aircraft designs should be so-called 'minimum change solutions'. This means that as much of the original aircraft' components, structure and systems should be used for the new designs in order to minimize the effort and consequently price for the tentative hydrogen versions. Following this philosophy, the first hydrogen aircraft version featured the same fuselage as the reference version RF00-KP. In consequence, the required fuel storage volume had to be subtracted from the available cargo compartment volume so that this design violated the ULD capacity requirement of seven LD3 containers. Therefore, the fuselages of the following hydrogen versions were stretched. A fuselage stretch generates additional internal space for hydrogen tanks and cargo capacity and allows for using the same fuselage cross section. This measure led to the fuselages of versions RF-23-HP-STR and RF25HJ. Version RF4075 is a further development of version RF23-HP-STR that became necessary as, although RF23-HP-STR fulfilled the ULD capacity requirement, the aircraft could not offer the same overall cargo volume of the original ATR 72 of 75 m^3. Therefore, in version RF4075 the fuselage is stretched by another 10 cm and the hydrogen tanks are shaped and installed differently over the full fuselage cross section. The versions RF10-KJ and RF25-HJ are the comparative jet versions to versions RF00-KP and RF23-HP-STR. Except for the propulsion system they feature the same design properties such as the fuselage length. The aircraft as well as their order of evolution are shown in Figure 4.1.

4.2 Engine Models

Within PrADO the aircraft engines are modeled according to the calculated thrust required to perform the given reference mission and to fulfill the certification requirements with respect to minimum climb angle after take-off and after a missed approach. The engines are sized based on the thermodynamic properties of air and the respective fuel as well as parametric geometric descriptions and efficiencies of the engine components. In consequence, not only operational data such as the specific fuel consumption are the results of an engine design sequence but also overall engine parameters such as the number of compressor and turbine stages, the sizes and masses of the engine components intake, compressor(s), combustion chamber, turbine(s) and nozzle.

The jet and turboprop engine models used during the aircraft design investigations of this thesis are based on existing reference engines. Therefore, in a first step these reference engines were re-modeled as 'fixed' kerosene engine models. This means that they were not up- or downsized according to the thrust requirements of the actual design but kept constant throughout a design sequence with the reference engines' original thrust. Afterwards, they could be used as 'rubber' engines, thus modified in size according to the determined thrust requirements and for kerosene as well as hydrogen as fuel.

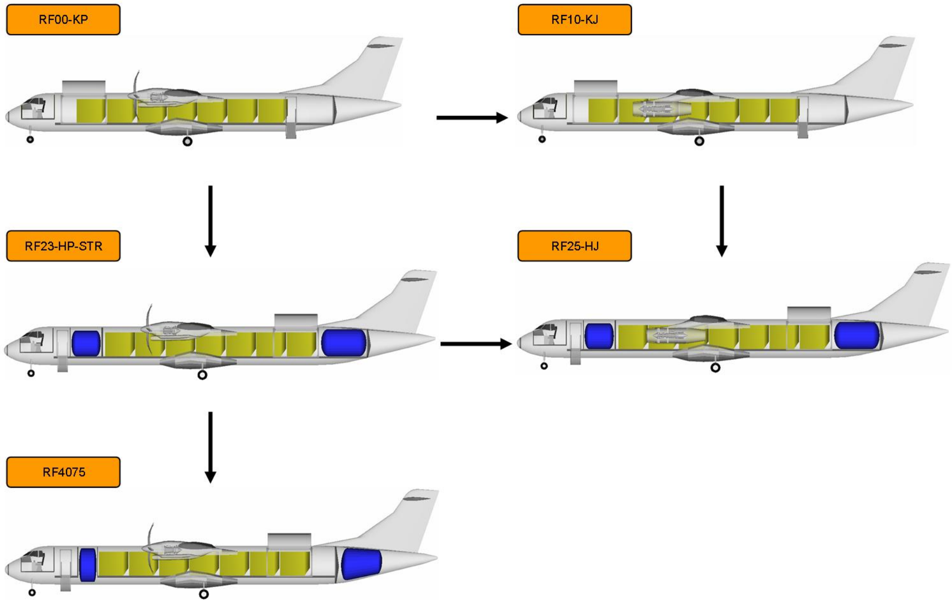


Figure 4.1: Aircraft Versions Overview

Jet Engine

The jet engine model used within the scope of the GF project and this thesis is closely geared to the General Electric CF-34 turbofan engine family. The engine model including its components is shown in Figure 4.2. The original engine parameters of the CF34-3B1 as well as the calculated PrADO results are collected in Table 4.1. The average variations from the original engine data lie within a region of -4.5 % to + 1 %. Most importantly, the relevant data for fuel consumption and mass show variations of only -0.9 % and -3.7 %.

Turboprop Engine

Inside PrADO, the newly developed module for turboprop engine investigation is based on the design module for two-shaft jet engines. This requires that inside PrADO the engine thrust is the sizing parameter and not the engine shaft power, which is the characteristic parameter of a real turboprop engine. Moreover, typical turboprop engine components such as radial compressors and reverse-flow combustion chambers cannot be modeled inside PrADO yet. Also, the propeller unit and the reduction gear are not included in the engine dimensioning. The properties of these components such as their dimensions, masses and efficiencies stay unchanged as the data given in a propeller template file.

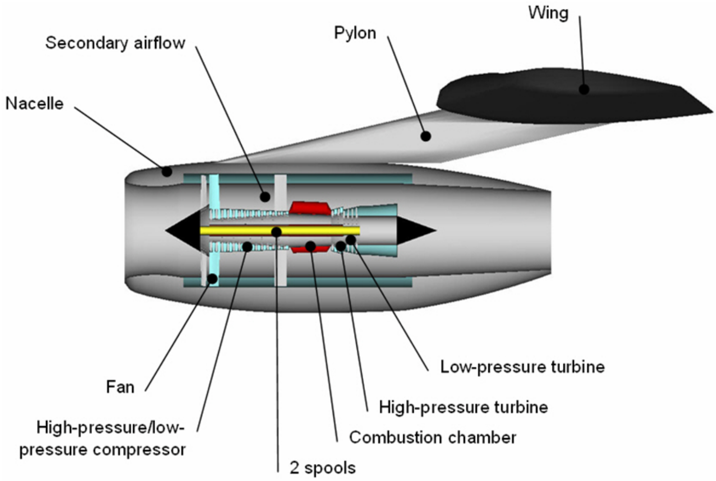


Figure 4.2: PrADO Jet Engine Model

Table 4.1: Comparison of GE CF34-3B1 Engine Parameters and PrADO Results (Rolls-Royce 2006)

Parameter	Unit	PrADO result	Original value	Variation
Fan diameter	m	1.07	1.12	-4.5 %
Bypass ratio	-	6.25	6.2	0.8 %
Overall Pressure Ratio (OPR)	-	21 *	21	-
Mass flow	kg/s	147	150.6	-2.4 %
Cruise SFC	mg/(Ns)	18.1	18.4	-3.7 %
Basic engine mass	kg	751	757.5	-0.9 %
Length	m	2.56	2.62	-2.3 %
Stages	-	Fan, 14 HPC, 2 HPT, 4 LPT	Fan, 14 HPC, 2 HPT, 4 LPT	-
Thrust	kN	38.8 *	38.8	-

* Input value

The reference turboprop engine used during the GF project and in this thesis is based on the real ATR 72's engine Pratt & Whitney Canada (PWC) PW127F. The geometric model of the propeller represents the original Hamilton Sundstrand HS 568F six-blade propeller of the newer ATR 72 versions. (Older versions use a four-blade propeller HS 247F.) The core engine is modeled with an axial compressor, an axial combustion chamber and two shafts instead of the radial compressors, reverse-flow combustion chamber and three shafts of the original engine (see Table 4.3). The inner shaft is extended to the front and ends inside a reduction gearbox that drives the propeller shaft. The geometric engine model including the nacelle is shown in Figure 4.3.

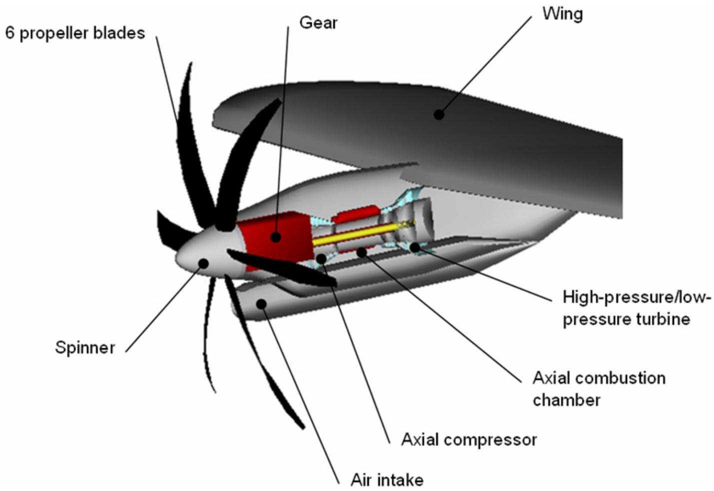


Figure 4.3: PrADO Turboprop Engine Model

The treatment of propeller engines is performed according to Mattingly *et al.* 1987. The total engine thrust T_{TOTAL} is calculated as the sum of propeller thrust T_P and core engine thrust T_{CORE}:

$$T_{TOTAL} = T_P + T_{CORE} \ . \tag{4.1}$$

While the core engine thrust is determined by the PrADO propeller engine module directly, the propeller thrust must be calculated from the propeller shaft power P_P and the propeller efficiency η_P and flight velocity V_∞:

$$T_P = \frac{P_P \cdot \eta_P}{V_\infty} \ , \tag{4.2}$$

where

$$P_P = \eta_{SHAFT} \cdot \eta_{GEAR} \cdot P_{PT} . \tag{4.3}$$

For these calculations the development of the propeller efficiency is needed, which is stored as propeller efficiency versus flight Mach number inside the propeller template file (see Table 4.2). As the real propeller efficiency data of the original ATR 72 are not published, data of the four-blade Hartzell HD-E6C propeller of the Dornier Do 328 are used (LTH 1994). Moreover, a calculation of the engine thrust at aircraft standstill is not possible as the propeller efficiency for standstill is zero as well as the flight speed, which is the denominator. In consequence, the Mach numbers for flight segments below Mach 0.1 is set to Mach 0.1.

Table 4.2: Propeller Efficiency Development over Mach Number for Hartzell HD-E6C Propeller (based on LTH 1994)

Mach number	Propeller efficiency η_P
0	0
0.1	0.64
0.28	0.83
0.57	0.86
0.6	0.85
0.69	0.8
0.7	0.78
0.74	0.7
0.77	0.6

Table 4.3 collects the main characteristics of the turboprop engine model. The mass properties of the engine components could be adjusted so that the mass of the original PW 127 engine is met with 0.9 % variation. In a second step the results of the aircraft version RF00-KP regarding overall fuel consumption for the reference mission were compared to data published for the original ATR 72 flying the same mission. This result shows that the reference mission fuel consumption is met with 1.3 % variation (see Section 4.3). The fuel consumptions for the missions "Range at Maximum Fuel" and "Ferry Range" are met with 4.1 % and 4.9 % variation (see Section 4.3).

4.3 Modeling of the Reference Version

Version RF00-KP is the PrADO model of the ATR 72 freighter version and marks this thesis' reference version. The aircraft is kerosene-fueled and driven by two turboprop engines. Its ULD capacity is seven LD3 containers and the total cargo compartment volume sums up to 79.4 m^3. The aircraft geometry model is shown in Figure 4.4.

Figure 4.5 shows the forward fuselage section of the aircraft in more detail. The model comprises the inner and outer fuselage surfaces, the forward pressure bulkhead, the cockpit area including cockpit installations and pilots, the nose landing gear, the aircraft structure including frames, windows and the large cargo

Table 4.3: PWC PW127F Engine and Hamilton Sundstrand HS 568F Propeller Parameters (Rolls-Royce 2006, Hamilton Sundstrand 2003, Pratt & Whitney Canada 1996)

Parameter	Unit	PrADO result	Original value
Number of shafts	-	2 *	3
Stages	-	Prop, 2 HPC, 3 HPT, 1 LPT	Prop, 1 LPC, 1 HPC, 1 HPT, 2LPT, 2 PT
Engine static thrust	kN	44.9	not published
Engine mass	kg	476.5	481
Propeller diameter	m	3.96 *	3.96
Propeller mass	kg	169.2 *	169.2

* Input value

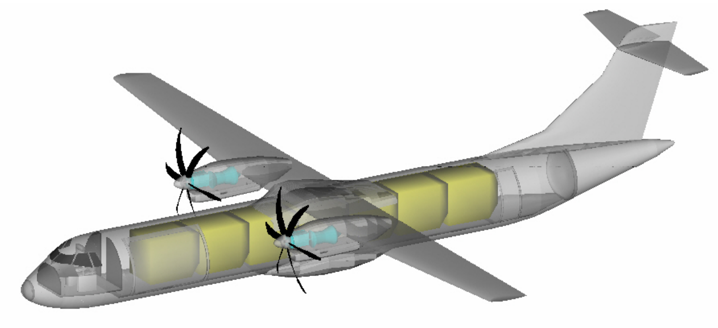


Figure 4.4: Version RF00-KP

door as well as LD3 containers inside the cargo compartment. The fuselage is 2.865 m wide and 2.64 m high. The cargo door dimensions are 2.95 m x 1.8 m.

The center fuselage section and the wing are drawn in Figure 4.6. In addition to the mentioned fuselage items, the wing structure including the front and rear wing spars and the wing ribs can be seen. The fuel tanks inside the wing are also modeled and included in the mass and CG model. The wing area is 61 m^2 at an aspect ratio of 12. This leads to a wing span of 27.1 m. In accordance with the original ATR 72 the aircraft features no leading edge high-lift devices and double-slotted flaps at the trailing edge. (The flaps are geometrically represented as single-slotted flaps).

The rear fuselage section and the tailplane are shown in Figure 4.7. The geometric model of the fuselage comprises the elements inner and outer surfaces, the fuselage frames, the passenger door including its door frame and the tail cone. The tailplane is modeled in T-tail configuration including fin, dorsal fin

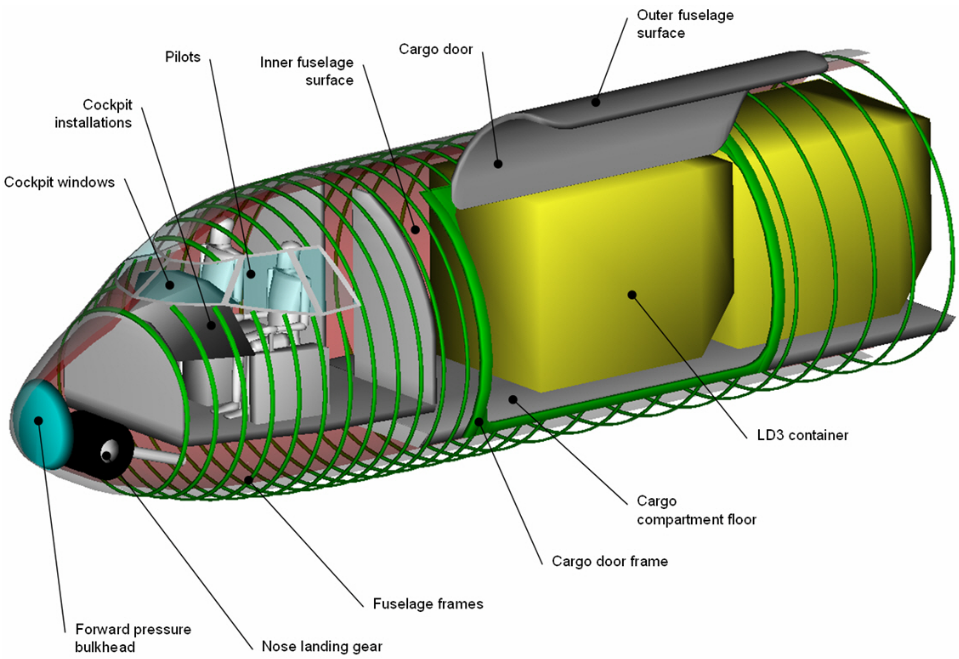


Figure 4.5: Version RF00-KP Forward Fuselage Section

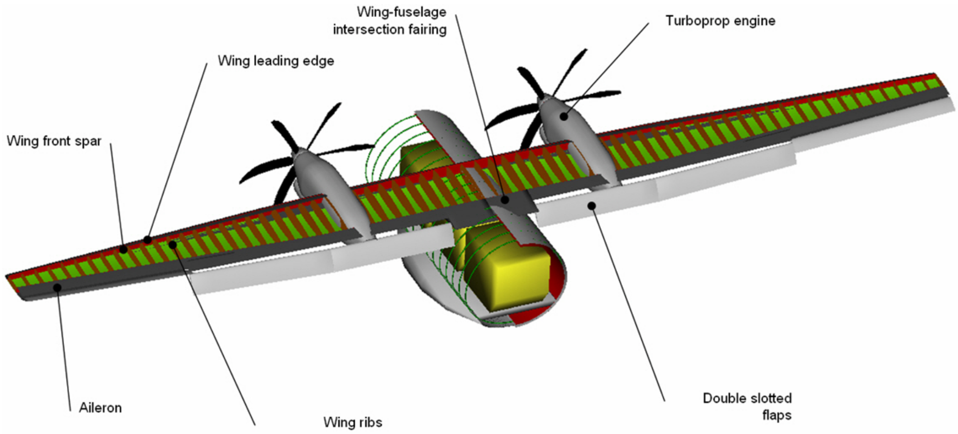


Figure 4.6: Version RF00-KP Wing and Center Fuselage Section

extension, rudder, horizontal stabilizer and elevator. The areas of the vertical and the horizontal tail are 14.8 m^2 and 10.7 m^2 respectively. The passenger door dimensions are 0.7 m x 1.73 m.

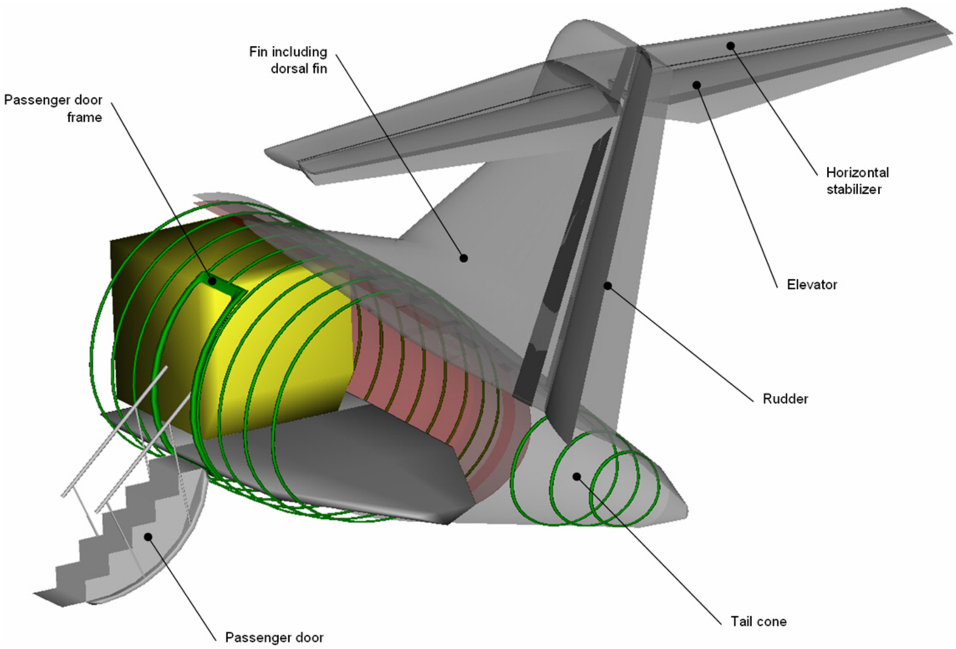


Figure 4.7: Version RF00-KP Tailplane and Rear Fuselage Section

Version RF00-KP has an operating empty mass of 11.8 t and a maximum take-off mass of 21.9 t. Table 4.4 shows the PrADO results of version RF00-KP in comparison to the data of the original ATR 72. It can be seen that the resulting aircraft masses (operating empty, maximum zero-fuel, maximum take-off and maximum landing mass) of RF00-KP lie close to the original ATR 72 data (-1 % to 0.5 % variation). This good accordance became possible through a detailed mass breakdown of the original ATR 72 provided by the Airbus FPO. Based on this mass breakdown individual aircraft component masses that were estimated as too large or small by the PrADO mass estimation methods could be adjusted by means of so-called mass technology factors. The adapted technology mass factors are listed in Table 4.5. The values of the presented technology factors are kept constant throughout all following aircraft versions based on RF00-KP, so that an objective comparison of all versions based on RF00-KP is guaranteed.

The take-off and landing field lengths of RF00-KP at maximum take-off and maximum landing mass are calculated as 1360 m and 1262 m respectively. These values mean relatively large variations of 5.4 % and 18.3 % to the values of the original ATR 72 (see Table 4.4). These variations result from the input data of the aerodynamic module used for take-off and landing investigation. This PrADO module uses fixed values for the changes in the lift-, drag- and pitching moment-coefficients caused by the selected high-lift system. The required input data for a double-slotted flap system are taken from Roskam 1990 (see Table 4.6). The given input data for lift, drag and pitching moment were not adapted because the original ATR 72's coefficients during take-off and landing were not available. However, all following versions apply the same aerodynamic input values, so that an objective comparison of the aircraft versions is possible based on their individual results in relation to each other.

Table 4.4: RF00-KP Results and Comparison to Original ATR 72 Data

Parameter	Unit	RF00-KP	ATR 72	Variation
Operational empty mass	t	11.8	11.9	-1 %
Max. zero-fuel mass	t	19.9	20	-0.5 %
Max. fuel mass	t	5	5	0 %
Max. take-off mass	t	21.9	22	0.5 %
Max. landing mass	t	21.2	21.4	- 1 %
Maximum ULD capacity (LD3)	-	7	7	0 %
Total cargo volume	m^3	79.4	75.5	5.2 %
Take-off field length	m	1360	1290	5.4 %
Landing field length	m	1262	1067	18.3 %

Table 4.5: Adapted PrADO Mass Technology Factors

Technology factor	Value
Fuselage mass	1.45
Horizontal tail mass	1.8
Vertical tail mass	1.2
Hydraulics system mass	0.5
Flaps and rudder control system mass	0.5
Electric system mass	0.5
Cargo compartment lining	2

Table 4.6: Effects of a Double-Slotted Flap on High-Lift, Drag and Pitching Moment (Roskam 1990)

Parameter	Unit	Value
Lift increase at max. deflection angle	-	1.4
Drag increase at max. deflection angle	-	0.23
Pitching moment increase at max. deflection angle	-	-0.41

Table 4.7 holds the calculated payload-range data of version RF00-KP in comparison to the original ATR 72. For the required reference mission of 8.1 t of cargo over a distance of 926 km a fuel consumption of 1975 kg is calculated. This corresponds to a variation of 1.3 % to the value given for the original ATR 72. The possible ranges for flight with maximum fuel and the ferry range are met inside an acceptable region of 4.1 % to 4.9 % variation. Figure 4.8 shows the resulting payload-range diagrams of RF00-KP and the original ATR 72. The lines of the original ATR 72 are drawn in red, and those of version RF00-KP are black.

Table 4.7: Payload-Range Data of RF00-KP and Original ATR 72 Data

Parameter	Unit	RF00-KP	ATR 72	Variation
Max. payload	t	8.1 *	8.1	0 %
Range at max. payload	km	926 *	926 0 %	
Fuel use for max. payload mission	kg	1975	2000	1.3 %
Payload at max. fuel	t	5.1 *	5.1	0 %
Range at max. fuel	km	3557	3390	4.9 %
Ferry range	km	4143	3980	4.1 %

* Input value

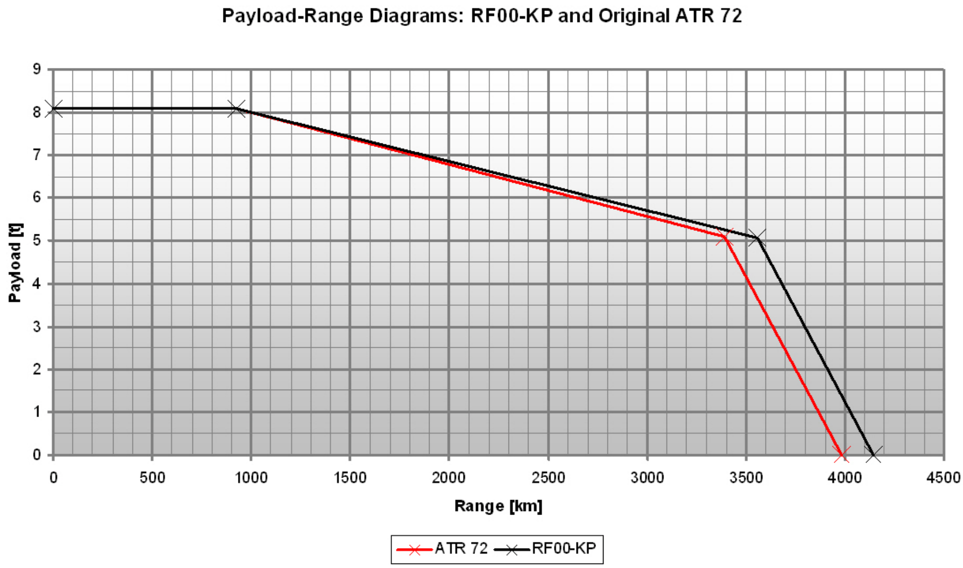


Figure 4.8: Payload-Range Diagrams of RF00-KP and Original ATR 72

In summary, RF00-KP marks a good reference model of the original ATR 72 and can be used as basis for the following derivative versions RF10-KJ, RF23-HP-STR and RF25-HJ. Especially the values for masses and fuel consumption for the reference mission are well met. Differences in e.g. take-off and landing field length are acceptable as all aircraft versions will be compared and assessed in relation to each other.

4.4 Modeling of Derivative Versions

In this section the individual differences of the aircraft versions RF10-KJ, RF23-HP-STR and RF25-HJ to version RF00-KP are described. An overall comparison of these versions to the reference version is presented in Section 4.5. Version RF4075, which is a further development of RF23-HP-STR, is presented and compared to versions RF00-KP and RF23-HP-STR in Chapter 5.

RF10-KJ

Version RF10-KJ is the comparative jet aircraft version to RF00-KP, which features the same aircraft geometry. The only design difference is the jet propulsion system. It is heavier (1841 kg) and uses more fuel for the reference mission (2490 kg). These higher masses and additional snowball effects such as a heavier fuselage due to a thicker fuselage skin lead to a higher operating empty mass of 12.4 t and a higher maximum take-off mass of 23 t. Also, the take-off and landing field lengths are longer: 1599 m and 1548 m. Figure 4.9 shows a 3D-View of the aircraft; the PrADO results are presented and compared in more detail in Section 4.5.

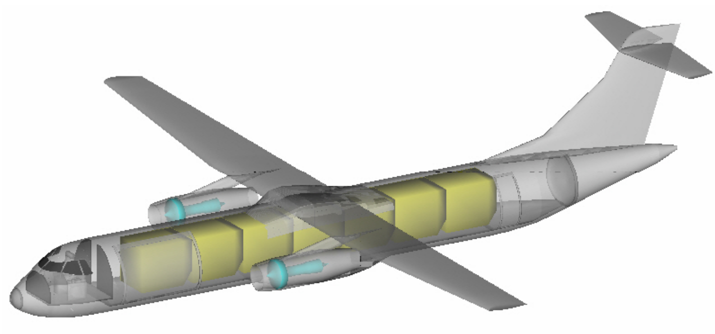


Figure 4.9: Version RF10-KJ

RF23-HP-STR

Version RF23-HP-STR is the first hydrogen version of this study. Figure 4.10 shows a 3D-View of the aircraft.

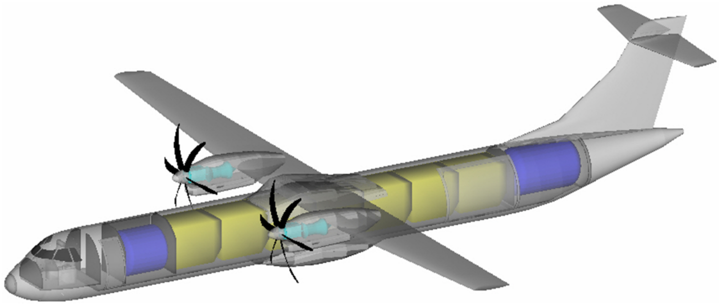


Figure 4.10: Version RF23-HP-STR

The aircraft is driven by a turboprop propulsion system, and its fuselage is stretched by 1.4 m in comparison to the fuselage of the reference version RF00-KP. In the forward and aft part of the fuselage two large hydrogen tanks are installed for liquid hydrogen storage. Their external diameters are 1.75 m (forward tank) and 1.85 m (aft tank), and they feature an insulation thickness of 15 cm of polyurethane foam. Furthermore, as the largo cargo door in its initial position would be obstructed by the forward hydrogen tank the door positions are switched. Figure 4.11 shows a comparison of the fuselages including the installed hydrogen tanks.

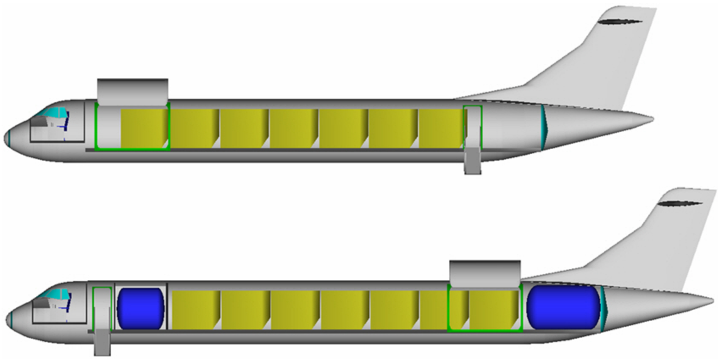


Figure 4.11: Fuselage Comparison of Versions RF00-KP (RF10-KJ) and RF23-HP-STR (RF25-HJ)

Table 4.8 collects the data used for the representation of the masses of the hydrogen fuel system components. As described in Section 3.4, the masses for fuel system components such as pumps and pipes are added to the hydrogen tank masses as virtual masses and are expressed as a larger area-specific tank masses. According to LTH 2008 the area-specific masses for a hydrogen tank of about 2 m diameter are 3 kg/m^2 for the structure and 5 kg/m^2 for the insulation. These values are increased to 24 kg/m^2 for the forward tank and 18 kg/m^2 for the aft tank to account for the missing hydrogen fuel system components. They sum up to an assumed mass of 330 kg (based on Batal 2010) and are split up into 165 kg per tank. It results an overall mass of the hydrogen fuel system of 547 kg.

Table 4.8: Liquid Hydrogen Tank Data - Versions RF23-HP-STR and RF25-HJ

Parameter	Unit	Forward tank	Aft tank
Outer diameter	m	1.75	1.85
Outer length	m	2	3.1
Fuel volume	m^3	3.3	5.7
Fuel mass	kg	234	405
Tank surface area	m^2	10.2	16.8
Area-specific mass (structure and insulation)	kg/m^2	24	18
Tank mass	kg	246 *	302 *

* Incl. virtual masses of LH_2 system

The propulsion system of version RF23-HP-STR weighs 1556 kg. For the reference mission it uses 633 kg of hydrogen. The operating empty mass is higher than that of version RF00-KP (12.6 t), but its maximum take-off mass is lower (21.4 t) due to the lower fuel mass. In consequence, the take-off and landing field lengths result as smaller than those of version RF00-KP (1291 m and 1263 m). The PrADO results of RF23-HP-STR are presented in comparison to the versions RF00-KP, RF10-KJ and RF25-HJ in Section 4.5.

RF25-HJ

Version RF25-HJ is the comparative hydrogen-fueled jet version to version RF23-HP-STR. Apart from the different propulsion system it features the same aircraft geometry as version RF23-HP-STR. Also the hydrogen tanks are the same. This limited fuel volume and the higher fuel consumption of the jet propulsion system cause that the aircraft is not able to fulfill the required reference mission. Its ranges at maximum payload and maximum fuel collapse into one point at a range of 524 km.

As the reference mission cannot be met PrADO does not determine the correct ferry range. In fact, PrADO calculates the ferry range with the same fuel mass that would be required for fulfilling the reference mission. As this fuel mass exceeds the available fuel mass (861 kg to 639 kg), the larger mass is also used for the ferry range determination. Thus, the given ferry range value in Table 4.9 in Section 4.5 is an assumption. It is not used for any further calculations or comparisons.

The jet propulsion system of version RF25-HJ weighs 1763 kg. The operating empty and maximum take-off masses of version RF25-HJ are determined as 13.3 t and 22.2 t, which leads to long take-off and landing field lengths of 1520 m and 1546 m. This very long landing field length that even exceeds its take-off field length results from the very high maximum landing mass of that version of 21.9 t. At the same wing area as the other versions, this requires a higher approach speed with consequently longer flare-out and breaking distances.

Figure 4.12 shows a 3D-View of the aircraft. Its PrADO results are presented in comparison to the previous versions in the following section.

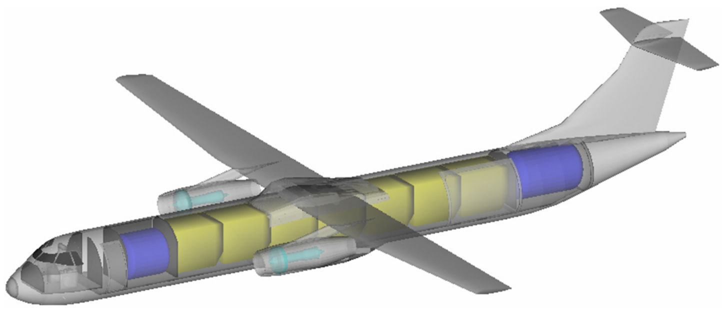


Figure 4.12: Version RF25-HJ

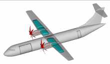
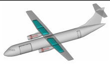
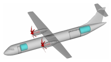
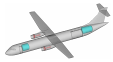
4.5 Comparison of Aircraft Versions

In this section the PrADO results of the previously described aircraft versions RF00-KP to RF25-HJ are presented and compared. The reference version for these comparisons is version RF00-KP.

Table 4.9 holds the payload-range data of the individual aircraft versions. Figure 4.13 shows the graphic representation of the calculated data as the aircraft's payload-range diagrams. The reference version RF00-KP is represented by red lines. Those of the kerosene-fueled version RF10-KJ are drawn in black, and those of the hydrogen versions RF23-HP-STR and RF25-HJ are blue and violet respectively.

It can be seen that except for version RF25-HJ all versions fulfill the required reference mission of 8.1 t of payload over 926 km range. Above this mission at maximum payload none of the derivative versions can offer as long ranges at reduced payload as the reference version. Moreover, it can be seen that the hydrogen versions are highly optimized for the mission 'flight at maximum payload'. Their ranges at maximum payload and maximum fuel collapse into one single spot.

Table 4.9: Payload-Range Data of Versions RF00-KP, RF10-KJ, RF23-HP-STR and RF25-HJ

					
Parameter	Unit	RF00-KP	RF10-KJ	RF23-HP	RF25-HJ
Max. payload	t	8.1 *	8.1 *	8.1 *	8.1 *
Range at max. payload	km	926 *	926 *	926 *	524
Payload at max. fuel	t	5.1 *	5.6	8.1	8.1
Range at max. fuel	km	3557	2691	939	524
Ferry range	km	4143	3132	1202	787 **

* Input value
** Value assumed

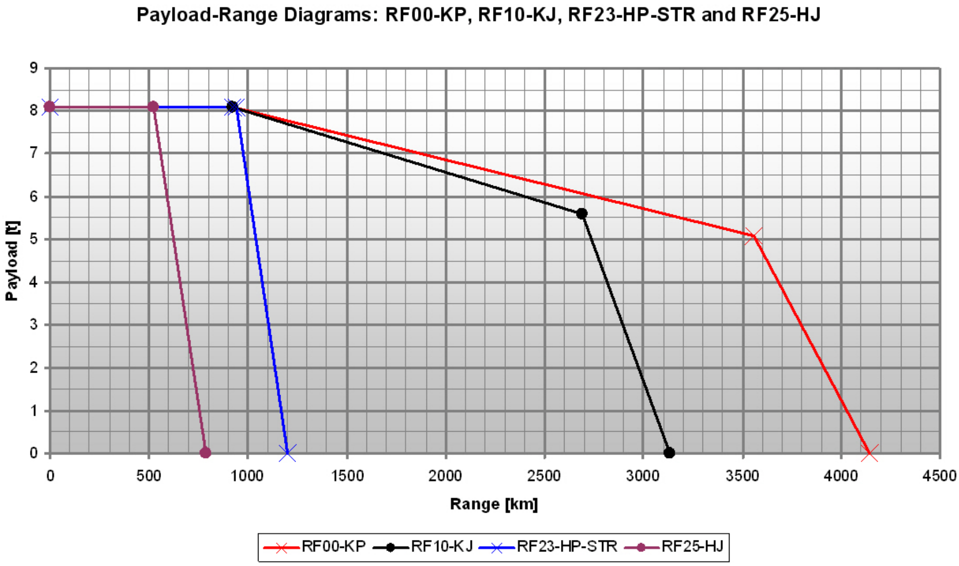


Figure 4.13: Payload-Range Diagrams of RF00-KP, RF10-KJ, RF23-HP-STR and RF25-HJ

Furthermore, the payload-range trade-off line in the payload-range diagram of hydrogen-fueled aircraft runs very flat. In consequence, a significant reduction in range brings only small gains in payload. Therefore, it is advisable to optimize and design hydrogen-fueled aircraft for one single design point in terms of range and payload in order to avoid oversized hydrogen storage capacity. However, such an optimization on concentration on one design point would reduce the operational flexibility of such aircraft.

Table 4.10 compares the PrADO results of a collection of important aircraft parameters of the versions RF00-KP to RF25-HJ. The 2.4 m stretch of the fuselages of the hydrogen-fueled versions causes a reduction in pitch ground clearance angle to 6.6°. However, this angle is still sufficient for take-off and landing of these versions and does not affect their take-off or landing capabilities. Despite the fuselage stretch the hydrogen-fueled aircraft versions RF23-HP-STR and HP25-HJ do not fulfill the cargo capacity requirement, as the numbers presented in Table 4.10 also contain the volumes of the hydrogen tank compartments. The total volume of liquid hydrogen sums up to 9 m^3. The issue of cargo capacity is treated by the improvement of the turboprop-driven version in Chapter 5 of this thesis.

The stretched fuselages of the hydrogen version are about 10 % (362 kg and 385 kg) heavier than those of their comparative kerosene versions, and the overall hydrogen system masses result as 547 kg. The use of hydrogen as fuel is beneficial for engine size and mass: the hydrogen-fueled engines are smaller and 4.2 % (jets) to 7.3 % (turboprops) lighter. In total, the operating empty masses of versions RF23-HP-STR and RF25-HJ are about 7 % (842 kg, RF23-HP-STR; 865 kg, RF25-HJ) higher than those of their kerosene-fueled competitors. Due to the low fuel masses of 633 kg and 861 kg (which is a theoretical value as this mass exceeds the available tank capacity, see Section 4.4 the maximum take-off masses result as 500 kg and 765 kg less than those of version RF00-KP and RF10-KJ. The low fuel masses of the hydrogen-fueled versions also have large influence on the maximum landing masses, as regional aircraft are typically capable to land with relatively full tanks (here: 66.5 % full). Thus, the landing masses of the hydrogen-fueled aircraft are also less than those of the kerosene aircraft versions: 63 kg (0.3 %, turboprop) and 236 kg (1.1 %, jet). The take-off field lengths of the hydrogen versions result as 69 m and 79 m shorter than those of the kerosene versions due to the much lower take-off masses. The landing field lengths of the hydrogen versions are only marginally less compared to those of the respective kerosene versions due to the small mass differences. In case of version RF25-HJ it is worth noticing that the landing field length exceeds the take-off field length due to the relatively very high maximum landing mass and the consequently high approach speed.

The cruise glide ratio values show that the higher masses and consequently wing loadings of the jet-driven versions are beneficial. They reach glide ratios of 18.7 and 18.6 compared to 16.8 and 16.3 of the turboprop designs. Also, during descent the glide ratios of the jet aircraft are higher than those of the turboprop versions. This causes that the required engine thrust of the turboprops for a go-around with one engine inoperative (OEI) is higher (45 kN to 38 kN and 37 kN). This flight condition is the sizing condition for all four aircraft versions.

Regarding reference mission fuel and energy it can be seen that the hydrogen-fueled aircraft are superior to the kerosene designs. Version RF23-HP-STR consumes 11 % less energy than version RF00-KP, and version RF25-HJ consumes 4 % less than version RF25-HJ. Moreover, the turboprop-driven aircraft are also superior to the jets. Version RF00-KP consumes 20.7 % less than version RF10-KJ, and version RF23-HP-STR consumes 26.5 % less than version RF25-HJ. Thus, regarding energy efficiency turboprop designs are significantly more advisable for the investigated reference mission. With respect to GWP the difference between hydrogen and kerosene designs is even larger. While the emissions of the kerosene designs sum up to GWP-values of 6439 eq.kg CO_2 and 8135 eq.kg CO_2, the values of the hydrogen versions are only 19 eq.kg CO_2 and 26 eq.kg CO_2 or about 99.7 % less. The largest amounts in GWP of the kerosene-fueled aircraft stem from CO_2 emissions; their shares of non-CO_2 emissions in their overall GWP-values are only 3.4 % and 3.6 %.

The DOC-results expressed as €/FTK show that the hydrogen versions are competitive to the kerosene versions. Both turboprop aircraft produce 1.10 €/FTK DOC, and the DOC of version RF25-HJ stay below those of version RF10-KJ with 1.11 €/FTK to 1.13 €/FTK. These results are due to the energy-equivalent fuel prices for kerosene and hydrogen so that the lower energy consumptions over the long aircraft life of 35 a equal or more than equal the higher purchase prices and costs for maintenance and spare parts of the hydrogen versions.

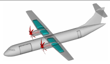
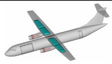
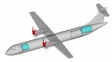
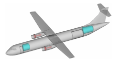
Figures 4.14 and 4.15 show graphic comparisons of the most important PrADO results in relation to reference version RF00-KP.

Figure 4.14 compares operating empty mass, maximum take-off mass and maximum landing mass of the versions RF10-KJ, RF23-HP-STR and RF25-HJ to the reference values of version RF00-KP. It can be seen that the jet-driven aircraft are inferior to the RF00-KP in every aspect. All values lie between 1.7 % and 12.6 % above the reference data. The turboprop aircraft RF23-HP-STR features a 7.1 % higher operating empty mass due to the extra installation for hydrogen storage, but a 9.8 % lower maximum take-off mass caused by the low fuel mass of hydrogen. As the maximum landing mass is calculated with 66.5 % filled tanks, this value of RF23-HP-STR is also still 0.3 % below the one of RF00-KP.

Figure 4.15 depicts the relative differences in reference mission energy and GWP of versions RF10-KJ, RF23-HP-STR and RF25-HJ to reference version RF00-KP. It becomes apparent that the jet versions RF10-KJ and RF25-HJ consume 26.1 % and 21.1 % more energy for the reference mission. The GWP of the kerosene-fueled jet aircraft is 2.3 % higher that that of version RF00-KP. The turboprop version RF23-HP-STR is significantly advantageous in reference mission energy (-10.9 %) as well as in GWP (-99.7 %).

The relative differences in take-off field length, landing field length and DOC (€/FTK) of versions RF10-KJ, RF23-HP-STR and RF25-HJ are displayed against the reference aircraft RF00-KP in Figure 4.16. Again, both jet versions show worth results regarding all aspects. The take-off and landing field lengths are

Table 4.10: Comparison of Versions RF00-KP, RF10-KJ, RF23-HP-STR and RF25-HJ

Parameter	Unit	 RF00-KP	 RF10-KJ	 RF23-HP	 RF25-HJ
Aircraft length	m	27.1	27.1	29.5	29.5
Ground clearance angle	°	7.7	7.7	6.6	6.6
Total cargo hold volume	m^3	79.4	79.4	89.5 *	89.5 *
Total fuel tank volume	m^3	6.3	6.3	9	9
Fuselage mass	kg	3463	3492	3825	3877
Propulsion system mass	kg	1678	1841	1556	1763
LH2-system mass	kg	0	0	547	547
Operational empty mass	kg	11784	12400	12626	13265
Max. take-off mass	kg	21852	22984	21352	22219 **
Max. landing mass	kg	21210	22175	21147	21939
Take-off field length	m	1360	1599	1291	1520
Landing field length	m	1262	1548	1263	1546
Cruise glide ratio	-	16.8	18.7	16.3	18.6
Engine thrust	kN	45 ***	38	45 ***	37
Ref. mission fuel	kg	1975	2490	633	861 *
Ref. mission energy	GJ	85.2	107.4	75.9	103.2
GWP	eq.kg CO_2	6439	8135	19	26
Non-CO_2 GWP share	-	3.4 %	3.6 %	100 %	100 %
DOC	€/FTK	1.10	1.13	1.10	1.11

* Including hydrogen tank compartments

** Exceeds hydrogen tank capacity

*** See Section 4.2

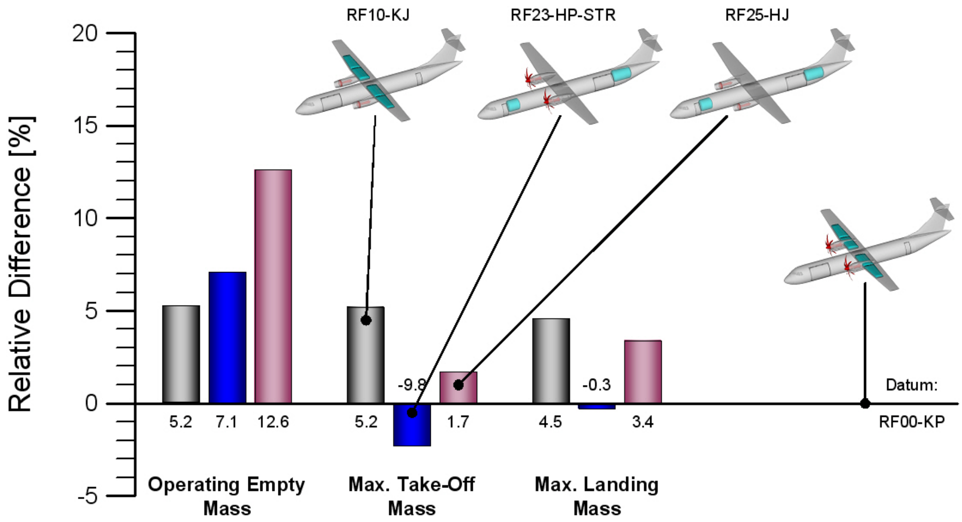


Figure 4.14: Relative Differences in Operating Empty, Max. Take-Off and Max. Landing Mass of Versions RF10-KJ, RF23-HP-STR and RF25-HJ to Reference Version RF00-KP

11.8 % to 22.7 % longer, and their DOC result as 0.9 % to 2.7 % higher. Version RF23-HP-STR has a 5.1 % shorter take-off field length due to the significantly lower maximum take-off mass and show the same results as version RF00-KP for landing field length and DOC.

The results of this section show that hydrogen-fueled aircraft show advantages regarding energy consumption and especially GWP. In terms of DOC they are at least competitive under the assumption of energy-equivalent fuel prices. Moreover, turboprop designs are clearly superior to jet aircraft in all measures of merit: reference mission energy consumption, GWP and DOC. Therefore, the following investigations concentrate on turboprop designs based on version RF23-HP-STR.

Although this version fulfills the requirements regarding ULD capacity and maximum payload, it cannot offer the full cargo volume of the original ATR 72 of 75 m^3. With respect to the utilization of regional freighter aircraft as feeder aircraft for logistics companies especially this feature is of large importance. Logistics companies transport parcels of low density so that these aircraft designs would be 'volume-limited' rather than 'mass-limited'. This is very undesirable, and would make them unattractive for logistics companies. This could endanger the whole business case of the new hydrogen-fueled regional freighter.

In the following section a further improved hydrogen-fueled turboprop version is set up and assessed against the turboprop version RF23-HP-STR that also fulfills the cargo compartment volume requirement.

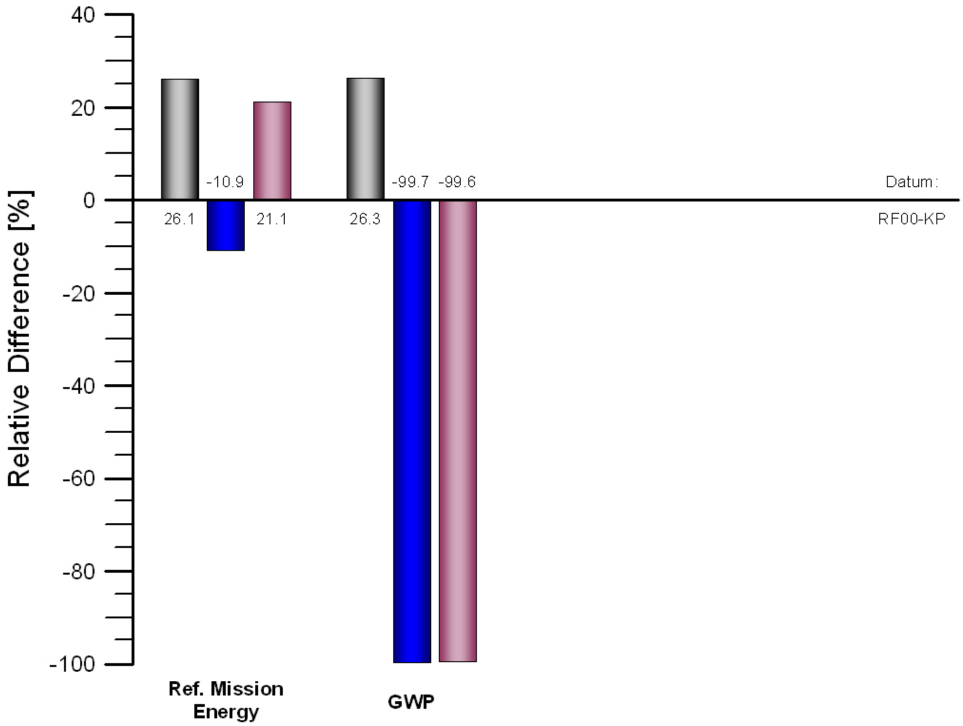


Figure 4.15: Relative Differences in Reference Mission Energy and GWP of Versions RF10-KJ, RF23-HP-STR and RF25-HJ to Reference Version RF00-KP

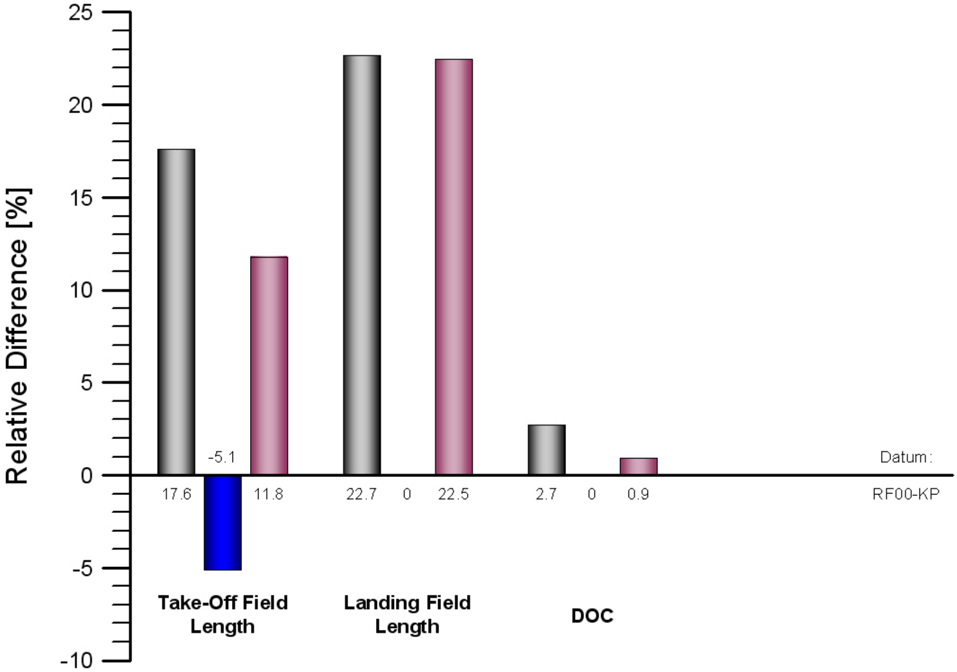


Figure 4.16: Relative Differences in Take-Off Field Length, Landing Field Length and DOC of Versions RF10-KJ, RF23-HP-STR and RF25-HJ to Reference Version RF00-KP

Chapter 5

Improvement of the Hydrogen-Fueled Turboprop Version

This section presents the conducted work on the improvement of the hydrogen-fueled aircraft version RF23-HP-STR. The name of the improved version is RF4075. The aircraft does not only fulfill the ULD capacity requirement of 7 LD3 containers but also the same overall cargo volume of the original ATR 72. Figure 5.1 shows a 3D-view of the aircraft.

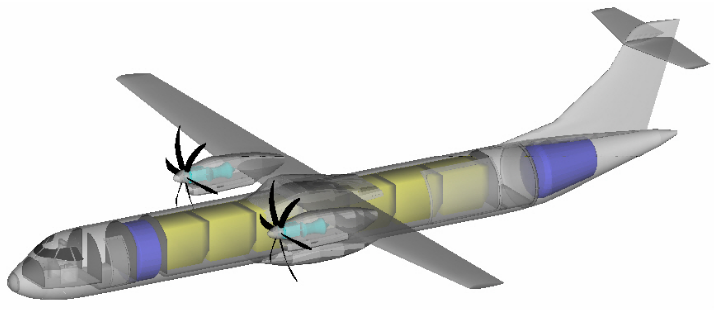


Figure 5.1: Version RF4075

5.1 Conducted Steps

In order to offer the full 75 m^3 of cargo compartment volume the fuselage of version RF4075 is stretched by another 10 cm compared to version RF23-HP-STR. Moreover, the hydrogen tanks are modified. Both tanks extend over the full fuselage cross section, which decreases their lengths and gives additional cargo compartment space. The aft tank is placed inside the forward part of the fuselage tail cone. Its shape is adapted to the outer fuselage contour. Figure 5.2 shows a comparison of the fuselages and hydrogen tank installations of versions RF23-HP-STR and RF4075.

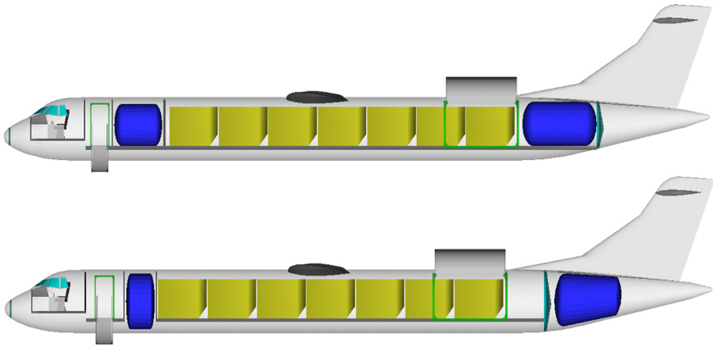


Figure 5.2: Comparison of Fuselages of Versions RF23-HP-STR and RF4075

The tanks are 2.3 m (forward tank) and 2.2 m (aft tank) in diameter. According to LTH 2008 the area-specific masses for a hydrogen tank of about 2 m diameter are 3 kg/m^2 for the structure and 5 kg/m^2 for the insulation (15 cm of polyurethane foam). These values are increased to 33 kg/m^2 for the forward tank and 19 kg/m^2 for the aft tank to account for the missing hydrogen fuel system components as in case of the hydrogen versions in the previous section but also for the imperfect hydrogen tank shapes. It results an overall mass of the hydrogen fuel system of 569 kg. Table 5.1 collects the hydrogen fuel tank data of version RF4075.

Table 5.1: Liquid Hydrogen Tank Data - Version RF4075

Parameter	Unit	Forward tank	Aft tank
Outer diameter	m	2.3	2.2
Outer length	m	1.2	2.8
Fuel volume	m^3	4.4	6
Fuel mass	kg	312	426
Tank surface area	m^2	8.1	15.9
Area-specific mass (structure and insulation)	kg/m^2	33	19
Tank mass	kg	266 *	303 *

* Incl. virtual masses of LH_2 system

In addition to the improvement of the lengths and positions of the hydrogen tanks, the position of the wing is optimized. For this purpose, the optimization algorithm "EXTREM" included into PrADO is applied. This simple optimization algorithm finds the nearest extremum for any PrADO database entry selected as measure of merit. A brief description of the algorithm is given in Appendix B. As measure of merit for the conducted optimization the reference mission fuel consumption is selected. As optimization variable the position of the wing relative to the fuselage (PrADO: FLPOS1(3)) is used with a starting value set to 0.4. The optimization task is to find a minimum value. The optimization algorithm delivers an optimized wing position relative to the fuselage of 0.397 (see Figure 5.2). Although the final wing position lies close to starting value, the algorithm needs 34 iteration steps.

The combination of the two improvement measures 'hydrogen tanks' and 'wing position' has significant influence on mass and performance of version RF4075, especially due to an improved CG position. It causes lower shearing forces and bending moments in the fuselage of version RF4075 compared to version RF23-HP-STR (see Figures 5.3 and 5.4). In consequence, the skin thickness of the fuselage of version RF4075 is reduced (Figures 5.5 and 5.6). This leads to a lighter fuselage and starts a complete reaction loop of snowball effects. Figure5.7 shows a simplified pictogram of this loop of snowball effects.

The sizing load cases in Figures 5.3 and 5.4 for both aircraft versions are the load cases 'Maximum Negative Load in Flight' and 'Touchdown Impact'.

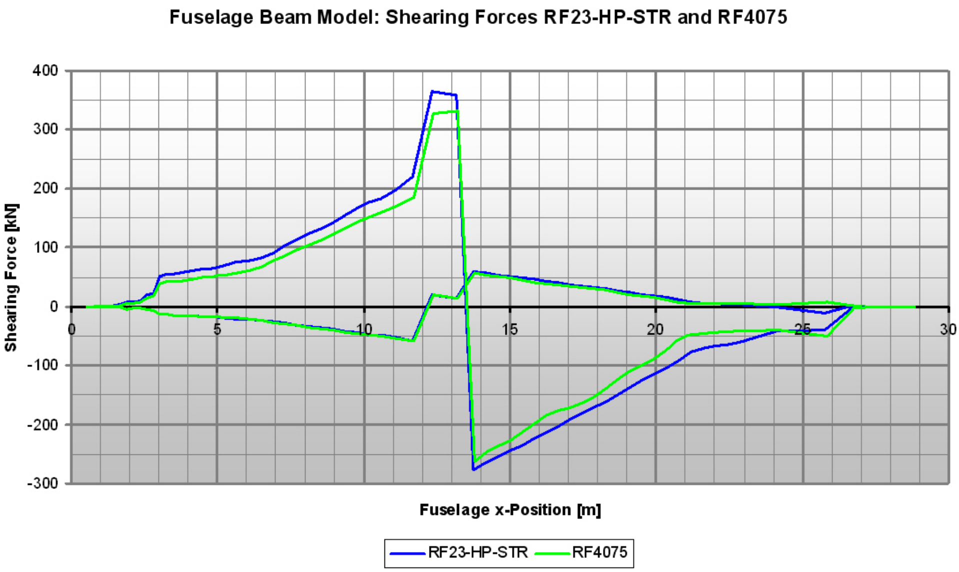


Figure 5.3: Fuselage Beam Model: Shearing Forces of Versions RF23-HP-STR and RF4075

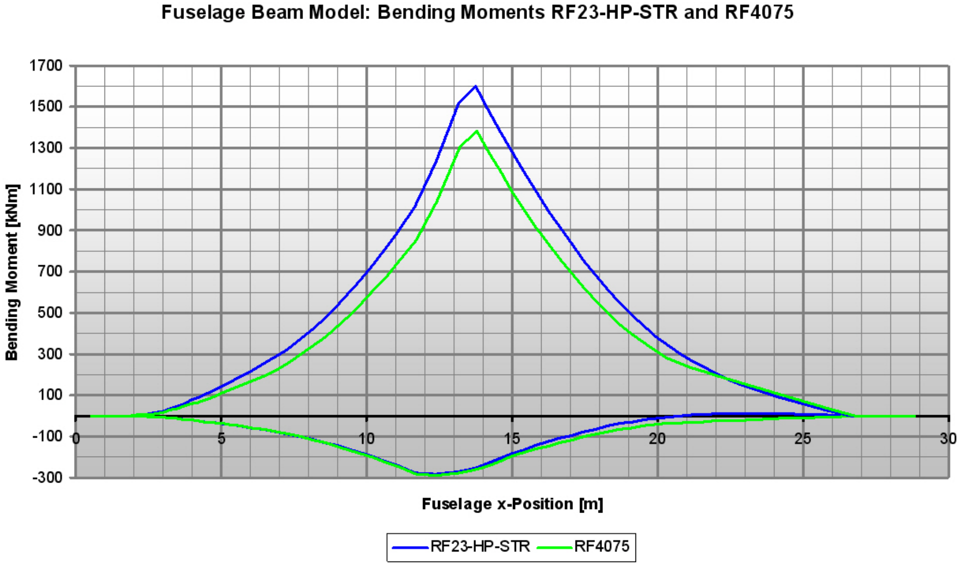


Figure 5.4: Fuselage Beam Model: Bending Moments of Versions RF23-HP-STR and RF4075

5.2 Results

Table 5.2 contains the payload-range data of the aircraft versions RF00-KP, RF23-HP-STR and RF4075; their graphic representation as the aircraft's payload-range diagrams is shown in Figure 5.8. The versions RF00-KP and RF23-HP-STR are again represented by red lines and blue lines; version RF4075 is added in green.

All versions fulfill the required reference mission of 8.1 t of payload over 926 km range. As in case of the previous hydrogen-fueled designs described in Section 4, the payload-range trade-off line of version RF4075 in the payload-range diagram runs very flat due to the low density of hydrogen. Therefore, as its tanks are not fully filled during the reference mission, it is capable to offer some additional 267 km range at a payload reduction of about 100 kg. This 29 % range increase is intended as compromise between not oversizing the hydrogen tanks and not reducing the operational flexibility of the aircraft too much. The ferry range of version RF4075 is calculated as 1498 km.

Table 5.3 collects the PrADO results of important aircraft parameters of version RF4075 in comparison to versions RF00-KP and RF23-HP-STR. A complete PrADO design data journal of version RF4075 is given in Appendix A.

The additional fuselage stretch of 10 cm compared to version RF23-HP-STR has no negative influence on the pitch ground clearance angle. Its value stays at 6.6° and

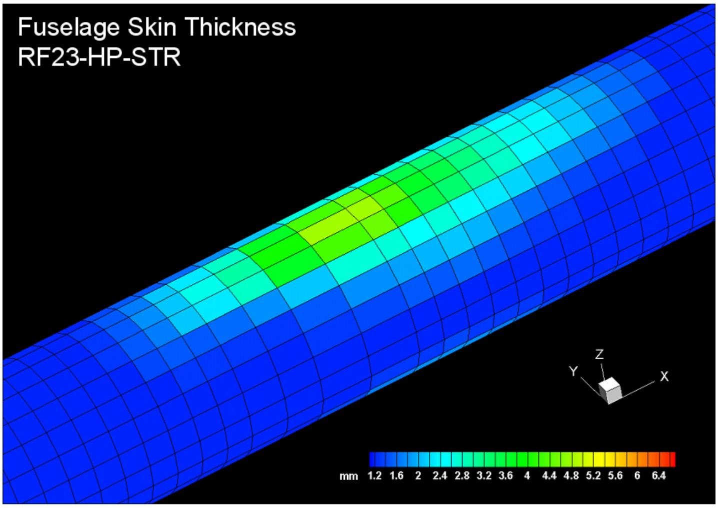


Figure 5.5: Fuselage Skin Thickness of Version RF23-HP-STR

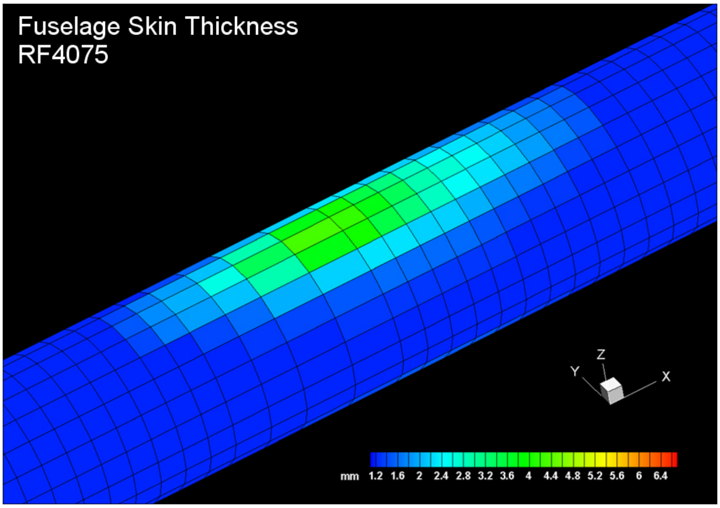


Figure 5.6: Fuselage Skin Thickness of Version RF4075

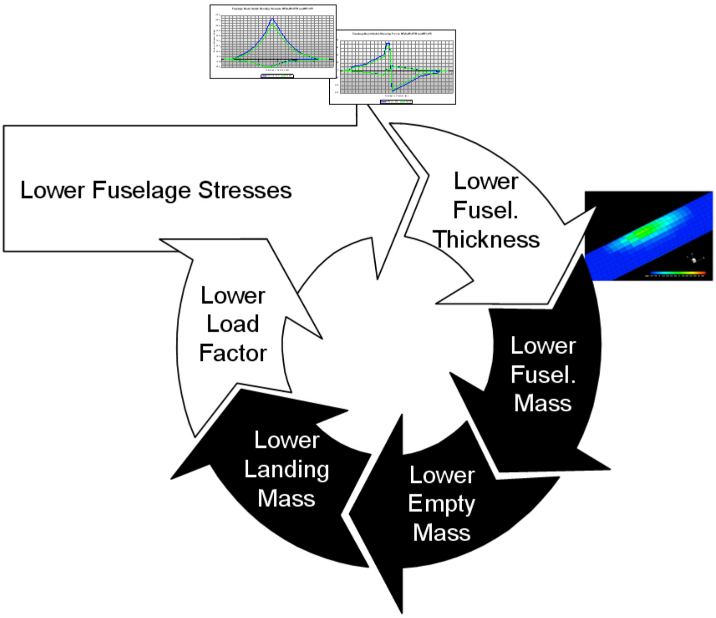
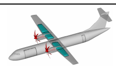
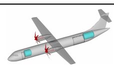
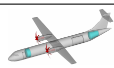


Figure 5.7: Direct Influences and Loop of Snowball Effects of Optimized Wing Position

Table 5.2: Payload-Range Data of Versions RF00-KP, RF23-HP-STR and RF4075

Parameter	Unit	 RF00-KP	 RF23-HP	 RF4075
Max. payload	t	8.1 *	8.1 *	8.1 *
Range at max. payload	km	926 *	926 *	926 *
Payload at max. fuel	t	5.1 *	8.1	8
Range at max. fuel	km	3557	939	1193
Ferry range	km	4143	1202	1498

* Input value

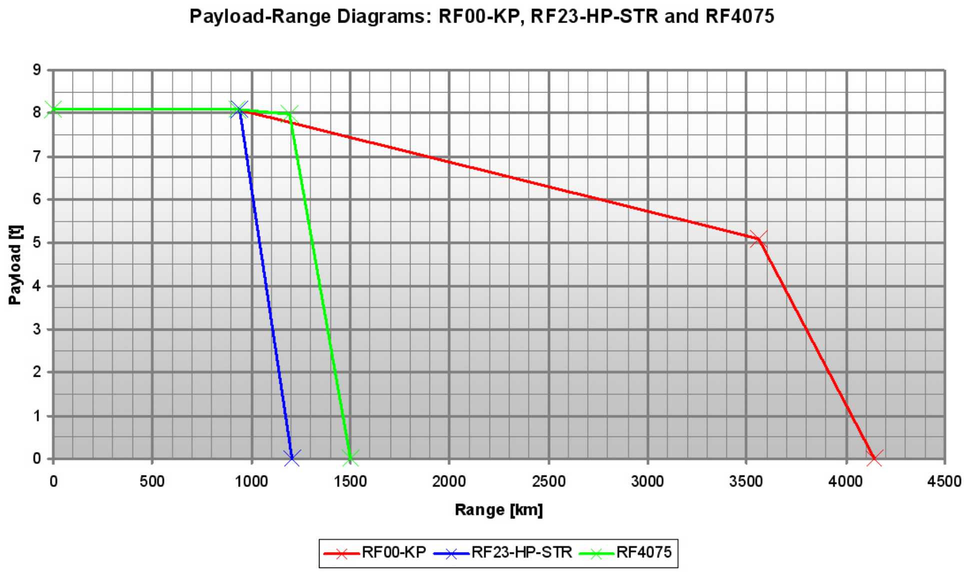


Figure 5.8: Payload-Range Diagrams of RF00-KP, RF23-HP-STR and RF4075

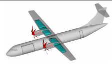
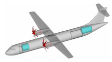
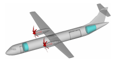
is fully sufficient for all investigated PrADO flight missions. Version RF4075's total cargo volume results as 76 m^3 so that not only ULD capacity requirement of seven LD3 containers is met but also the original ATR 72's cargo compartment volume. The additional range flexibility of 29 % causes a total hydrogen tank capacity of 10.4 m^3 or 738 kg. The mass of the complete hydrogen fuel system is estimated as 569 kg.

As described in the previous section the improvements of hydrogen tank installation and wing position have beneficial influence on the aircraft masses: The fuselage of version RF4075 is 227 kg lighter than that of version RF23-HP-STR. Due to this direct mass reduction and the following snowball effects its operational empty mass results as 316 kg, the maximum take-off mass as 322 kg and the maximum landing mass as 320 kg less. These reduced masses also downsize the propulsion system to 44 kN maximum engine thrust, so that the complete propulsion system weighs 18 kg less. The take-off and landing field lengths of version RF4075 are 19 m, respectively 17 m, shorter, although the glide ratio slightly reduced by the smaller aircraft masses to e.g. 16.2 in cruise.

Version RF4075 consumes 627 kg of liquid hydrogen for the reference mission, which corresponds to about 1 % less energy than version RF23-HP-STR and even 11.7 % less energy than the reference version RF00-KP. Its climate impact in terms of GWP results as about 19 eq.kg CO_2. The DOC expressed as €/FTK lie 1.8 % below those of version RF00-KP and RF23-HP-STR

The following Figures 5.9 and 5.10 illustrate the relative differences of the most

Table 5.3: Comparison of Versions RF00-KP, RF23-HP-STR and RF4075

				
Parameter	Unit	RF00-KP	RF23-HP	RF4075
Aircraft length	m	27.1	29.5	29.6
Ground clearance angle	°	7.7	6.6	6.6
Total cargo hold volume	m^3	79.4	89.5 *	76
Total fuel tank volume	m^3	6.3	9	10.4
Fuselage mass	kg	3463	3825	3598
Propulsion system mass	kg	1678	1556	1538
LH2-system mass	kg	0	547	569
Operational empty mass	kg	11784	12626	12310
Max. take-off mass	kg	21852	21352	21030
Max. landing mass	kg	21210	21147	20827
Take-off field length	m	1360	1291	1272
Landing field length	m	1262	1263	1246
Cruise glide ratio	-	16.77	16.3	16.2
Engine thrust	kN	45 **	45 **	44 **
Ref. mission fuel	kg	1975	633	627
Ref. mission energy	GJ	85.2	75.9	75.2
GWP	eq.kg CO_2	6439	19	19
Non-CO_2 GWP share	-	3.4 %	100 %	100 %
DOC	€/FTK	1.10	1.10	1.08

* Including hydrogen tank compartments
** See Section 4.2

important parameters of version RF4075 in comparison to its baseline design version RF23-HP-STR. Version RF4075's operating empty mass, maximum take-off mass, take-off field length and landing field length are 1.3 % to 2.5 % smaller or shorter than the corresponding values of version RF23-HP-STR. Moreover, version RF4075 is superior to version RF23-HP-STR regarding all three main assessment criteria reference mission energy, GWP (marginally) and DOC.

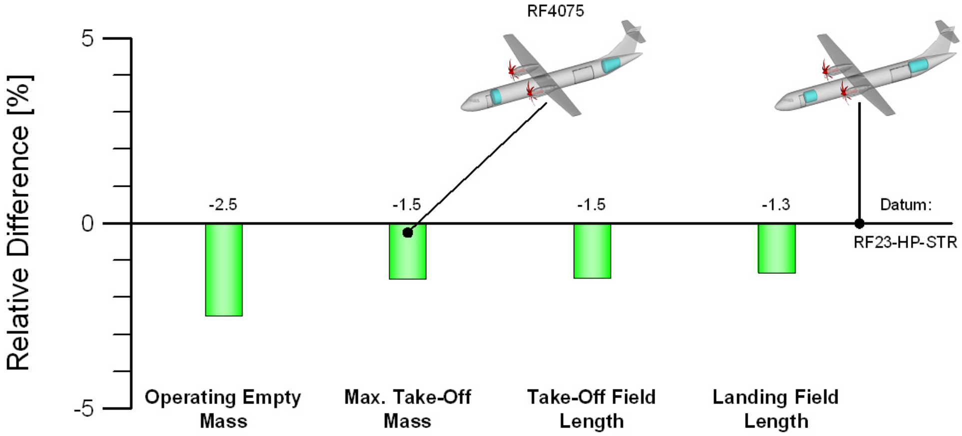


Figure 5.9: Relative Differences in Operating Empty Mass, Max. Take-Off Mass, Take-Off Field Length and Landing Field Length of Version RF4075 to Version RF23-HP-STR

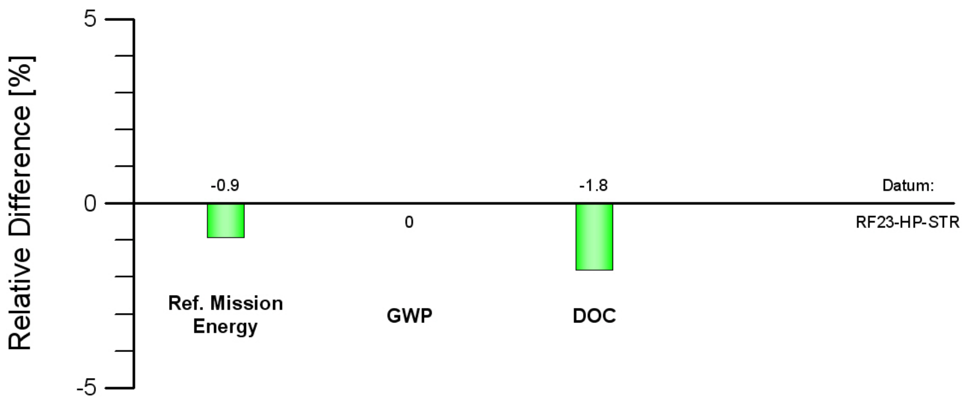


Figure 5.10: Relative Differences in Ref. Mission Energy, GWP and DOC of Version RF4075 to Version RF23-HP-STR

Chapter 6

Summary and Conclusions

This thesis has presented the conceptual design of kerosene- and hydrogen-fueled regional freighter aircraft based on the reference aircraft ATR 72. Both jets as well as turboprop aircraft have been examined. The individual designs have been compared and assessed on the basis of a reference mission of 926 km with 8.1 t of payload. The assessment criteria were

- Energy consumption for the reference mission,
- Climate impact in terms of GWP and
- Direct operating costs expressed as Euro per FTK.

The results indicate that hydrogen-fueled regional freighter aircraft are feasible from an aircraft design perspective. Turboprop designs are clearly favorable due to their significantly lower consumption of energy. The hydrogen-fueled jet version RF25-HJ is not able to fulfill the range requirement. In order to reach the required range much larger tanks would be necessary to store the necessary amount of fuel. This would directly cause higher tank and fuel masses but also further snowball effects such as a larger and heavier fuselage, a larger and heavier propulsion system and further decreased take-off and landing performance or a larger and heavier wing.

The payload-range trade-off line in the payload-range diagram of hydrogen-fueled aircraft runs very flat, which causes that a significant reduction in range brings only small gains in payload. Therefore, it is advisable for hydrogen-fueled aircraft design to focus on one single design point in terms of range and payload in order to avoid oversized hydrogen storage capacity. However, such concentration on one design point would reduce the operational flexibility of the aircraft. Aircraft version RF4075 represents a possible compromise between optimization for one single design point and flexibility by offering additional fuel volume for a 28 % range increase at a moderate payload reduction of 0.1 t.

Turboprop-driven hydrogen aircraft consume less energy than the kerosene-fueled reference aircraft to perform the reference mission, which is partly due to lower flight masses. Although hydrogen-fueled aircraft show higher operating empty masses than the comparative kerosene versions due to the larger fuselages and additional hydrogen tanks, their maximum take-off masses are smaller because of the high gravimetric energy density of hydrogen. Also, for regional aircraft that feature high maximum landing masses with 66.5 % filled tanks, the maximum landing masses are lower. This causes shorter field lengths for take-off and landing when flying at masses close to the maximum values.

The climate impact caused by the emissions of hydrogen-fueled regional freighter aircraft is less than 1 % of that of kerosene-fueled aircraft. This is due to

- No emission of carbon dioxide,
- Smaller amounts of emitted nitrogen oxides and especially
- A low cruise altitude at which the emissions of nitrogen oxides have little and water vapor even no influence on the climate.

Given an energy-equivalent price for kerosene and hydrogen, the hydrogen-fueled turboprop designs are competitive to the kerosene-fueled reference aircraft in terms of DOC per FTK. This is due to the long operative life of freighter aircraft of typically 35 years. The savings in fuel costs over this time span more than equal the higher purchase price and maintenance costs. If environmental efficiency becomes an economic advantage in the future, e.g. by means of emissions related taxes, the potential cost benefits will be even higher.

In consequence to the listed results, regional freighters appear favorable as demonstrators and first applications of hydrogen as aviation fuel. They are comparatively cheap in purchase price, and they are typically operated within small networks of airports. This would reduce the number of airports being affected by the required changes to airport infrastructure. By this means, cargo airlines and logistics companies may act as technology drivers for more sustainable air traffic.

However, regarding the overall manmade impact on radiative forcing and climate impact, the mitigation potential of regional freighter aircraft alone is marginal. Air cargo traffic sums up to about 3.3 % of all air traffic, and 24 % of all air cargo traffic is national and regional air cargo traffic. Assuming 2 % to 8 % share of air traffic in overall manmade climate impact, this accounts for shares of

- 0.07 % to 0.26 % of overall air cargo traffic and
- 0.016 % to 0.064 % of national and regional air cargo traffic in global manmade climate impact.

This marginal share also represents the maximum reduction potential of regional freighter aircraft. In fact, the share of regional air traffic in climate impact is even less than its 0.8 % share in overall air traffic due to the low typical cruise altitudes of such aircraft.

Chapter 7

Discussion and Future Work

Hydrogen as Aviation Fuel

This study indicates that aircraft hydrogen aircraft propulsion is feasible and environmentally promising from an aircraft design point of view. Also, regarding hydrogen systems technology literature review showed that the necessary technologies are almost completely available today. In terrestrial and space applications hydrogen has been successfully in use for decades. However, despite the principle technical feasibility, there is no economic scenario foreseeable in the midterm future that makes the wide application of hydrogen appear as positive or desirable for aircraft manufacturers or airlines. Kerosene and its drop-in successors appear to stay the sole and aircraft fuel of choice for the next decades to come. The most important reason for this is the big difference in price for kerosene and hydrogen - especially if environmentally friendly produced. But there are further issues that object the introduction of hydrogen as aviation fuel from different perspectives.

From an aircraft manufacturer's point of view there must be a large enough market to introduce a new technology. Thus, regarding hydrogen-fueled regional freighter aircraft there must be the prospective for further types of aircraft to follow. The development of a new type or family of aircraft means high development costs and risks. A failure would mean to jeopardize the whole company. Risks have to be minimized, which often means that technically outdated products are offered to keep established family concepts upright, and superior successor products are postponed. Regional freighter aircraft alone do not justify a switch to hydrogen. Their main potential lies first and foremost in their role as demonstrators of hydrogen aircraft technology.

A cargo airline will only buy and operate a new type of aircraft if that replacement appears directly beneficial for the airline. An optimization of the aircraft for one single design point in terms of payload and range means less operational flexibility for the aircraft operators. Furthermore, freighter aircraft must enable a fast and reliable turnaround under all weather conditions. Thus, the aircraft have to be robust and easy to operate. Issues such as a complicated refueling process of cryogenic fuel or losses of expensive hydrogen due to boil-off during daytime mean important operational disadvantages.

The application of hydrogen as fuel for military aircraft appears very improbable. Combat aircraft require capabilities of very high maneuverability and supersonic speed, which means that their size and mass must be reduced to a minimum. In consequence, the large storage volume of hydrogen makes it not feasible for such aircraft. Moreover, military aircraft in general require as simple as possible operative processes. Kerosene or its drop-in replacements can be stored in tanks and barrels at ambient pressure and temperature without the need for cooling and/or boil-off losses. The refueling procedures are also comparatively simple. Thus, hydrogen that needs to be stored at cryogenic temperatures and/or under high pressure and requires a complex refueling process is less feasible.

If the introduction of hydrogen as aviation fuel shall be promoted, the task for politics is to make environmental advantages also economic benefits, e.g. by means of emissions related taxes. However, the recently introduced European emissions trading scheme (EU ETS) does not aim at a reduction of aircraft emissions. In aviation technology, fuel burn reduction (and consequently reduction of emissions) has always been a major aim of new designs and improvements. Thus, in aircraft technology it is difficult, expensive and only limitedly possible to reach further large improvements because much has already been achieved. The overall aim of the EU ETS is to make aviation buy emission certificates from other branches of industry, so that CO_2 emissions are reduced elsewhere on ground, where larger improvements are still possible and cause less technical and financial effort. This offers a larger total CO_2 reduction potential than reductions in aircraft emissions directly but furthermore reduces the chances for hydrogen to become the new aviation fuel. A shift to easier to introduce drop-in replacements of crude oil-based kerosene is more probable in the foreseeable future. However, in this case it is important not to switch to other fossil feedstocks such as coal or gas. Although this would deliver aircraft fuel the overall emissions of CO_2 and the climate impact of air traffic could even increase.

The current activities of the aviation sector to mitigate climate change concentrate on the reduction of CO_2 and NO_x emissions. The aim of many companies such as airlines or industrial enterprises is so-called 'carbon-neutral growth'. This means further growth of the business but at today's emissions of CO_2. However, in the light of the long lasting climate impact of CO_2 and the already accumulated amount in the atmosphere it becomes clear that it is not enough to just reduce new emissions. CO_2 stays in the atmosphere and climate active for decades. Thus, the challenge today is not a problem of efficiency of the existing technology; in fact, it is a fundamental problem of fuel and its feedstock. If not switching to sustainable fuel and feedstock only the amount of new pollution is reduced. For real sustainability this has got to change. In this context it is important that for an overall assessment of the environmental impact of hydrogen as aviation fuel the total 'well-to-wake' chain and especially the production process of hydrogen and its feedstock are crucial. If there is a market for hydrogen in general, suppliers will show up that beat the price of sustainably produced hydrogen and offer hydrogen from any feedstock and energy in the cheapest possible way. In this case, the use of hydrogen would be significantly environmentally inferior to kerosene - even in terms of CO_2 emissions.

Aircraft Models

The Green Freighter project was the first application of PrADO at HAW Hamburg. Experience with PrADO has been built up, models have been set up and propeller aircraft have been investigated for the first time using PrADO. The scope of the GF project comprised many areas of input data and models that still offer possibilities for improvement:

- Structural sizing and airframe mass estimation: The current structural models of the aircraft fuselages apply a simplified beam model of the fuselage. This model does not take into account the cutout for the large cargo door in the highly stressed rear part of the fuselage. Consequently, additional masses for doublers and stiffeners around the cutout are not taken into account.

- Engine thermodynamics: The hydrogen-fueled engine models feature the same turbine entry temperature as those of the kerosene-fueled ones. As mentioned in the respective sections, different sources from literature indicate that this temperature might be higher as well as lower. Higher values would be beneficial for engine size and mass and might be possible due to e.g. better turbine blade cooling using hydrogen. Here, a more detailed investigation and exchange with experts in the field of hydrogen-fueled turbo engines appears advisable.

- Hydrogen system: The hydrogen fuel system components are not modeled in detail in the current models but added as virtual increases of the hydrogen tank masses. This offers two possibilities for improvement: Firstly, the added virtual masses for hydrogen system components could be checked against more recent data than available for the cited student project. Secondly, a new PrADO module could be set up to model and size the individual hydrogen system components to avoid the use of area-specific tank mass given by the user.

- Climate impact: The GWP climate model does not take into account the effects of exhaust particles and their impacts on cloud formation as well as the potential climate effects of contrails and cirrus clouds. Today, there is still discussion about the effects of contrails and clouds on the climate, and they still cannot be quantified. Also, the GWP model is not suitable for short-lived emissions and their climate effects. The applied GWP model is based on relatively old data and models from the end 1990s and beginning 2000s.

- Noise and local air quality: So far, these issues of overall environmental friendliness have not been taken into account. Their quantification and inclusion into the final assessment of different aircraft versions is desirable.

- Combination of environmental friendliness and costs: Current DOC models do not offer the possibility to include environmental benefits also as economic advantages. One way to achieve this could be the inclusion of emissions-related taxes, e.g. as money per mass of CO_2 or money per mass of CO_2-equivalent based on the GWP.

Further Aircraft Versions

Besides the mentioned improvements to the existing aircraft models the conducted investigations showed potential for further aircraft versions.

- Dropping of family concept: Version RF4075 still falls under the minimum-change requirement. By dropping this family concept and allowing for larger design modifications the overall capability of a new version could be further improved. Especially downsizing of the vertical and horizontal tails is desirable. This is possible due to the stretched fuselage compared to the original ATR 72 and the resulting longer tail lever arms. In fact, the original ATR 72's tails, which are still the same as those of the basic version ATR 42, are already oversized.

- Unmanned designs: Further investigations of unmanned aircraft designs appear advisable. Switching to an unmanned design generates additional internal space for hydrogen tank installation in the former cockpit area, and the cargo volume decrease is smaller. Moreover, several aircraft systems, such as the environmental control system (ECS), that are mandatory when humans are onboard can be scaled down or be completely omitted.

- Range at maximum fuel: The reference mission for the investigations presented in this thesis was the mission 'Range at Maximum Payload' of the original ATR 72. Another reference version of interest would be the mission 'Range at Maximum Fuel' (5.1 t over 1,830 NM (3,390 km)). This mission would be more challenging to fulfill due to the longer range and increased hydrogen tank volume. Due to the low density of typical air cargo such as parcels of logistics companies, the challenge could even be intensified by keeping up the requirement of 75 m^3 of cargo compartment volume. Such an aircraft could very probably no longer be designed with the same fuselage as the original aircraft and would lead to an increased fuselage cross section offering new potential for other types of cargo containers and pallets.

PrADO

The work on the current aircraft studies showed the following potential for new PrADO modules and/or improvements of the existing ones:

- Engine sizing: For turboprop designs it is desirable to directly use engine power for engine sizing instead of thrust.
- Propeller efficiency: Currently, the propeller efficiency development (versus Mach number) is given by the user in the propeller template file. Firstly, the propeller efficiency model could be estimated more accurately if plotted versus flight speed and so-called propeller disc loading. Secondly, the propeller efficiency could be calculated within a new PrADO propeller efficiency model to avoid the use of a propeller efficiency template.
- NO_x formation: While the emissions of water vapor and CO_2 are directly related to fuel consumption, NO_x formation is highly dependant on engine technology. Therefore, the corresponding engine parameters such as combustion temperature could be used for a more accurate estimation of NO_x emissions.
- Output of GWP: The GWP due to the individual trace gases as well as the total GWP could be calculated by PrADO directly and be included in the output files.
- Hydrogen system: As already mentioned, a new PrADO module could be set up to model and size the individual hydrogen system components to avoid the use of area-specific tank mass given by the user. This model could also include more detailed aspects such as crashworthiness requirements of the hydrogen tanks and the installation masses of hydrogen tanks.

Research Potential from Non-Technical Perspectives

As shown, hydrogen is only economically competitive to kerosene at high energy costs. However, if this is the case, flying will be more expensive in general and will become only affordable to a limited number of countries and/or layers of society. This would cause significant social as well as economic implications. Decreasing markets for air traffic and aircraft would endanger the whole aviation sector. These aspects offer potential for further investigations of social and economic scenarios for the introduction of hydrogen or other renewable fuels from non-engineering points of view such as business, economy or social sciences.

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Appendix A

Version RF4075 – PrADO Design Data Journal

Aircraft Version Characteristics:

- Turboprop propulsion system
- Hydrogen-fueled
- Stretched fuselage (compared to ref a/c)
- Installation of full cross section forward hydrogen tank and conical aft hydrogen tank
- Full 75 m^3 cargo volume
- Optimized wing position

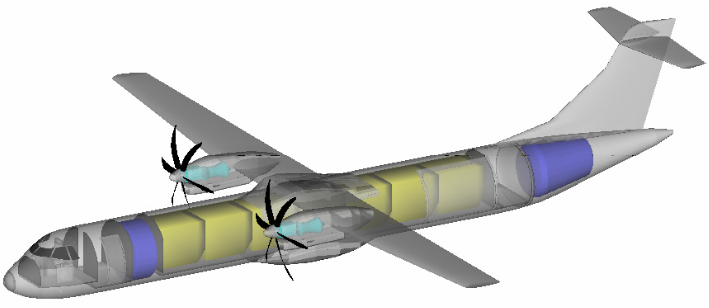

Figure A.1: Version RF4075

```
Institute of Aircraft Design and Lightweight Structures
TU Braunschweig WH c 30.09.2009
--------------------------------------
Design Program P r A D O
--------------------------------------
I Preliminary I
I Design I
I Data I
--------------------------------------


Version:  TA2/10.2007 30.09.2009

Nachentwurf eines zweimotorigen
Regionalfrachtflugzeugs
===========================================
ATR72 Full Freighter Version (angelehnt)
Antrieb:  Propeller
Kraftstoff:  Wasserstoff
Triebwerk:  PW127F
Variationen:  gestreckter Rumpf, LH2-Tanks Full Cross Section
KTETMAX von RF00
Nachrechnung mit PrADO

Editor K. Seeckt
Report
Date 27.08.2010
Time 14:39:25

--------------------------------------
DESIGN ANALYSIS
--------------------------------------
Project RF4075



Fuselage geometry
=================
Fuselge No.                                                 1
Max.length                          LGR    m           29.500
Max.height                         DARZ    m            2.640
Max.width                          DARY    m            2.865
Fuel tank volume                   VTKR    m**3           0.0
Wetted area
- without fairings                   OR    m**2         222.4
- with fairings                 ORMFAIR    m**2         238.0
Slenderness ratio              DARZ/LGR    %             8.95
Elliptic form ratio           DARZ/DARY                0.9215


Wing geometry (FL)
=================
Wing No.                                                    1
Aspect ratio                     LAMDAF                 12.00
Taper ratio                     TAF/TIF                 0.590
Sweep (25%-chord line)           PHI25F    deg           2.29
Tickness-chord ratio             DELTAF    %            14.71
Reference area                       FF    m**2          61.0
Span                                 BF    m           27.055
Root chord                          TIF    m            2.601
Fuel tank volume                   VTKF    m**3           0.0
Wetted area                          OF    m**2         112.4


Horizontal tail geometry (HLW)
=============================
HLW No.                                                     1
Tail volume coefficient            VHLW               1.15886
Reference area                       FH    m**2          10.7
Moment arm length (HLW-FL)           RH    m           15.237
Fuel tank volume                   VTKH    m**3           0.0
Wetted area                          OH    m**2          21.8
```

Vertical tail geometry (SLW)
============================

SLW No.			1
Tail volume coefficient	VSLW		0.23775
Reference area	FS	m**2	14.8
Moment arm length (SLW-FL)	RS	m	13.240
Fuel tank volume	VTKS	m**3	0.0
Wetted area	OS	m**2	30.0

Landing gear geometry
=====================

No. of legs	NFW		3
No. of wheels	NRAD		6
Max.wheel base	XRADST	m	11.711
Max.track base	YSPURW	m	3.724
LCN (rigid runway)	LCNS		0.000
LCN (flexible runway)	LCNE		0.000

LH2 tank geometry
=================

Tank No.			1	2
Max.length	LGLHTK	m	1.200	2.800
Max.height	DALHTKZ	m	2.300	2.200
Max.width	DALHTKY	m	2.300	2.200
Fuel tank volume	VLHTK	m**3	4.4	6.0
Wetted area	OLHTK	m**2	8.1	15.9
Slenderness ratio	DALHTKZ/LGLHTK	%	191.67	78.57
Elliptic form ratio	DALHTKZ/DALHTKY		1.0000	1.0000

Engine nacelle geometry
=======================

Nacelle No.			1	2
Max.length	LTG	m	4.118	4.118
Max.height	DATGZ	m	1.179	1.179
Max.width	DATGY	m	0.880	0.880
Wetted area	OTG	m**2	19.1	19.1
Elliptic form ratio	DATGZ/DATGY		1.3398	1.3398

Aircraft geometry
=================

Max.length	XMAXLFZ	m	29.620
Max.width	YMAXLFZ	m	27.058
Max.height	ZMAXLFZ	m	7.521
Reference area	FLFZ	m**2	61.0
Wetted area	OLFZ	m**2	440.5
Total fuel tank volume	VTKLFZZ	m**3	10.4
Total cargo hold volume	VFLFZ	m**3	76.0
Roll angle/ground contact	WIFW	deg	18.156
Pitch angle/ground contact	THETAFW	deg	6.605
Max.wing loading	WAMAX/FF	kg/m**2	344.761

Engine data
===========

Engine No.			1	2
Engine type			1	1
Bypass ratio	BYPASS		0.00	0.00
Max.length	LTW	m	1.970	1.970
Max.diameter	DATW	m	0.653	0.653
Static thrust at SL(ISA)	SOTW	N	44406.	44406.
SFC at takeoff				
- Fuel type 1	SFC	kg/N/h	0.00680	0.00680
- Fuel type 2	SFC	kg/N/h	0.00000	0.00000
- Fuel type 3	SFC	kg/N/h	0.00000	0.00000
- Fuel type 4	SFC	kg/N/h	0.00000	0.00000
- Fuel type 5	SFC	kg/N/h	0.00000	0.00000
SFC at cruise				
- Fuel type 1	SFC	kg/N/h	0.01547	0.01547
- Fuel type 2	SFC	kg/N/h	0.00000	0.00000
- Fuel type 3	SFC	kg/N/h	0.00000	0.00000

```
- Fuel type 4                            SFC    kg/N/h     0.00000    0.00000
- Fuel type 5                            SFC    kg/N/h     0.00000    0.00000


Propulsion group data
=====================
SFC in different flight situations
(All engines/operating conditions)
- Takeoff                             SFCATO    kg/N/h     0.00680
- Climbing flight                      SFCAC    kg/N/h     0.01039
- Crusing flight                       SFCAR    kg/N/h     0.01547
- Descending flight                    SFCAD    kg/N/h     0.01058



Aerodynamics
============
                                             Cruise *)    Takeoff    Approach    Landing
Max.lift coefficient        CAMAXi             1.54717    1.86896     1.86896    2.19069
Angle of attack              ALFAi    deg         1.89
Lift coefficient               CAi             0.60439
Drag coefficient               CWi             0.03729
Lift to drag ratio     GZi=CAi/CWi            16.20768
*) Mission with max.payload/intial point



Performance
===========
Mission 4:  design mission
Mission 1:  mission with max.payload
Mission 2:  mission with max.fuel
Mission 3:  ferry mission (no payload)
Mission 5:  flight of DOC calculation

                                                          Mission 4   Mission 1   Mission 2
Range                                     Ri    km             926.        924.       1193.
Flight time                            TIMEi    h              2.07        2.07        2.64
Number of passengers                     NSi                      0           0           0
Freight weight                         WNLFi    kg            8093.       8093.       7983.
Cruise Mach number                       RMi                 0.4100      0.4100      0.4100
Cruising speed                           VRi    km/h         467.05      467.05      467.05
Altitude
- Initial cruise                         HRi    m             6.000       6.000       6.000
- Final cruise                        HRMAXi    m             6.123       6.122       6.170
Lift to drag ratio
- Initial cruise                        GZRi                  16.20       16.21       16.20
Payload weight                           WNi    kg            8093.       8093.       7983.
Fuel weight
- Fuel type 1                       WKGiV(1)    kg             627.        627.        737.
- Fuel type 2                       WKGiV(2)    kg               0.          0.          0.
- Fuel type 3                       WKGiV(3)    kg               0.          0.          0.
- Fuel type 4                       WKGiV(4)    kg               0.          0.          0.
- Fuel type 5                       WKGiV(5)    kg               0.          0.          0.
- Sum                                   WKGi    kg             627.        627.        737.

                                                          Mission 3   Mission 5
Range                                     Ri    km            1498.        926.
Flight time                            TIMEi    h              3.29        2.07
Number of passengers                     NSi                      0           0
Freight weight                         WNLFi    kg               0.       8093.
Cruise Mach number                       RMi                 0.4100      0.4100
Cruising speed                           VRi    km/h         467.05      467.05
Altitude
- Initial cruise                         HRi    km            6.000       6.000
- Final cruise                        HRMAXi    km            6.315       6.123
Lift to drag ratio
- Initial cruise                        GZRi                  12.10       16.21
Payload weight                           WNi    kg               0.       8093.
Fuel weight
- Fuel type 1                       WKGiV(1)    kg             737.        628.
- Fuel type 2                       WKGiV(2)    kg               0.          0.
- Fuel type 3                       WKGiV(3)    kg               0.          0.
- Fuel type 4                       WKGiV(4)    kg               0.          0.
```

- Fuel type 5	WKGiV(5)	kg	0.	0.
- Sum	WKGi	kg	737.	628.

Takeoff & Landing
==================

Takeoff field length (FAR25)	SBERF	m	1272.
Landing field length (FAR25)	LBERF	m	1246.
Approach speed	VA	m/s	70.31

Operating empty weight ** weight breakdown **
===

		kg	%
1 Wing	WFL	2102.	17.076
2 Fuselage	WR	3598.	29.226
3 HTP	WHLW	186.	1.511
4 VTP	WSLW	281.	2.280
5 Winglets	WWL	0.	0.000
6 Fairings	WFAIR	414.	3.366
7 Pylons	WPYL	0.	0.000
8 Landing gear	WFW	702.	5.706
9 Power unit	WAT	1538.	12.494
10 Systems	WSYS	1781.	14.472
11 External tanks	WEXTK	0.	0.000
12 LH2 tanks & systems	WLHSYS	569.	4.621
13 LCHx tanks & systems	WLCHSYS	0.	0.000
14 Furnishings	WAUS	900.	7.309
Manufacturing empty weight (1-14)	WME	12071.	98.062
15 Operator items	WOPA	239.	1.938
Operating empty weight (1-15)	WOE	12310.	100.000

Takeoff weight (design mission) ** weight breakdown **
==

		kg	%
Operating empty weight	WOE	12310.	58.534
Payload weight	WN4	8093.	38.482
Fuel weight			
o Mission			
- Fuel type 1		402.	1.911
- Fuel type 2		0.	0.000
- Fuel type 3		0.	0.000
- Fuel type 4		0.	0.000
- Fuel type 5		0.	0.000
- Sum	WKR4	402.	1.911
o Reserve			
- Fuel type 1		225.	1.072
- Fuel type 2		0.	0.000
- Fuel type 3		0.	0.000
- Fuel type 4		0.	0.000
- Fuel type 5		0.	0.000
- Sum	WKRES4	225.	1.072
o Total			
- Fuel type 1		627.	2.984
- Fuel type 2		0.	0.000
- Fuel type 3		0.	0.000
- Fuel type 4		0.	0.000
- Fuel type 5		0.	0.000
- Sum	WKG4	627.	2.984
Takeoff weight	TOFW4	21030.	100.000

Aircraft weights
================

Max.payload weight	WNMAX	kg	8093.

```
Max.fuel weight                          WKMAX   kg               737.
Max.takeoff weight                       WAMAX   kg             21030.
Max.landing weight                       WLMAX   kg             20827.
Max.zero fuel weight                   WZFWMAX   kg             20403.


CG-Region (GKS)
===============
X direction (front...rear)                 XSP   m             12.549       13.356
Y direction (left ...right)                YSP   m             -0.032       -0.019
Z direction (low ...up)                    ZSP   m              0.423        0.585


Direct Operating Costs (DOC)
============================
Airframe price                             PZA   Mio.EURO        7.98
Engine price                               PTW   Mio.EURO        1.06
Unit price/max.payload weight              ZPV   EURO/kg        1247.
Years of Operation (= Life Cycle)           BJ   a              35.00
Range of DOC calculation                    R5   km              926.
Fuel price
- Fuel type 1                           KKR(1)   EURO/kg       0.5000
- Fuel type 2                           KKR(2)   EURO/kg       0.0000
- Fuel type 3                           KKR(3)   EURO/kg       0.0000
- Fuel type 4                           KKR(4)   EURO/kg       0.0000
- Fuel type 5                           KKR(5)   EURO/kg       0.0000

Life Cycle Costs
                                                             Mio.EURO            %
                                                             -------------------
Aircraft costs                            GFLZ                56.2196       69.976
Fuel costs                                 GKR                 1.9963        2.485
Crew costs                                GBES                 7.5658        9.417
Maintenance costs                           GW                 9.4574       11.772
Charges                                   GGEB                 5.1021        6.351
Total costs                                GKS                80.3412      100.000

Life Cycle Transport Work
                                            TA   Mio.Skm      372.085
                                                 Mio.tkm       74.417
                                                 Mio.km         9.195
                                                 h          20552.354
                                                 Flights     9930.195

Direct operating costs
                                           DOC   EURO/Skm     0.21592
                                                 EURO/tkm     1.07961
                                                 EURO/km        8.737
                                                 EURO/h      3909.101
                                                 EURO/Flight 8090.599


Design quality parameter
========================
GROWTH factor                      WAMAX/WNMAX                  2.599
Ratios
Payload                             WN4/TOFW4                   0.385
Fuel                               WKG4/TOFW4                   0.030
Operating empty weight              WOE/TOFW4                   0.585
Thrust to weight ratio           SO/TOFW4/GN                    0.430


Noise analysis (noise area)
===========================
o Takeoff case
Limit noise value                       LGMAXS   dBA(EPNdB)    89.000
Ground area                              ALGLS   m**2        0.000000
o Landing case
Limit noise value                       LGMAXL   dBA(EPNdB)    90.000
Ground area                              ALGLL   m**2        0.000000


Noise analysis (noise measurement points/FAR 36)
===============================================
```

```
o Takeoff/flight point 6500 m after break release
Allowed noise value                     XLFARS   EPNdB             0.000
Aircraft noise value                      XLIS   dBA(EPNdB)        0.000
o Takeoff/side line point 450 m to runway line
Allowed noise value                     YLFARS   EPNdB             0.000
Aircraft noise value                      YLIS   dBA(EPNdB)        0.000
o Landing/flight point 2000 m before touch down
Allowed noise value                     XLFARL   EPNdB             0.000
Aircraft noise value                      XLIL   dBA(EPNdB)        0.000



Checking of design constraints
==============================

RB(i) = -111.111                          Design constraints could not be determinated
RB(i) <= 0                                Design constraint is satisfied
RB(i) > 0                                 Design constraint is not satisfied

Takeoff field length               RB(1)   -0.15188
Landing field length               RB(2)   -0.16945
Total fuel volume/fuel type 1      RB(3)   -111.11100
Total fuel volume/fuel type 2      RB(4)   -111.11100
Total fuel volume/fuel type 3      RB(5)   -111.11100
Total fuel volume/fuel type 4      RB(6)   -111.11100
Total fuel volume/fuel type 5      RB(7)   -111.11100
Static maximum thrust              RB(8)   -111.11100
Aircraft length                    RB(9)   -0.62974
Aircraft width                    RB(10)   -0.66177
Aircraft height                   RB(11)   -0.68662
Approach speed                    RB(12)   -0.21882
Total cargo hold volume           RB(13)   -0.01458
Max.flight altitude               RB(14)   -0.36850
LCN (rigid runway)                RB(15)   -1.00000
LCN (flexible runway)             RB(16)   -1.00000
Rotation angle at takeoff         RB(17)   -0.08276
Horizontal tailplane area         RB(18)   -0.36364
(Control & stability)
Vertical tailplane area           RB(19)   -0.47689
(Control & stability)
Front X-CG Position               RB(20)   -0.75682
(Control & stability)
Rear X-CG Position                RB(21)   -0.03427
(Control & stability)
```

Appendix B

Optimization Algorithm "EXTREM"

The optimization algorithm "EXTREM" finds the nearest local extremum of a given target function. Due to the simplicity of the algorithm it features a broad area of possible applications, and, which is especially helpful for its use within PrADO, the gradients of the target function do not need to be known. The algorithm employs a parabolic extrapolation to search for the nearest extremum (See Figure B.1). In case of more variables, the so-called Gram-Schmidt-orthogonality procedure is applied, which means that a second search direction is used that stands orthogonally to the first search direction. The algorithm may be applied with an arbitrary number of input variables.

Based on a user-defined starting value C_1, an initial step size DC and the search task M ($M = +1$ in case of search for maximum and $M = -1$ in case of search for minimum) the algorithm determines the function values F_1, F_2 and F_3 at the positions C_1, C_2 and C_3, where

$$C_2 = C_1 + DC \tag{B.1}$$

$$C_3 = C_1 - DC. \tag{B.2}$$

The parabolic extremum C_4 is estimated as

$$C_4 = C_1 + \frac{DC}{|F_3 - 2F_1 + F_2|} \frac{F_2 - F_3}{2M}. \tag{B.3}$$

This procedure is repeated until a user-defined level of accuracy is reached. Further information on the optimization algorithm "EXTREM" is given in Jacob 1982.

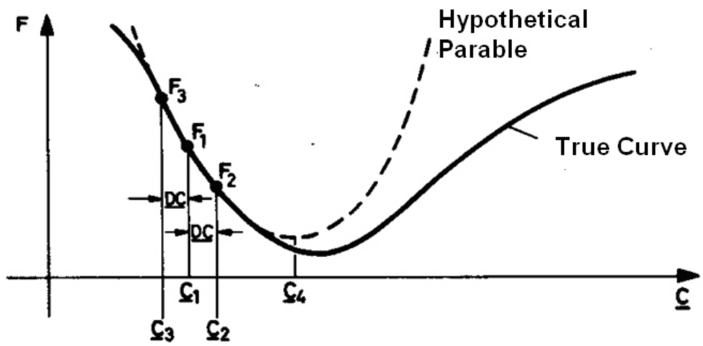

Figure B.1: EXTREM Parabolic Extrapolation (based on Jacob 1982)