# Life cycle assessment of current and future passenger air transport in Switzerland

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# Abstract

The aviation sector strongly facilitates the growth of modern economies. Around 10% of all passenger-kilometers are travelled by aircraft. The demand for this means of transport is projected to grow in the years to come. Air transportation emits globally about 600 million tons of carbon dioxide yearly to the atmosphere. Its contribution is estimated to be 2% of total global $CO_2$ emissions and 12% if we look at the share in the transportation sector only.

The goal of this study is to examine the current environmental impacts of air transport in Switzerland and to assess how future developments and technology improvements may influence the results in year 2050. Furthermore, the results are examined with respect to the change in the variables such as aircraft weight, fuel consumption, flight length or assumption about filling up the baggage hold that is used for passenger luggage (practice known as belly cargo). Life Cycle Assessment (LCA) methodology is used in this thesis to assess the environmental impacts of passenger air transport in Switzerland for aircraft with construction year 2015 and 2050. Five different generic models of passenger aircraft (regional; small and large narrow body; small and large wide-body) are developed and further examined.

Presented results show that the cruise phase is responsible for the majority of the greenhouse gas emissions (GHG). Much smaller, but still significant contributions come from the landing and take-off cycles and fuel production. They differ considerably due to the underlying assumption of average flight distance that is related to plane size. Regional aircraft are found to emit 157 g of $CO_2$ equivalent per passenger-kilometer (PKM), while the large wide-body one 71 g of $CO_2$ equivalent per PKM assuming the fill-up rate of 100% and average flight distances.

Belly Cargo in the case of low seat load factor was found to have crucial impact on the results. Sensitivity analysis shows that without applying this practice, GHG emissions may rise even up to 50% depending on the plane category. Two other crucial developments that influence the environmental impacts of future aircraft are fuel efficiency and exhaust emissions improvement rates and light-weighting of the aircraft structure.

This work implies that the most effective way to address the environmental impacts from air transport is to reduce fuel consumption while at the same time increasing the number of passengers on board or use the spare volume to carry additional freight.

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## List of abbreviations

| Abbreviation | Definition |
|---|---|
| ASK | Available Seat Kilometers |
| CAEP | Committee on Aviation Environmental Protection |
| CC | Climate Change |
| CCD | Climb, Cruise, Descent |
| CFRP | Carbon Fiber Reinforced Plastic |
| ETH | German: Eidgenössische Technische Hochschule. English: Swiss Federal Institute of Technology |
| FOCA | Federal Office of Civil Aviation |
| GFRP | Glass Fiber Reinforced Polymer |
| GHG | Greenhouse Gas |
| ICAO | International Civil Aviation Organization |
| kN | Kilo Newton (measure of thrust) |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LF | Load factor |
| LNB | Large Narrow-Body |
| LTO | Landing and take-off cycle |
| LWB | Large Wide-Body |
| $NO_x$ | Oxides of nitrogen |
| OEW | Operating Empty Weight |
| PAX | Passenger |
| PKM | Passenger Kilometer |
| PMF | Particulate Matter Formation |
| POF | Photochemical Oxidant Formation |
| RPK | Revenue Passenger Kilometer |
| RTK | Revenue Ton Kilometer |
| SCCER | Swiss Competence Center for Energy Research |
| SNB | Small Narrow-Body |
| SWB | Small Wide-Body |
| TA | Terrestrial Acidification |
| VFR | Visual Flight Rules |
| ZRH | Zürich Airport |

# 1. Introduction

## 1.1.Background and motivation

### 1.1.1. Advantages of air transport

The development of the aviation sector has brought considerable benefits to many economies across the world. In many dimensions, such as speed and mobility, aviation offers incomparable advantages over other transportation methods. Its traffic is forecasted to grow steadily at the rate of 4.9% over the period 2010-2030 (Airbus Global Market Forecast, 2014). The increase in demand will translate into a higher need for additional financial and natural resources.

Apart from being able to transport goods and people easily and quickly, air transport does not require infrastructure comparable with other means of transport. Unlike railways and road transport, there is no need to construct tracks and roads to move goods, only investment in airport construction is essential. On account of taxation, aviation sector is a net contributor to national treasuries, since it entirely covers its infrastructure costs.

Additionally, air transport is not limited by physical barriers. Due to the high altitudes where flights occur, natural barriers such as mountains, lakes, valleys do not interfere with the airplane routes.

Aviation brings along also numerous social and economic benefits. It provides a vast spectrum of holiday destinations, enriching people’s cultural and leisure experiences. It allows visiting friends and relatives in distant areas. For abundant regions throughout the world, it improves living standards and alleviates poverty through the development of tourism. This boosts the economic growth, provides income from taxes and creates new jobs. The economic development of many areas would not be possible without international trade. Air transport enables movement of goods from the regions which were less accessible in the past. As a result of high speed, airplanes facilitate the delivery of humanitarian aid, medical supplies and organs for transportation (Air Transport Action Group, 2005).

All the above mentioned benefits that air transport provides, combined with its expectations to grow, constitute reasons for this thesis.

### 1.1.2. Environmental impact of aviation

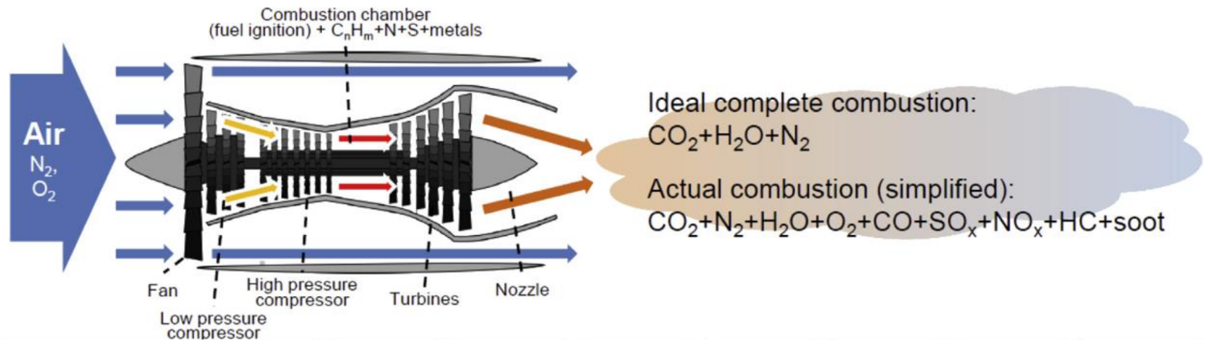
Over the recent years scientific communities have been conducting numerous high level researches on environmental phenomena such as climate change or ozone depletion. That has led to the increased level of environmental awareness and better understanding of those issues by general public. Consequently, more regulations and laws were put in place in order to reduce the environmental footprint.

Transportation sector represents high contribution to the global climate change due to the emissions of anthropogenic greenhouse gas (GHG), of which most concern is carbon dioxide ($CO_2$). Emissions produced by aircrafts are similar to those produced by other fuel combustion engines.

Aviation sector globally emits about 600 million tons of carbon dioxide yearly to the atmosphere. Its total contribution in the global $CO_2$ emissions is therefore estimated to be 2% of total global $CO_2$ emissions and 12% of $CO_2$ if we look at the share in transportation sector only (ICAO, 2010b). It is forecasted that total $CO_2$ emissions of the aviation sector will continue to increase at the rate between three and four percent per year. Worldwide airline carriers try to therefore take countermeasures in order to improve the environmental performance. Apart from the GHG emissions that are predominantly discussed, International Civil Aviation Organization in the reports also evaluates the effects of the noise and local air quality emissions (ICAO, 2013).

Figure 1-1 illustrates combustion occurring in a turbofan engine. Emissions of complete combustion ideally would include only carbon dioxide ($CO_2$), water vapor ($H_2O$) and nitrogen ($N_2$). However, the conditions under which combustion occur are not ideal. Atmospheric nitrogen is converted to nitrogen oxides under high temperatures, and not all fuel is completely combusted, leading to CO, unburned hydrocarbons, and soot. Furthermore, impurities in the fuel lead to the emissions of sulphur dioxide and heavy metals (Masiol, 2014).

**Figure 1-1 Simplified diagram of a turbofan engine (upper left); products of ideal and actual combustion in an aircraft engine (upper right); and related atmospheric processes,**



Source: (Masiol, 2014)

Majority of the publications provide environmental comparisons basing their models only on the tailpipe emissions. However, a comprehensive and holistic analysis will include not only emissions from fuel combustion (Facanha and Horvath, 2007), but will develop a systematic methodology looking at the other life cycle phases as well. A detailed aircraft fleet analysis will allow for improved understanding of environmental impacts of air transportation now and in the future as the technology develops. One expected future development is light-weighting of the aircraft. On one hand this process may cause reduction of fuel use, on the other hand however, one may expect higher environmental impacts occurring during the manufacturing stage due to the production of more complex materials.  Additional argument for using LCA is that apart from considering only direct emissions, it also tries to avoid burden shifting.

According to the “polluter pays principle”, environmental costs should be paid by the end user. In order to find the actual external costs the lifecycle costs of air transport must be known. This thesis provides a first step on this pathway by performing a Life Cycle Assessment (LCA).

### 1.1.3. Environmental impacts in Switzerland and the Swiss Energy Strategy 2050

Transportation in Switzerland uses in total more energy than the households. Greater mobility apart from the benefits, brings unwanted threats as well. Share of the transport sector in the domestic energy sale in year 2013 was as high as 35%. Petroleum products satisfy 96% of the transport energy requirements. Road and air transport are responsible for 37% of $CO_2$ emissions (FSO, 2015).  Biggest contributors of the air pollution and GHG are road and air transport. They release large amount of substances that are harmful to human health. The transport sector relies mostly on petroleum products for now, but this reliance is likely to decrease in the coming decades. According to the Federal Office for the Environment, only 0.8% of $CO_2$ emissions in Switzerland come from air transport. This number however includes only national air movements which in case of Switzerland constitute a marginal contribution of total movements. Globally, aviation is responsible for about 12% of GHG emissions. Therefore, another motivation to perform this research was to examine in details the share of air transport in Switzerland in environmental emissions (FSO, 2014).

Following up the Fukushima Daiichi nuclear accident in 2011, the Swiss Federal Council has decided to withdraw from the use of nuclear energy and to perform transition into more sustainable energy sources. Five existing nuclear power plants will be decommissioned at the end of their safe service lives. For that reason the Energy Strategy 2050 was created with a main goal to provide long-term energy policy focused on restructuring Swiss energy system in order to meet climate goals. The three scenarios were created (Prognos, 2012):

1) The Business As Usual (BAU) – current policies shall remain in place and improvements will remain their historical rates;

2) The Political Measures (POM) – implementation of currently discussed political measures and retaining of historical improvement rates;
3) The New Energy Policy (NEP) - scenario of reduction annual GHG emissions down to 1-1.5 t per capita.

Despite population and transport demand growth in Switzerland, depending on the scenario, the $CO_2$ emissions in transport sector compared with year 2010, are projected to reduce by 38-86% in 2050 (Prognos, 2012). Main argument for this decrease is an expected improved energy efficiency of transport technologies.

### 1.1.4. Efficiency improvements

Since the development of an aircraft, the technology improvements have enabled to make it more fuel efficient. This better efficiency generally translates into lower environmental emissions. Aircraft manufacturers through the world set as their goal to continue on achieving those improvements for the years to come. Nevertheless, the demand growth in air traffic is outpacing the rate of efficiency improvement. Therefore, the pressure to create and develop new, better fuel-efficient technologies is even greater than before. Efficiency gains and reduction of pollutants may come from various sources such as: changes in design, improved air traffic management or optimized operations.

Introduction of new materials such as composites or advanced alloys, have significantly contributed to the weight reduction of an aircraft. The use of those advanced materials has caused weight and fuel savings over the years. New models (e.g. Airbus A350, Boeing 787) feature even up to 70% of light-weight materials (ICAO, 2010a). Additionally, new manufacturing processes and techniques cause weight reduction as well. Innovative manufacturing methods such as laser beam or electron beam remove need for traditional rivets decreasing aerodynamic drag and lowering manufacturing costs (ICAO, 2010a). Nonetheless, the use advanced materials like carbon fiber reinforced plastic (CFRP) increases the GHG emissions during the manufacturing process compared to conventional materials such as steel and aluminum (Ecoinvent, 2014). One of the motivators to write this thesis was to evaluate whether the environmental costs of producing light-weight materials outweigh the benefits afterwards or not.

Aerodynamic improvements were also caused by the use of advanced materials. Reducing skin friction, minimizing the number of intersection on the fuselage and improving exhaust devices are just some of the examples. They were however found to be out of scope for this study.

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Improvements in engine performance decrease emissions, lower noise levels and reduced maintenance costs. This continuous process delivers better results in fuel burn observed during the testing of commonly used engine types. Additionally, the ground tests with the use of blends of jet and alternative fuels were also performed. Results provide significant amounts of fuel savings and benefits related to the $CO_2$ emissions (ICAO, 2010a).

Despite the fact that improved fuel consumption, reduced drag and noise levels are main drivers during the design process, manufacturers need also to remember about another factors such as performance, maintenance costs, durability, comfort or timing. The proposed efficiency improvements must provide a balance between economic feasibility and environmental requirements.

Additional motivation for this thesis was a long-term vision of aircraft in year 2050. Significant improvement of efficiency is a long process. Design phase of an aircraft can take up to 10 years. Manufacturing can run even for 30 years. Many models are in operation for over 20 years, and some live even up to 40 (ICAO, 2010a). Products with such a long lifetime demand diligent and sound choices during their planning stage. Aircraft engine and body should address the environmental and technological questions of the future, trying to minimize their burden on the Earth’s atmosphere. International Civil Aviation Organization’s (ICAO) committee tries to develop a stable regulatory framework based on the scientific knowledge and to develop international standards in aviation. One of them is a “$CO_2$ standard for new aircraft types”, as an example of a measure that should be taken. ICAO attempts to gather all stakeholders involved in aviation: manufacturers, suppliers, airports, airlines, research institutes and service providers, and encourage a cooperation to meet a common goal which is to decrease the overall impact on the environment. The united strategy of ICAO partners assumes following:

- Average decrease in fuel consumption of 1.5% per annum.
- Neutral growth of carbon emissions from year 2020.
- Cutback of $CO_2$ emissions in year 2050 by 50% compared with 2005.

Achieving those aggressive goals can be met by cooperation of all parties involved in the industry as well as policy making. This thesis tries to evaluate how the implementation of some of those targets can influence overall environmental impacts of an aircraft and how important are the efficiency improvements in achieving those long-term aims.

## 1.2.Research goal

The primary objective of this thesis is to analyze the environmental performance of Swiss air transport. Contributions coming from the results may be used to possibly improve the reporting of emissions and to better understand the environmental impacts. The first assessment is done using the current available technologies. Afterwards, the projections are made for 2050 based on the technology improvements.

The main research question can be written as follows:

*What are the life cycle environmental impacts of passenger air transport in Switzerland? How may they change over the time until year 2050, given the technology developments?*

This main goal has been broken into three goals, which may be formulated in a following way:

1. *Assess the life cycle environmental impacts of passenger and freight aircraft transport in Switzerland.*
2. *Compare impacts of year 2015 technology with estimated 2050 technology.*
3. *Examine impacts with variables such as aircraft sizes, lifetime, flight distances or rate of technology improvements.*

## 1.3.Current methodological limitations

Current Life Cycle Impact Assessment (LCIA) methods use characterization factors for pollutant emissions for ground level. This thesis attempts to differentiate impacts based on their location. It breaks them into those that occur during landing and take-off (LTO) and climb, cruise, descent (CCD) cycle. Development of new LCIA method in this work was out of scope, however the results provided here can be used as a starting point for further regionalization of air travel impacts.

## 1.4.Future outlook

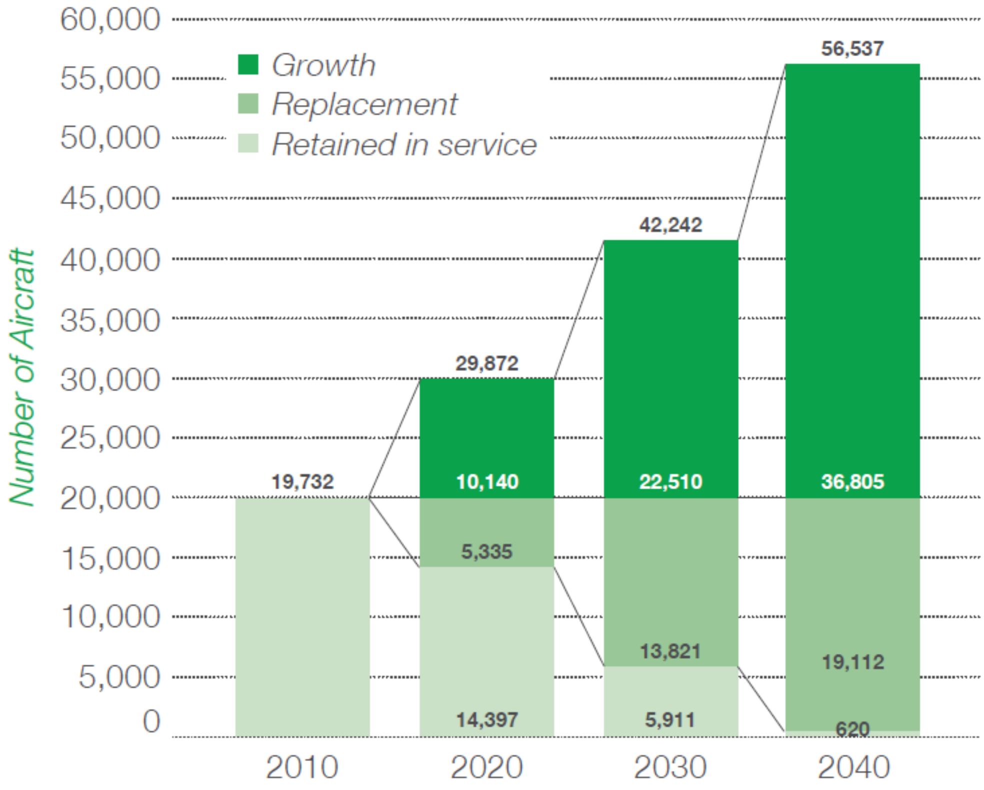
For better understanding of environmental impacts of air transportation, it is essential to evaluate the future evolution of aviation industry and differences that may be result of it. That includes the supply and demand development, delivery forecast, capacity growth and financing requirements.

This work describes those dynamics in order to analyze current and future market trends and in result select airplane models for study.

### 1.4.1. Passenger and freight fleet forecast

World passenger fleet is currently estimated at around 21,000 aircraft (AVLON, 2014). This number is expected to triple by the year 2040. Most of 2013 fleet is likely to retire and be replaced by new deliveries by then (ICAO, 2013). Likewise passenger fleet also freight is going to grow. Dominating positions of Airbus and Boeing is not expected to change and those two companies will account for approximately 90% of total delivery dollars (AVLON, 2014). New models are to have smaller environmental footprint, which gives an indication that LCA performed in this thesis for year 2050 may have different results than those of 2015. Figure 1-2 presents the forecast of the global aircraft fleet development.

**Figure 1-2 Global passenger fleet evolution. Source: Airbus.**



### 1.4.2. Passenger and freight traffic forecast

Global passenger traffic is projected to develop at a steady rate. Until the year 2030, expressed in the revenue passenger kilometers (RPKs), it would grow from five billion in 2010 to almost 20 billion in 2040. International traffic is expected to grow at a slightly faster rate per annum – 5.1%, than domestic one – 4.4% p.a. The share of intra-European routes would amount to 1.3 billion RPKs in the year 2040. The traffic within Europe will remain among top five route groups in term of passenger volumes (ICAO, 2013).

Freight is expected to grow from over 200 billion revenue ton kilometers (RTKs) to almost 900 billion RTKs in year 2040. That results in a growth of 5.2% p.a. from 2010 to 2030 and 4.6% from 2030 to 2040.

## 1.5. Overreaching research project

This master thesis is conducted as a part of the governmental research program Swiss Competence Center for Energy Research in Mobility (SCCER - Mobility). It concerns the topics of mobility in transportation sector in Switzerland. The overreaching goal of the program is to stimulate innovation in order to find new solutions to the challenges that Swiss transportation sector is facing. SCCER aims to create a sustainable system with minimized $CO_2$ output and virtually zero-pollutant emissions. Research teams involved in the project come mostly from the ETH-Domain and Universities of Applied Sciences, but many foreign institutions are committed as well (SCCER Mobility, 2015). This work will contribute to the development of work package B2.2 “Transport Impact Assessment”.

This thesis is a part of PhD dissertation of Brian Cox, performed at Paul Scherrer Institute (PSI), Swiss Federal Institute of Technology Zurich. His main objective is to develop a bottom-up economic and environmental life cycle assessment model of the entire Swiss transport sector. In the first stage of his work, a model for the current (2015) year will be developed. Unlike sector scale models which often evaluate only tailpipe emissions, this PhD work will incorporate complete life cycle assessment of chosen transport technologies. In result, the holistic model will allow for comparison of environmental and economic impact among all major freight and passenger transportation means in Switzerland. Furthermore, the model will be adjusted for potential technology developments until year 2050. This objective fits into the goal of Swiss government of reducing energy consumption and environmental impacts coming from the transportation sector. Gathering of large amount of data for the life cycle inventory, will allow for the development of dynamic LCA. This methodology will enable for improved usability and understanding of the results and  (Cox, 2014).

## 2. Literature review

The aim of this section is to provide the reader with the overview of sources relevant to the environmental and economic assessment of air transport. By doing so, it allows to gain better view of the background information and in result to make the whole thesis more understandable. Additionally, this chapter will try to analyze major strengths and weaknesses of included studies. Finally, it will provide steps that should be taken in order to strengthen the analysis and fill gaps of other literature sources.

**"Transport Services. ecoinvent report No. 14" (Spielmann, 2007)**

Michael Spielmann, Christian Bauer and Roberto Dones (Paul Scherrer Institut) are authors of the report of transport related datasets in ecoinvent. Main objective of this work is to provide data for transport modes with an aim to complete a variety of product life cycles. Authors generated data for air-, rail-, road- and water transport, representing average conditions in Switzerland and Europe. The functional unit used here for goods is one tone kilometer (TKM) and passenger kilometer (PKM) for passenger transport data.

For air transport, authors model impacts for all life cycle phases: manufacturing, operation, maintenance, disposal, infrastructure construction, operation and disposal. This project models emissions for two flight types: intra-European and intercontinental. It neglects analysis of specific freight aircrafts since they are mostly used for transportation of goods with large dimensions and military functions. Instead, the work assumes that most of the world's freight is carried in passenger aircraft. Determination of energy consumption is performed taking into account the most important international airports in Switzerland. The analysis also shows that intercontinental transport is responsible for 95% of the total freight from Swiss airports. The fuel consumption results obtained in this project for long haul flights are close to those available in other literature sources. The authors state however that for short distance flights, the difference and therefore uncertainty is higher. When calculating the consumption expressed in PKM, this study employs a representative mass of 240 kg per one passenger. The disposal effect of an aircraft has not been taken into account due to the low total environmental impact. For estimating manufacturing impacts, authors consider a breakdown of only two materials: plastic (10%) and aluminum (90%). To measure energy expenditures in the production phase, authors use data collected for 16 manufacturing facilities of Airbus. Environmental results for the airport infrastructure are calculated using the data available for the Zurich Airport. Authors mention many uncertainties connected with the study and evaluate the overall quality of data as medium.

It is the most comprehensive modeling of background data for air transportation so far. This utilizes the production datasets provided in the report, such as how much electricity or water per passenger (PAX) is being consumed during the manufacturing process. It can be said that work of Spielmann and co-authors is a base for environmental results from the phase of infrastructure construction and energy production for the manufacturing of aircraft. Data produced in this report is currently used in ecoinvent, the largest Life Cycle Inventory (LCI) database in the world. Nevertheless, the report does not provide forecasts for the future on how the impacts can change given the efficiency improvements.

### “Life-cycle Environmental Inventory of Passenger Transportation in the United States” (Chester, 2008)

Chester in his paper performs full LCA of passenger transportation in the United States including following modes: automobiles, buses, rail and aircraft. To accurately represent the entire commercial fleet in the USA he chooses to analyze three aircraft models: Embraer 145, Boeing 737, and Boeing 747. Author also uses the ICAO reference times for LTO and estimates emission factors for each of the LTO stage for three analyzed aircraft. He mentions that operational phases are responsible for the majority of GHG emissions and energy use during plane’s lifetime. Cruise accounts for 55% (Embraer 145) and 74% (Boeing 747), LTO for 27% and 4% (for the same plane models respectively) of GHG emissions and energy use. Manufacturing phase in case of 747 is responsible for 6% of environmental impacts. Fuel production accounts for around 10% (Chester, 2008).

### “Life Cycle Assessment of the Airbus A330-200 Aircraft” (Lopes, 2010)

Author in his master thesis work carries out a LCA of the Airbus A330-200. To collect the large amount of data needed, he cooperates with Portuguese airliner “TAP Portugal”. The work provides detailed information about weight and material composition of each aircraft component, which was used in this thesis. Therefore a manufacturing phase and LCA results for it were thoroughly modeled. Lopes uses ecoinvent unit processes, the same database that is used in this study. Concerning the functional unit used, author adopts PKM, which is a standard practice in the literature. The results show that 99.9% of total process contribution to climate change is a result of the fuel burn process, which already includes fuel production. Despite their marginal role, author points out that airport construction and aircraft maintenance create higher environmental burden than manufacturing phase of an aircraft. Manufacturing phase represents only $4.68\text{x}10^{-6}$% of total climate change impact.

End-of-life scenario is responsible for 1.23x$10^{-6}$% positive contribution out of total impact. Similarly to the work of Lewis (2013), Lopes also states a high impact of manufacturing the wing and engine structure. The disposal phase is analyzed with great detail and underlines importance of life cycle approach for company like Airbus, regarding the possibility of recycling and in effect reducing the costs. In addition, this paper shows the need of using alternative fuels as well, in order to improve environmental performance of an aircraft.

### “A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios” (Lewis, 2013)

Tyler Lewis (Norwegian University of Science and Technology) evaluates the total environmental impacts of air transport using a life cycle framework in his Master thesis. He uses process-based LCA and economic input-output tables. This method estimates the required resources and environmental emissions by the activities in our economy. It uses aggregated data (usually in the form of input-output tables) on the sector level to calculate the impacts. Because this analysis relies on sector-average values, it might provide less representative results than the full LCA. However, the results are more complete because they include the whole value chain.

Lewis recognizes a need to evaluate not only tailpipe emissions but entire system performance. He uses three various flight scenarios (935 km, 2,991 km and 5,178 km) to capture emission impact. In order to best replicate the typical flight, he assigns three various aircraft types to his scenarios. The shorter distance is analyzed considering Airbus A320, medium-range scenario Airbus A330 and the longest one using Airbus A380. To understand how various aircraft elements contribute to the environment, author presents a detailed breakdown of material by aircraft structural components. Findings present that at least 70% of all environmental impacts coming from manufacturing are connected entirely to the wing and engine structures. Therefore, those parts are first to be analyzed when looking for efficiencies. Among three considered plane types, A320 presents a more balanced contribution of structures to total climate change, than A330 and A380. In order to normalize results of environmental impacts, Mr. Lewis applies three different functional units: passenger kilometer of travel (PKM), vehicle kilometer of travel (VKM) and lifetime vehicle travel (LKM). According to his findings, between 16% and 21% of total emissions, come from non-tailpipe. As a result of high energy requirements for landing and take-off cycle (LTO), short flights demonstrate larger emissions per passenger kilometer of travel. In general, the author comes to the conclusion that different life cycles of an airplane have significant contribution to the environmental impact as well as plane specifications and flight characteristics.

### “Environmental life cycle assessment of commercial passenger jet airliners” (Howe et al., 2013)

The study utilizes a LCA of an Airbus A320 to determine environmental impacts of life phases. They include production, operation and disposal. The results show that the manufacturing phase of A320 contributes only by around 0.01% to the environmental impact. On the contrary, the operational cycle represents over 99%. Disposal shows a positive return of 10% of the overall manufacturing phase, which, when considered return over the lifecycle, translates only to 0.001%. Calculations are performed with the assumption of 20 year service life time and 81.5% load factor. In addition, authors show interesting comparisons between traditional and alternative aviation fuels across different categories. Concerning the climate change, biofuel produced from a mixture of biomass (algae, jatropha) absorbs $CO_2$ emissions and there reduces the GHG emissions by 60-85%. This work does not use input-output analysis but performs full LCA. The overall research effort of this study provides an important framework for a future investigation.

### Other scientific papers

High importance of the aircraft emissions on human health are underlined by a scientific paper of Steven Barret, Rex Britter and Ian Waitz from University of Cambridge and Massachusetts Institute of Technology in their 2010 work *Global Mortality Attributable to Aircraft Cruise Emissions*. They show their estimates of ~8000 premature mortalities per year due to the aircraft cruise emissions, which is about 80% of the total impact of aviation sector when including landing and take-off emissions. At the same time $NO_x$ emissions cause oxidation of non-aviation $SO_2$ to increase, and therefore further changing the air quality (Barret, 2010). Due to the fact that the ReCiPe method used in this thesis does not correctly asses emissions created during cruise phase, the characterization factors for photochemical oxidant formation (POF) and particulate matter formation (PMF) categories have been set to zero. Terrestrial acidification impacts caused by nitrogen oxides from the cruise phase are still considered. This approached is also applied in this thesis and further discussed in the section 3.2.2.

Another area that currently receives a lot of attention in scientific research of aviation is the development of alternative fuels. Simon Blakey, Lucas Rye and Christopher Wilson from the Department of Mechanical Engineering of University of Sheffield in their paper *Aviation gas turbine alternative fuels: A review*, summarize commercially available technologies to produce alternative fuels. Furthermore a lifecycle analysis of alternative fuels is compared with the data for standard jet fuel. Results show that although alternative fuels may not contribute to reduce greenhouse gas emissions, the air quality around the airports may improve due to the reduced particulate emissions.

Authors however conclude that the data to perform full LCA was not always consistent and the methods to obtain it should be standardized (Blakey, 2011). The analysis of use of alternative fuels was found to be out of scope for this thesis.

$CO_2$ emissions in the transportation sector among 27 European Union countries are the main topic of a 2012 paper *Technology Limits for Reducing EU Transport Sector $CO_2$ Emissions* by Laynnette Dray, Andreas Schäfer and Moshe Ben-Akiva. Authors estimate lifecycle carbon-dioxide emissions from the transport sector in 27 EU countries. They look at the scenario in the absence and presence of adopted policies for the year 2050. According to the authors, $CO_2$ emissions are strongly dependent on the country's economic development and geographical area rather than on uncertainties in technologies. The absence of polices planning to reduce the emissions, show however larger environmental impacts coming from the transportation sector. Meeting goals proposed by policymakers requires reduction of GHG emissions in 2050 compared with 1990 values. Authors conclude that only very strong changes in technologies would allow for emissions reduction from heavy trucks and aviation (Dray, 2012).

Lynnette Dray in a 2013 paper *An analysis of the impact of aircraft lifecycles on aviation emissions mitigation policies*, looks at various options that would reduce environmental impact coming from aviation sector. Author looks how variable such as retrofits, new technologies or early retirement influence emissions reductions. The mean fuel burn of new orders between 1970 and 2005 is analyzed, and author estimates the average fuel improvement to be between 0.4% and 1.6% per year, depending on the aircraft type. Fuel burn and kerosene costs have turned out to have a small significance when airlines when choosing for an aircraft to purchase between the years 1970 and 2005. Dray also analyses the retirement curves, and concludes that they differ depending on the plane type as well as the manufacture year. The retrofits of the analyzed global fleet did not however show significant potential for fuel burn reduction. Policies aiming to increase fuel prices show to have impact on purchasing and retirement decisions only when the prices rise above the historical levels. The area with the highest potential for reducing global emissions turned out to be the policies that focus on increasing the rate of technology improvements (Dray, 2013). The same author together with other co-authors in the other paper from 2014 looks into the replacement of fleet subsidized by the carbon tax. The results show that compared with non-policy scenario, this approach may reduce by around 34% aviation related global carbon dioxide emissions by year 2050. Those big $CO_2$ savings come mostly from the use of new technologies caused by the fleet replacement (when planes reach 20 years of age), higher carbon prices and both demand reduction and rise in the use of biofuels. High variability of the carbon price is mentioned as one of the drawbacks of such policy application (Dray, 2014b). Another 2014 paper of Dray, looks into the timescale over which the new technology enters the fleet and what factors may influence that. Among others she mentions demand for new aircraft and policy measures. Author states that global carbon dioxide emissions could be reduced by 10% if the global aircraft fleet were replaced with the lowest-emissions present-day models of the same range and capacity. However, long aircraft lifetime influences the pace at which new technologies are introduced which may further increase the new policies aimed at reducing emissions through technologies (Dray, 2014a).

Anthony Evans and Andreas Schäfer in their 2013 paper *The rebound effect in the aviation sector* analyze the "rebound effect" in aviation. This offset of the energy efficiency improvement potential is created when introducing more fuel efficient technology does not allow to exploit the energy savings potential because it generates extra demand for other energy services. It is expressed as the percentage offset of the reduction in energy consumption as offered be the more fuel-efficient technology alone. Authors look into details at an air traffic network of the 22 busiest airports and come to interesting conclusions that the average rebound effect on those sites is about 19% for the range of aircraft fuel burn reductions considered. This corresponds to the net impact of a growth in supply to meet the air transportation demand. Authors state that such a large rebound effect would require significant fuel tax increase which would not be economically viable for an industry that operates at very small profit margins (Evans, 2013).

W.R. Graham from the Institute for Aviation and the Environment, University of Cambridge, reviews studies on emissions coming from the aviation and compares the results with targets suggested by NASA and ACARE (Advisory Council for Aviation Research and Innovation in Europe). Findings of this paper prove that goals set by those two organizations are quite unrealistic to achieve in the next 20-40 years. It is however possible to gain significant advantages in the future when it comes to the technology. The paper reviews how the future technology may influence the reduction of $CO_2$, $NO_x$, and noise emissions. Author concludes that oxides of nitrogen have a high potential of being reduced independently from the other two emissions. Improving fuel consumption rate is a more challenging task and involves a list of radical technological changes. If combined with the goal to decrease noise pollution, this target becomes more difficult and the compromise between fuel efficiency and noise reduction might be needed. Generally speaking, in order to achieve significant fuel-burn benefits, author proposes to fly slower and utilizing propeller engines when possible (Graham, 2014).

P. Krammer, L. Dray and M. Köhler are authors of a paper analyzing global aviation biofuel use and what effect may the $CO_2$ reductions have on the climate change. To stimulate the feedback of the aviation system to the changes in costs and available technologies, this work utilizes Aviation Integrated Modelling (AIM) concept. This model comprises of seven interconnected modules such as: the air transport demand, the airport activity, the aircraft technology, cost, fuel burn, fleet turnover and the aircraft movement. After all the modules are run, the output is calculated with regard to the global climate change when using biofuels. Under the assumptions of this paper, authors show that the total climate change impact of widespread biofuel use in aviation may still be large. Aviation fuel lifecycle carbon dioxide emissions may be however reduced when combined with other factors such as weaker demand due to increase in fuel prices, strong demand for biofuels and adoption of radical technology improvements (Krammer, 2013).

In a paper published in 2009, David Lee performs a historical analysis and future forecast of aviation emissions to the climate change. He uses radiative forcing as a measure to quantify the climate change impact of aviation. In his 2050 forecast, due to the increase in traffic he expects growth of radiative forcing despite the technological changes that are taken into consideration as well. For all five tested cases, carbon dioxide emissions in 2030 compared with 2002, increase by factors ranging from 3.29 to 1.98. As the reference case, author assumes the average fuel efficiency of 1.3% per year to 2010, 1% to 2020 and 0.5% until 2050. Paper lists major areas which may have the biggest impact in mitigating aviation climate forcing: improving the fuel efficiency, alternative fuel use, air traffic management, changing (mainly lowering) the cruise altitudes and decreasing flight speeds. Since rates of passenger load factors were at historical maximum, author assumes no further significant improvements. The long lifetime of an aircraft, increases complexity of estimating the rate at which new technologies enter the fleet. Demand-driven growth in aviation may however outweigh the potential future environmental gains (Lee, 2009).

Another example of a study that tries to estimate the future emissions is a paper of Andrew Macintosh from 2009. He tries to answer the question of how intense the improvements in aviation until year 2025 should be in order to offset for the rising international demand. In the projections made in this paper, international $CO_2$ emissions from civil aviation in 2025 are likely to be 111 or 144 per cent (depending on the scenario) compared with the year 2005. Author states that without imposing the pricing on carbon emissions, which would restrain demand, it will become difficult to keep the carbon dioxide emissions below 100 per cent level more than in the base year 2005. In order to keep the international $CO_2$ emissions from aviation in 2025, 111 or 144 per cent above 2005 levels, average annual improvement rate of carbon dioxide emissions would need to be 1.7 and 1 per cent respectively. Another scenario shows that to keep the emissions at the 2005 level, the rate of improvement would have to be 5.2% p.a., which appears to be unlikely given the current technology progression. This paper does not take into account other emissions but focuses on $CO_2$ only (Macintosh, 2009).

Andrew Timmis together with another authors looks in his 2015 paper into aviation emission reduction due to the use of composite materials. He performs LCA of a Boeing 787 Dreamliner using

SimaPro software together with ecoinvent database. He uses an estimate of 20% weight saving between CFRP and aluminum alloy structure, a lifespan of 30 years of an aircraft and 150 million kilometers operating lifetime. During the manufacturing phase, CFRP shows higher environmental impacts than aluminum due to the higher energy consumption used during production. However, in the full life cycle of an aircraft, application of composite materials shows potential of 14-15% fleet-wide $CO_2$ emissions reduction. Other benefits of using CFRP according to the author are: reduced fuel consumption, lower operating costs, and reduced weight. Author uses the output of three integrated assessment models: Integrated Global System Model (IGSM), Model for Evaluating the Regional and Global Effects (MERGE), and Mini-Climate Assessment Model (MiniCAM) as for the base scenarios of future predictions. Following values have been estimated with regard to Mt per PKM of $CO_2$: year 2005 – 0.135; 2020 – 0.125 (no composites), 0.118 – (composites); 2050 – 0.127 (no composites), 0.100 (composites). Even though CFRP shows higher emissions during manufacturing and disposal phase, due to the major share of operation phase, it shows significant reduction in impact during plane’s lifetime (Timmis, 2015).

### Flightradar24, PlaneSpotters.net, Airliners.net

This work could not be realized without the data gathered from crowd-sourced websites of aviation fans. Three main sources used in this thesis are:

1. Flightradar24.com – website service that presents real-time flight information. It allows tracking on a map almost any commercial flight in the world. It includes data such as: departure and arrival spots, flight tracks, altitudes, airlines, aircraft types, speeds and heading. Additionally, what was vital for part of this thesis, it provides graphic information about LTO and operating cycles. The website gathers information from following sources:
    a. Automatic dependent surveillance-broadcast (ADS-B) – is a system of receivers gathering the data about the flight from the aircraft transmitters. Devices are run usually by volunteers and aircraft enthusiasts.
    b. Multilateration (MLAT) – navigation technique used to locate the aircraft by determining the time it takes to receive the signal from aircraft.
    c. Federal Aviation Administration (FAA) – United States authority that presents the data with 5 minutes delay. Includes most of the traffic in USA, Canada, Pacific and Atlantic Ocean (FlightRadar24, 2015b).
2. PlaneSpotters.net – internet service that provides comprehensive data on airlines and their aircraft. It has significantly contributed in this thesis to define characteristics of the Swiss

aircraft fleet. It allows showing all machines of a specified airline that are in active use, stored, scrapped or written off (Planespotters.net, 2015).

3. Airliners.net – the largest aviation website in terms of the database and page-views. Its detailed Aircraft Data & History section allowed for gathering of specific plane information. This included schematics, history, power plants, performance, weights, dimensions and capacity information (Airliners.net, 2015a).

### Summary and comparison

This thesis varies from above described sources in different ways. First of all, unlike the paper of Lewis (2013), it does not use economic input-output tables with sector-average values, but performs the full LCA. Secondly, Lewis analyzes three various flight scenarios to capture emission impacts. This work provides more flexibility since the flight distance appears as a parameter that the user can change to obtain individualized outcome. Moreover, Lewis does not try to model the potential changes in the future. This paper does it by estimating potential environmental results given technology improvements up to year 2050.

Lopes (2010) performs LCA with a strong focus on material composition of Airbus A330-200. Interestingly enough, his analysis shows that 99% of total process contribution to climate change is a result of the fuel burn process. On the other hand, Lewis discovers that 16-21% emissions have a non-tailpipe source. Lopes mentions different scenarios of fleet development until 2030. He however does not use them to perform LCA but only calculates the change in global $CO_2$ emissions from aviation until 2030 assuming different cases. This thesis utilizes the datasets from Lopes' work, especially on aircraft weight and material composition.

Spielmann (2007) models emissions only for intra-Europe and intercontinental flights. This work, as mentioned above, uses parameterization of flight distance. Additionally, Spielmann uses mass of 240 kg for one passenger to transform ton kilometer into passenger kilometer. The reason for that is that Spielmann also considers the weight of the parts of the plane that passengers use (i.e. seats), which this work does not take into account. In this thesis, a weight of 100 kg per passenger is applied. It is based on Swiss statistics that takes into consideration an average weight of 70 kg per person plus 30 kg of luggage (BAZL/BFS, 2002). In reality, most of the freight is transported on passenger planes, and this work additionally assumes that empty seats are replaced with freight, which makes 100 kg assumption more accurate allocation method than 240 kg. Spielmann uses the reference data from 1999 and takes into account only two materials in material composition: plastic (10%) and aluminum (90%). That does not reflect the material breakdown of aircraft being currently in service and certainly does not align with the forecasts. Therefore, this thesis performs analysis with the use of more materials in the breakdown and tries to evaluate how their share may change in the future. Spielmann's production data sets of aircraft and airport manufacturing are the best estimates available at the moment of writing this thesis and are utilized here.

To summarize, research papers mentioned in this section give following important values:

- the average fuel improvement rate between 0.4% and 1.6% per year between 1970 and 2005 (Dray, 2013),
- 0.5% annual fuel efficiency improvement rate between 2020 and 2050 (Lee, 2009),
- 14-15% reduction of $CO_2$ emissions due to the light-weighting and 20% weight reduction (Timmis, 2015),
- most likely scenario of reducing international $CO_2$ emissions from aviation by 111 or 144% in 2025 compared with 2005, assumes average annual improvement rate of carbon dioxide emissions of 1.7 and 1% (Macintosh, 2009),
- cruise phase is responsible for 55% (Embraer 145) and 74% (Boeing 747), LTO for 27% and 4% (for the same plane models respectively) of GHG emissions and energy use. Manufacturing phase in case of 747 accounts for 6% of environmental impacts and fuel production for around 10% (Chester, 2008),
- 99.9% of climate change impact in case of A330 is a result of the fuel burn process, which already includes fuel production (Lopes, 2010),
- manufacturing phase of A320 causes only around 0.01% of environmental impacts. Aircraft have a lifetime of 20 years and 81.5% load factor (Howe, et al., 2013),
- normalizing the results and assuming 83% seat load factor of a regional plane authors calculate following results: Chester (2008) – 181 g $CO_2$ eq/PKM; Spielmann (2007) – 170 g $CO_2$ eq/ PKM
- for the small wide-body plane seat load factor equals 75%. All five studies show following results (in g CO2 eq/PKM): Spielmann (2007) – 111; Chester (2008) – 128; Lopes (2010) – 126; Lewis (2013) – 126 g $CO_2$ eq/ PKM.

All above mentioned studies were relevant reference points in production of this work. This thesis aims at improving on the weaknesses of those papers and tries to perform full LCA in a most holistic way, given the available resources.

# 3. Methodology - Life Cycle Assessment

The evaluation of environmental impact used in this thesis is performed by life cycle assessment (LCA). This method stands out as a holistic way to quantify and interpret environmental burdens, taking into account the whole life cycle. This chapter describes the background and methodological aspects of the study.

## 3.1.Background

Increasing environmental awareness has encouraged various industries to assess the effects of their activities. The overall trend opts towards less environmentally harmful products and processes. In order for companies to improve various areas of products life cycle, they need comprehensive methods to address this challenge. One of the tools allowing for that is LCA.

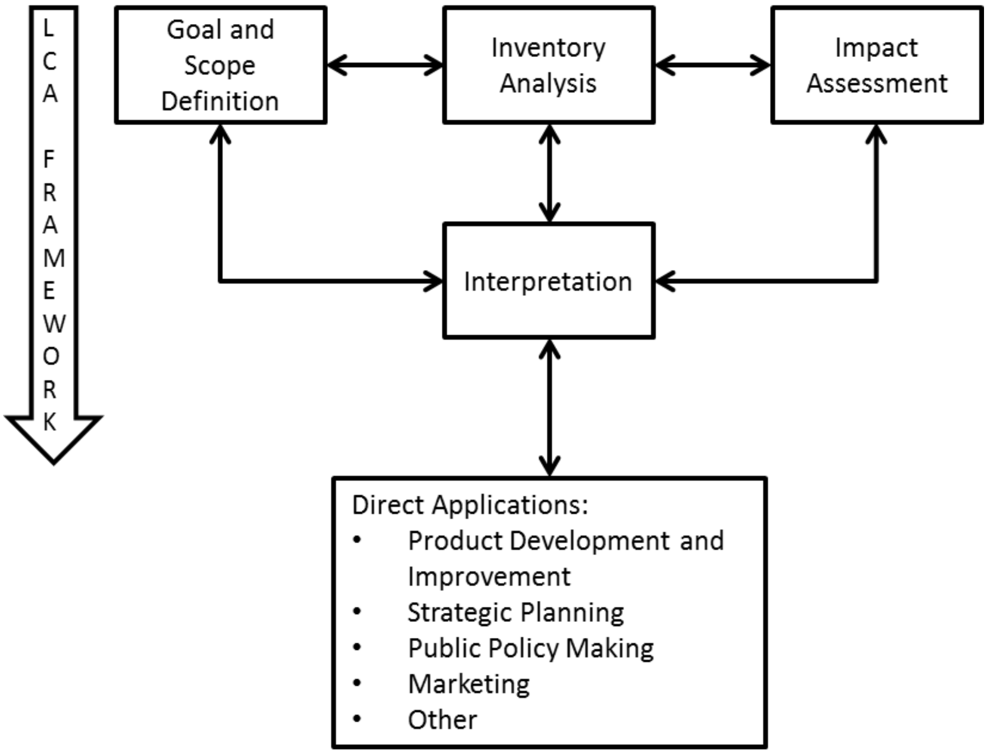
International Organization for Standardization (2006) has defined LCA as a “compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle”. That includes all activities starting with the process of extracting the resources to manufacturing and retailing to the usage of the product to the end-of-life disposal. Environmental inputs and outputs include materials needed for the production process, emissions during the usage and the reuse of materials obtained from the recycling stage.

Due to the complexity of the analyzed data, methodology and transparency are crucial factors in the analysis. Since LCA can be used to compare the environmental impacts of products that have the same application, a consistency in the choice of methodology allows for clear benchmarking among similar products and their performance. Nevertheless, the comparison must be performed throughout the complete lifecycle in order to guarantee the correctness of the obtained results. ISO 14040 and ISO 14044 standardize the whole LCA process and present specific data quality requirements (International Organization for Standardization, 2006).

## 3.2.LCA stages

ISO 14040 requires LCA to be performed in four stages: goal and scope definition, inventory analysis, impact assessment an interpretation. Figure 3-1 represents all LCA stages. Following subsections will address each of the phases separately.

**Figure 3-1 Phases and applications of an LCA (based on ISO 14040, 1997)**



### 3.2.1. Goal and Scope Definition

This phase distinctively describes an aim and means to include life cycle environmental results into decision-making process. Furthermore, it specifies a target audience to which the results can be applicable. This initial phase determines also the amount of effort required to complete the study. It serves as a specific guideline throughout the work and allows for a proper planning.

Due to the increasing awareness of environmental impacts throughout industries in the recent years, ecological issues have gained much larger attention. Aviation sector itself is on a constant growth track and according to the forecast, will stay on it in the future. For this reason, a tool such as LCA addresses many of the issues in a holistic way. Assessment of the environmental impacts of passenger and freight aircraft transport in Switzerland is one of the reasons to carry out this study. Furthermore, it aims to perform a comparison of the current technology and with the forecasted technology changes in year 2050 and see how the environmental performance may change over the years. In addition, examining impacts with respect to the specific variables is another reason for performing this research. Decision and policy makers, together with aircraft manufacturers and airline companies are part of a target audience that may benefit from this work. Eventually, this thesis will be a part of a PhD dissertation which will present all transportation modes in Switzerland for a comprehensive comparison of environmental performance. This study will be released to the scientific community in form of an academic publication.

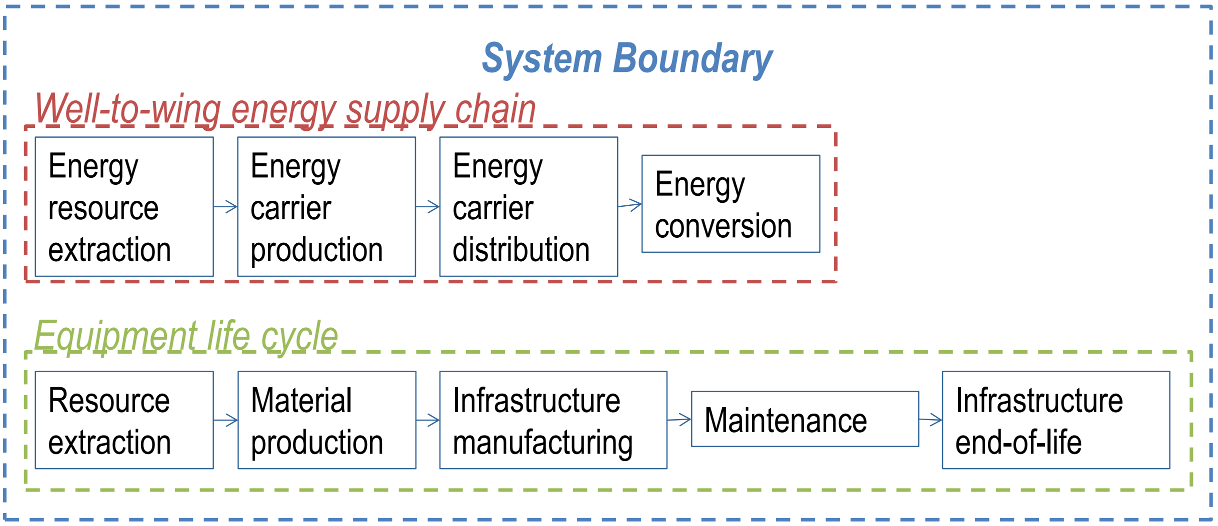
Functional unit quantifies and measures performance of the product, and characterizes input and output data. It allows for a clear comparison with other products that use the same functional unit. International Organization for Standardization (2006) defines functional unit of an LCA as "quantified performance of a product system for use as a reference unit". Most broadly used functional unit in the LCA in aviation is passenger kilometer (PKM) (Spielmann, 2007). This work utilizes it as well. Additional reason for deciding to use PKM is that results can be directly compared with other LCA papers that also use this unit. With regard to this study, PKM can be explained as follows: it represents a transport of one passenger over one kilometer. For a flight of 1000 km with 100 people on board, passenger kilometer unit is a multiplication of both, which in that case is equals 100,000 PKM. The product, which in case of this work is an aircraft, will be analyzed in reference to one passenger that travelled one kilometer.

Scope should be limited to appropriate borders, including definition of all inputs and outputs used in the analysis. Setting system boundaries should also take into consideration formerly defined motivation and all steps leading to obtaining the LCA results. In general, scope should include all necessary characteristics that will allow addressing the issues stated as goals of the work. It consists of following components (International Organization for Standardization, 2006):

- The product system that shall be analyzed;
- The functions of that product;
- The functional unit;
- The system boundary and procedures for allocation;
- Categories on which the product will have an impact;
- Necessary data;
- Assumptions and limitations of the study;
- Requirements for quality of initial data;
- Type and format of critical review and final report.

Scope of the work defines what the LCA includes and what not. The scope of this thesis includes complete life cycle from the resource extraction, through production, operation and end-of-life processes. Therefore, all environmental burdens that come from those phases are considered. Figure 3-2 shows the system boundary for functional unit PKM. It was divided into two sections. First one, well-to-wing energy supply chain, covers the life cycle steps of the aircraft from energy extraction to conversion. The equipment life cycle includes manufacturing of a plane and an airport, energy usage, maintenance and recycling. Those two systems provide supporting information, necessary to perform complete LCA.

**Figure 3-2 Simplified scheme of a System Boundary of the airplane LCA; adapted from Nordelöf et al. (2014).**



All commercial passenger airliners that operate on the Swiss airports were taken into consideration in this work. Private jets and military planes were not analyzed due to their marginal share in the Swiss air traffic movements or limited information. Regarding airborne emissions, the location of the emission; i.e. low population density area or stratosphere, was not distinguished when analyzing the performance. It has to be mentioned that this work does not consider the use of biofuels, which as described in the paper of Howe (2013) may decrease the greenhouse gas emissions even by 85%. Processes describing the aircraft life cycle and the impacts refer to one unit of product. Similar conditions apply to analyzing the infrastructure. All generated data, describes primarily Swiss conditions.

### 3.2.1. Life Cycle Inventory Analysis

This LCA stage consists of collecting all the necessary data for a future analysis. It includes the flow of the material and energy into a predefined system boundary, as well as outflow of emissions to the environment. This phase focuses on capturing the most of the data and synthesizing it into results. The decision on which processes should be included is based on the defined goal and scope.

Inventory data for the energy supply chain system in this work was obtained from the ecoinvent 3.1 database. Further on, it has been processed in the SimaPro 8 software that allowed for modeling environmental emissions. For the freight allocation, this work uses mass of 100 kg per passenger to transform ton kilometer into passenger kilometer. Average weight of 70 kg per person and 30 kg per luggage is applied.

In this thesis, a LCI of future technology is also performed. Similarly to other prospective LCAs, this work uses current production datasets for the background data such as carbon fiber or jet fuel production. The changes are made to the foreground parameters such as material composition, fuel consumption and exhaust emissions.

### 3.2.2. Life Cycle Impact Assessment

The impacts related to the environment, human health and resource depletion of all the resources and pollutants calculated during life cycle inventory (LCI) phase are obtained during the life cycle impact assessment (LCIA). Analysis usually includes several impact categories predefined by a specific method. This study uses ReCiPe methodology to convert the LCI into potential impacts (Goedkoop, 2009). It is able to perform calculation of both midpoint and endpoint indicators. There are 18 midpoint categories (such as ozone depletion or terrestrial acidification) that specify problems in a detailed and robust way. On the other hand, endpoint categories provide more generic description and refer to damage to human health and ecosystem plus resource depletion. This study will represent the results for chosen midpoint categories. The reason for this is that endpoint categories usually show similar results as midpoint ones, but at the same time seem to be more uncertain (Goedkoop, 2009).

Out of the 18 midpoint (environmental) impacts, the thesis presents results for four of them in the main section, while the others are presented in the appendix. The selection was based on the preliminary calculation of impact results from SimaPro of all 18 environmental impacts. Those calculations indicated following categories to be the most relevant: Climate Change, Terrestrial Acidification, Photochemical Oxidant Formation and Particulate Matter (PM) Formation. In addition, other LCA papers mention those midpoint categories to be of the highest importance in the amount of emissions produced by the transportation sector (Bauer, 2015). Table 3-1 describes four categories used in this thesis.

**Table 3-1 Four selected environmental (midpoint) impact categories, based on Goedkoop (2009) and Miotti (2013).**

| Impact category name | Short description | Unit |
|---|---|---|
| Climate Change | Change in the atmospheric concentration of greenhouse gases, affects the global climate. | kg $CO_2$ equivalents |
| Terrestrial Acidification | Provides indication on potential environmental impacts based on $NO_x$ and $SO_2$ emissions. Indicates change in the soil acidification that has effect on the growth conditions for plants. | kg $SO_2$ equivalents |
| Photochemical Oxidant Formation | Also called "summer smog". It is a formation of ground-level ozone through $NO_x$ emissions, unburned hydrocarbons and sunlight. It has a deteriorating impact on human health and may cause inflammation of airways, damage of lungs and increase the frequency of asthma. | kg NVMOC equivalents |
| Particulate Matter (PM) Formation | Represents potential danger to human health due to primary PM emissions and secondary PM formation. When inhaled, particulate matter causes health problems since it reaches airways and lungs. | kg PM10 (particles $\leq 10\ \mu m$) equivalents |

Nevertheless, it has to be mentioned that the ReCiPe method is not always valid for emissions that occur during cruise phase. Although environmental impacts of greenhouse gasses and terrestrial acidification can be quantified at the cruise altitude, the photochemical oxidant formation and particulate matter formation are not taken into consideration. The reason for this is that the ReCiPe method characterization factors for emissions above the ground level are not correct and therefore they were set to zero.

Peter Fantke from the Technical University of Denmark claims that, particulate (PM) and unburned hydrocarbon (NVMOC) emissions in the altitude that aircrafts cruise (7000-12000m for regular transit) do not typically cause any human health effects in the impact categories considered as there is no exposure in this altitude. The reason for that is inside aircrafts the air is usually filtered and outside the particulates (PM) would need to fall all the way down to the breathing zone (0-100 m above earth surface) in order to reach the human population. Modeling becomes complex as everything in the upper troposphere is well-mixed in all models, so the PM rather adds to the background in this altitude instead of being deposited as a certain fraction onto the earth surface. Hence, as approximation a zero effect of PM can be assumed. However, what is more important for the humans inside aircrafts is the ozone in that altitude, which is a pre-cursor of PM, but ozone formation and related health effects are treated in a separate midpoint category and might therefore not be relevant here (Fantke, 2015).

### 3.2.3. Interpretation

In this step the results are analyzed and discussed with respect to the consistency, completeness and uncertainty. Another important element is the validation and sensitivity analysis that may cause changes and adjustments to the previously determined processes. This thesis and LCA in general, consists of iterative processes which result in continuous testing and repeating until obtaining the satisfactory results.

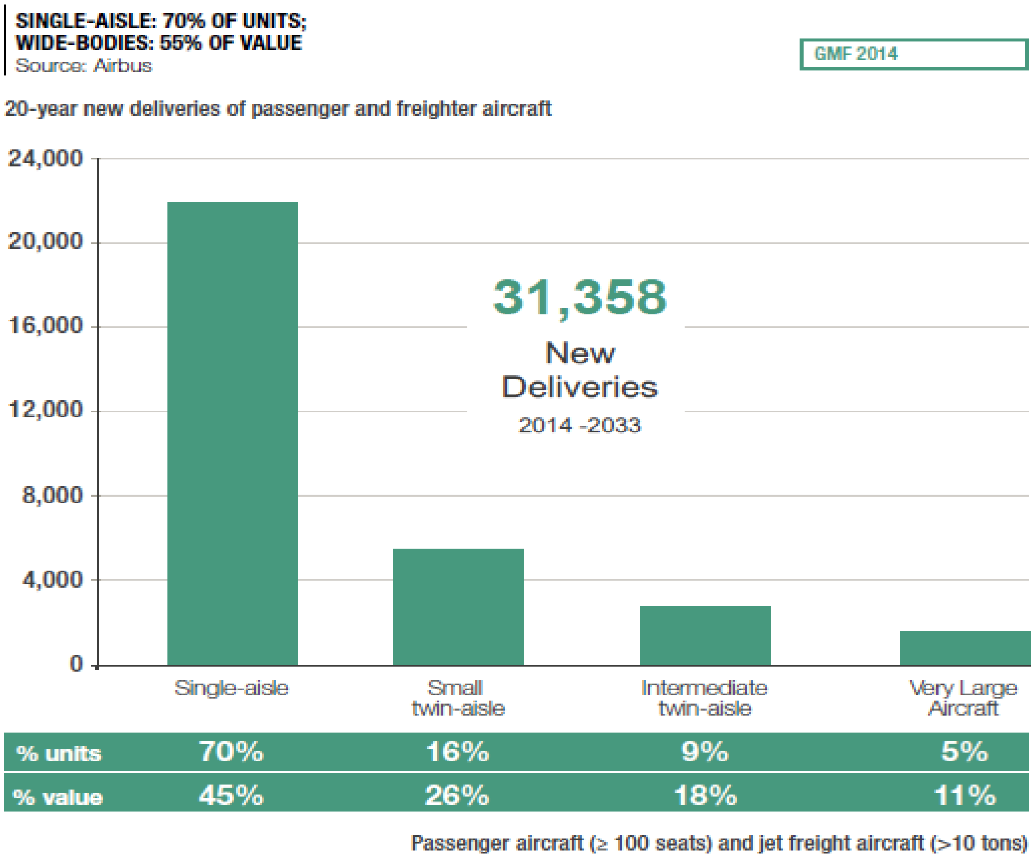
# 4. Life Cycle Inventory of Swiss aircraft fleet

## 4.1.Aircraft choice

Aircraft operating on the Swiss market are vastly diversified in terms of technical characteristics. They vary with regard to number of seats, operating empty weight, thrust, maximum range or cargo volume they can carry. Therefore, a crucial part of this thesis is a careful consideration of those characteristics and in result a selection of aircraft that in a best way reflect the entire Swiss fleet. Nevertheless, an understanding of ongoing market dynamics is a decisive factor for modeling the future outlook.

Figure 4-1 represents a forecast of new passenger and freighter aircraft delivery according to Airbus. In 2033, total number of planes is expected to more than double the current one. Most of the deliveries for the European market will occur in the single-aisle and small twin-aisle segment. Demand for very large aircraft will come mostly from the Asia-Pacific region. North America and Europe will try to focus on replacing their old fleet with the new, more eco-efficient models (Airbus Global Market Forecast 2014-2033, 2014).

**Figure 4-1 20-year development of new deliveries of passenger and freighter aircraft.**



When looking at global fleet breakdown by manufacturer for aircraft in service, Boeing and Airbus share the majority of the market (39.7% and 28.7% respectively) (Centre for Aviation, 2013). They produce jetliners ranging from 100-seat category up to over 800-seat in case of Airbus A380, being the largest commercial aircraft in service. Most-produced large jet-powered civilian aircraft of all times is Boeing 737 with over 8 thousand pieces produced (Boeing, 2015). From the Airbus side, the highest popularity belongs to the Airbus A320 family with over 6 thousand pieces (Airbus S.A.S., 2014).

Since this thesis focuses on analyzing Swiss market, it is important to incorporate into the analysis other significant models as well. The biggest airline in terms of fleet size and number of passengers in Switzerland is Swiss International Air Lines. The majority of its aircraft comprises of different Airbus types. Swiss Air Lines announced to update its long-haul fleet in 2016 by six Boeings (Swiss International Air Lines, 2015). This study considers the following Airbus models: A318, A319, A320, A321, A330, A340, A350 and A380. From the Boeing side, considered models include: 717, 727, 737, 747, 757, 767, 777 and 787. Remaining types that are also analyzed consist mostly of small, regional jets used for either domestic or intercontinental flights. To gain a better overview of an entire Swiss market, all active aircraft types that are in service in Switzerland were taken for an initial review (Planespotters.net, 2015).

Narrow Body Aircraft is a term used to describe an airliner with single aisle. Seats in narrow body are typically arranged from 2 to 6 abreast along a single aisle. Typical fuselage diameter is between 3 and 4 meters. Those narrow body aircraft that do not allow for transcontinental journeys are commonly known as regional airliners. On the contrary, Wide Body Aircraft describes a twin aisle vehicle. They are wide enough to accommodate seven or more seats abreast and have typically a fuselage width of 5 to 6 meters. Wide body airliners are also commonly used for the transport of commercial freight and cargo.

Narrow-body jets dominate on the Swiss market, but significant flights with wide body jets also take place. However, Switzerland is a relatively small country that provides a dense network of connections. Main airports include: Zürich, Geneva and Basel-Mulhouse. Figure 4-2 presents traffic movements on the Swiss airports. Most of the other airports in Switzerland serve non-commercial flights, or only national flights. The longest travel air route between Zürich and Geneva does not exceed 230 km. Therefore, smaller regional aircraft such as Dornier 328 or Saab 2000 still bring a valuable contribution and are taken into the consideration as well.

**Figure 4-2 Take-offs and landings in civil aviation in Switzerland, 2014. Source: Federal Office for Civil Aviation (2014).**

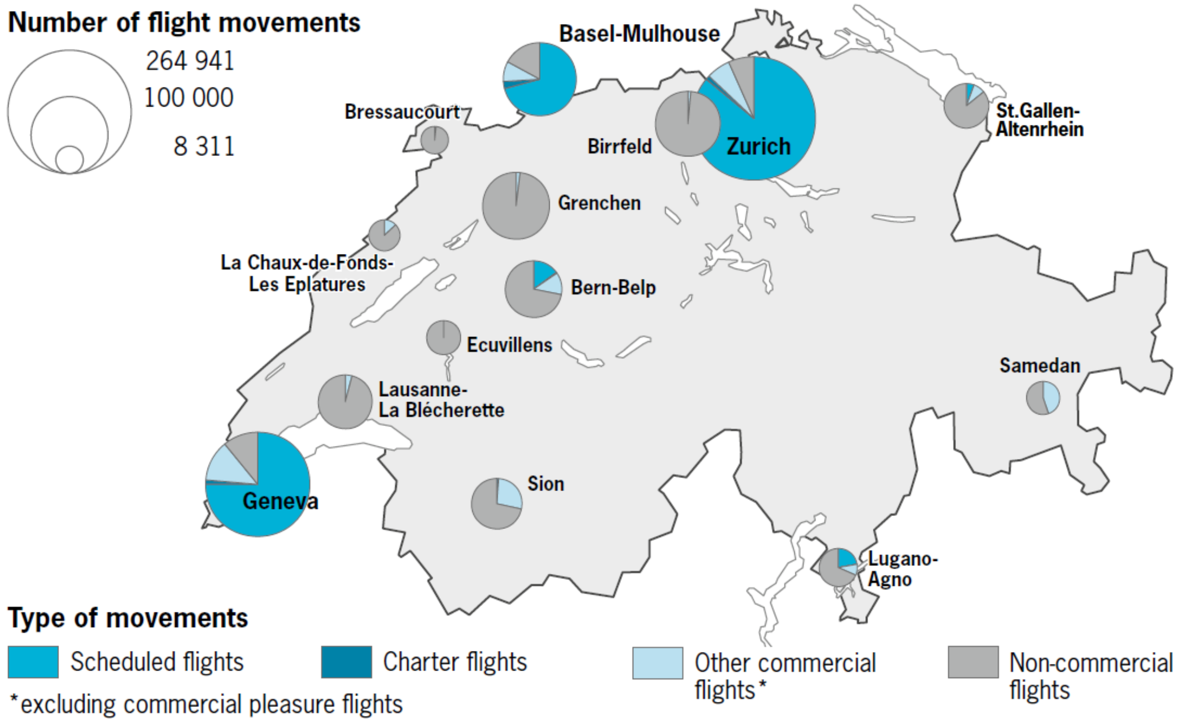


Table 4-1 presents the most common civil aircraft models active in Switzerland as for today. It does not include only planes operated by Swiss airlines, but also those that have their departure and/or arrival destinations at airports in Switzerland. The analysis also takes under consideration ongoing market dynamics, and the list include another types that are expected to be of significance in the future. Characteristics such us maximum number of seats, operating empty weight[3] or range, demonstrate differences among selected aircraft and provide valuable contribution for the future analysis. Specific characteristics for each aircraft model were taken from following sources: (Planespotters.net, 2015) and (Airliners.net, 2015b).

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[3] Operating empty weight (OEW) - is the basic weight of an aircraft including the crew, all fluids necessary for operation such as engine oil, engine coolant, water, unusable fuel and all operator items and equipment required for flight but excluding usable fuel and the payload. Also included are certain standard items, personnel, equipment, and supplies necessary for full operations.

**Table 4-1 List of aircraft models taken for initial analysis of the Swiss market.**

| Manufacturer | Model | ICAO Code | Type | Max Seating | OEW (kg) | Range (km) |
|---|---|---|---|---|---|---|
| Dornier | Do-328 | D328 | Regional | 33 | 8,920 | 1,850 |
| Embraer | ERJ-135 | E135 | Regional | 37 | 11,420 | 2,409 |
| Saab | 2000 | SB20 | Regional | 58 | 14,500 | 1,908 |
| ATR | 72–500 | AT75 | Regional | 74 | 12,950 | 1,454 |
| Embraer | ERJ-190 | E190 | Small Narrow-body | 114 | 27,737 | 1,850 |
| Boeing | 717-200 | B712 | Small Narrow-body | 117 | 31,674 | 2,645 |
| Fokker | 100 | F100 | Small Narrow-body | 122 | 24,375 | 2,450 |
| Boeing | 737-200 | B732 | Small Narrow-body | 124 | 27,448 | 3,800 |
| Bombardier | CSeries 100 | BCS1 | Small Narrow-body | 125 | 33,300 | 5,463 |
| Avro | RJ100 | RJ1H | Small Narrow-body | 128 | 23,897 | 2,909 |
| Airbus | A318-100 | A318 | Small Narrow-body | 132 | 39,500 | 5,750 |
| Airbus | A319-100 | A319 | Large Narrow-body | 156 | 40,800 | 6,850 |
| Airbus | A320-200 | A320 | Large Narrow-body | 180 | 42,600 | 6,100 |
| Boeing | 737-800 | B738 | Large Narrow-body | 184 | 41,400 | 5,445 |
| Boeing | 727-200 | B722 | Large Narrow-body | 189 | 45,360 | 3,100 |
| Boeing | 767-300 | B763 | Large Narrow-body | 218 | 86,070 | 7,890 |
| Airbus | A321-200 | A321 | Large Narrow-body | 236 | 48,024 | 5,950 |
| Boeing | 757-200 | B752 | Large Narrow-body | 239 | 57,840 | 7,222 |
| Boeing | 787-8 | B788 | Small wide-body | 381 | 118,000 | 14,500 |
| Boeing | 777-200 | B772 | Small wide-body | 440 | 134,800 | 9,700 |
| Airbus | A330-300 | A333 | Small wide-body | 440 | 124,500 | 11,300 |
| Airbus | A340-300 | A343 | Small wide-body | 440 | 130,200 | 13,700 |
| Airbus | A350-900 | A359 | Small wide-body | 440 | 115,700 | 14,350 |
| Boeing | 777-300 | B773 | Large wide-body | 550 | 160,500 | 11,120 |
| Boeing | 747-300 | B743 | Large wide-body | 608 | 178,100 | 12,400 |
| Airbus | A380-800 | A388 | Large wide-body | 853 | 276,800 | 15,700 |

Many research papers when determining the amount of people that a specific plane carries and later on an impact per passenger, use seating configuration defined as “typical”. However, this approach was found not to be consistent, especially when analyzing many plane categories. Small regional planes are often operated in 1-class seating configuration. On the other hand, aircraft such as A380 or Boeing 747 can appear in 1-, 2- or 3-class seating. Additionally, 3-class configuration for A380 may vary from 400 to 650 seats. Therefore, this work uses 1-class maximum seating configuration as a base for further analysis. This ensures that all aircraft are easily comparable.

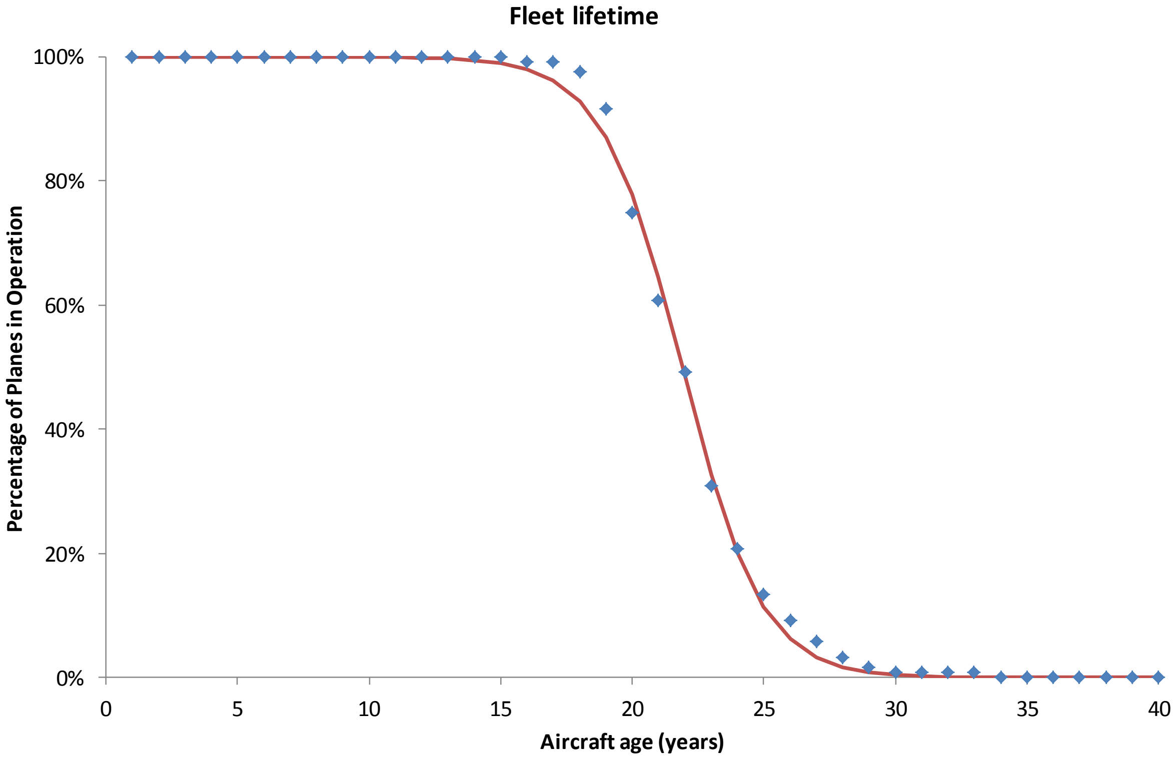
## 4.2.Synthetic plane lifetime

According to the data provided by the website PlaneSpotters, the current average age of the fleet of Swiss Airlines only, was estimated to be 13.6 years. However, in order to estimate total amount of kilometers flown during the plane lifetime, the number of years when plane is disposed is required. Historical data shows that the airline carriers in Switzerland typically do not scrap their planes when they are done using them. Aged models are rather sold to the carriers in other countries (Planespotters.net, 2015). Therefore a question arises: how to allocate the impact of producing planes if they are used by different carriers in different countries? The decision was made to allocate the aircraft production over the total service life of the plane, regardless of where it operates.

To evaluate average aircraft lifetime in Switzerland a comparable analysis was performed on the other major, European carriers. Consequently, past data of Air France, British Airways, KLM Royal Dutch Airlines, Lufthansa and SAS Scandinavian Airlines with regard to the scrapped planes was gathered. After researching at which age, each of the plane models described in Table 4-1 was disposed, an average plane lifetime was estimated to be 22 years. There was no significant difference in terms of plane model and age when scrapped. Accordingly, the age of 22 years was assumed to be an accurate fit for further analysis of all five synthetic plane types in year 2050.

Figure 4-3 represents a scatter plot of aircraft age versus the likelihood that it is still in operation. Blue points indicate single, analyzed aircraft and red line follows the trend. 18 years after manufacturing date, 98% of researched planes are still in operation. Starting in year 19, a rapid decline in remaining planes in operation can be observed. Only around 1% remains in service longer than 33 years.

**Figure 4-3 End of life chart representing planes remaining in service after a given time elapse.**



## 4.3.Determining synthetic planes characteristics

Previous researchers (Lopes (2010) and Lewis (2013)) include in their work Airbus A320, A330 and A380 for life cycle assessment. This study however does not select an already given aircraft model for analysis but rather tires to create generic one  that is parameterized based on certain characteristics and dependencies, thus enabling sensitivities and fleet level uncertainties to be better investigated. The collected data is then further analyzed for patterns in the following categories:

- OEW (kg) and maximum one-class seating capacity;
- Maximum structural payload (kg) and OEW (kg);
- Cargo volume ($m^3$) and OEW (kg);
- Total thrust (kN) and OEW (kg);
- Wing area ($m^2$) and OEW (kg);
- Maximum range (km) and OEW (kg);
- Maximum range (km) and maximum one-class seating capacity.

The main idea of this analysis was to firstly determine a relationship between number of seats and other parameters such as typical OEW (t), typical thrust (kN), typical range (km) or typical structural payload (kg) of all planes operating shown in the Table 4-1. Upon inspecting the data is was found that all relationships were linear or very close to it. Based on this finding, linear relationships were determined to describe the synthetic planes. By selecting only the number of seats on the plane, all other important parameters could then be calculated based on the linear relationships. From this result, five synthetic plane models were created to be analyzed in terms of life cycle assessment. It became a first step in developing a parametric LCA that provides a more flexible approach to evaluate environmental emissions based on desired input data.

Figure 4-4 presents scatter plot between variables: plane weight (OEW) (t) and maximum one-class seating configuration. Bubbles represent five synthetic planes and dots represent each analyzed plane. Figures below show the results for other parameters as well. It this worth observing how linear other relationships are. That linearity allowed for better estimation of characteristics of synthetic planes.

**Figure 4-4 The relationship between Aircraft Operating Empty Weight and maximum number of seats with synthetic plane characterization.**

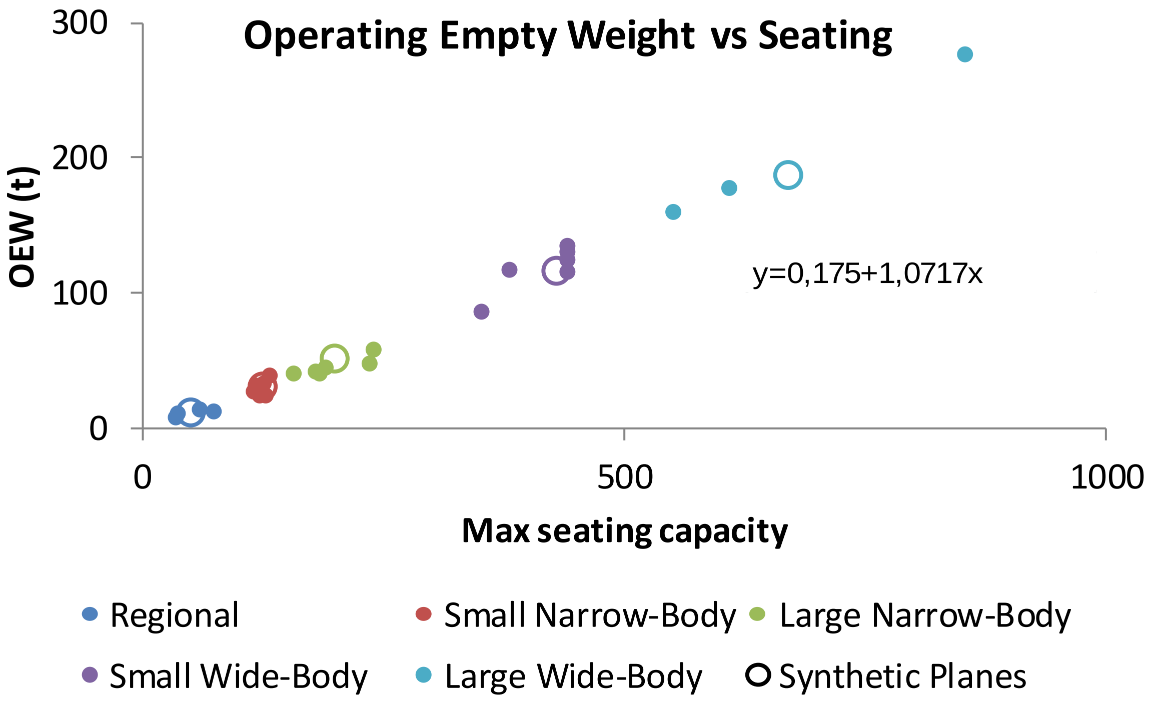


**Figure 4-5 The relationship between Aircraft Thrust and maximum number of seats with synthetic plane characterization.**

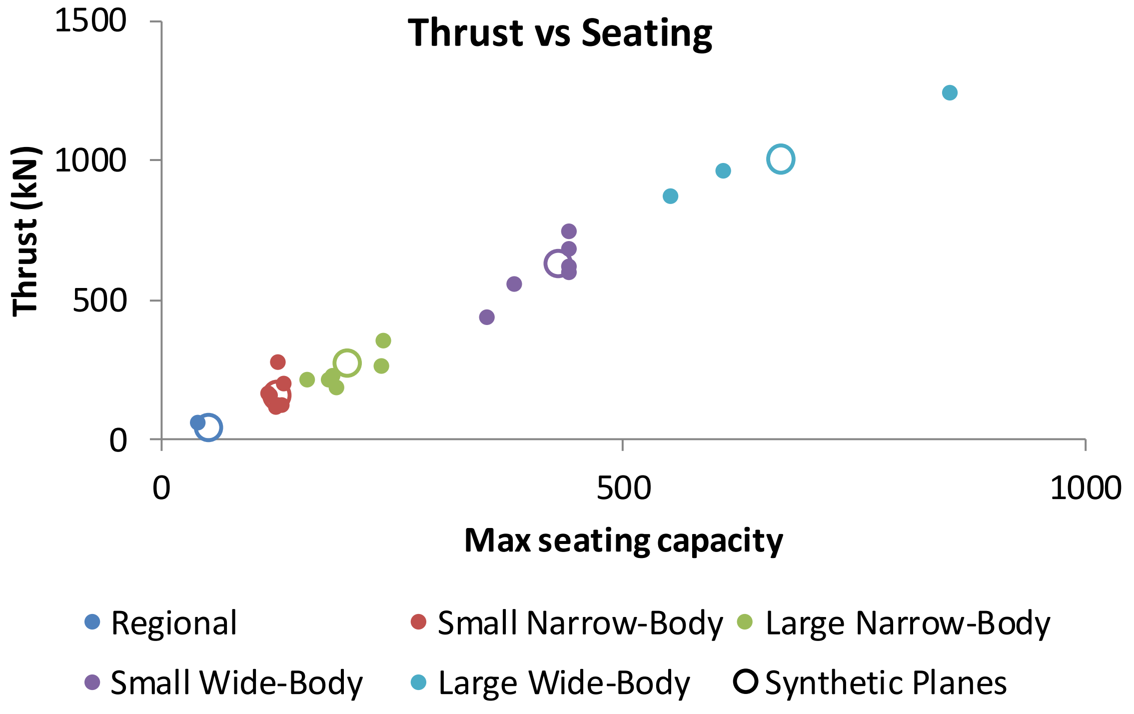


**Figure 4-6 The relationship between Aircraft Range and maximum number of seats with synthetic plane characterization.**

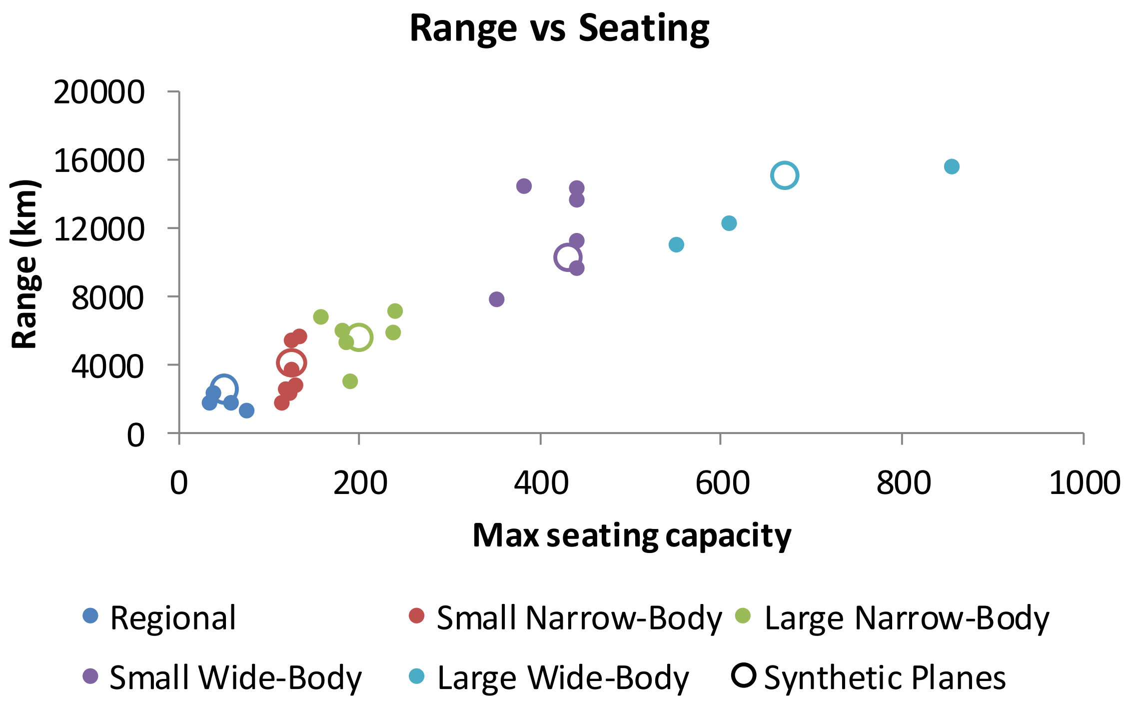


**Figure 4-7 The relationship between Aircraft Wing Area and maximum number of seats with synthetic plane characterization.**

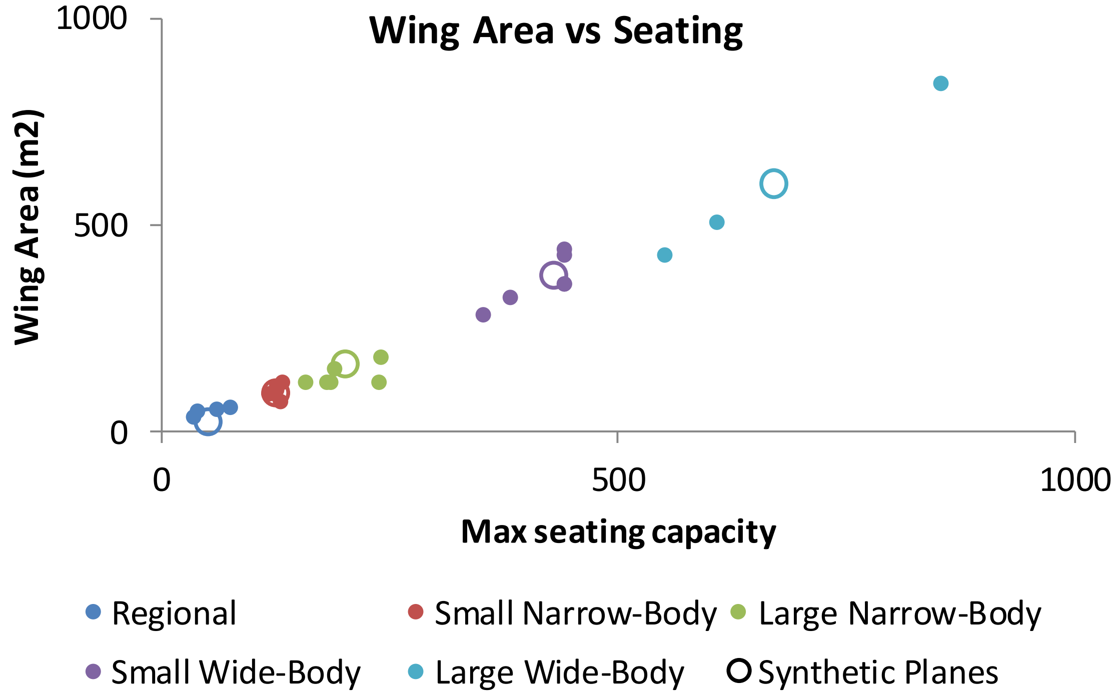
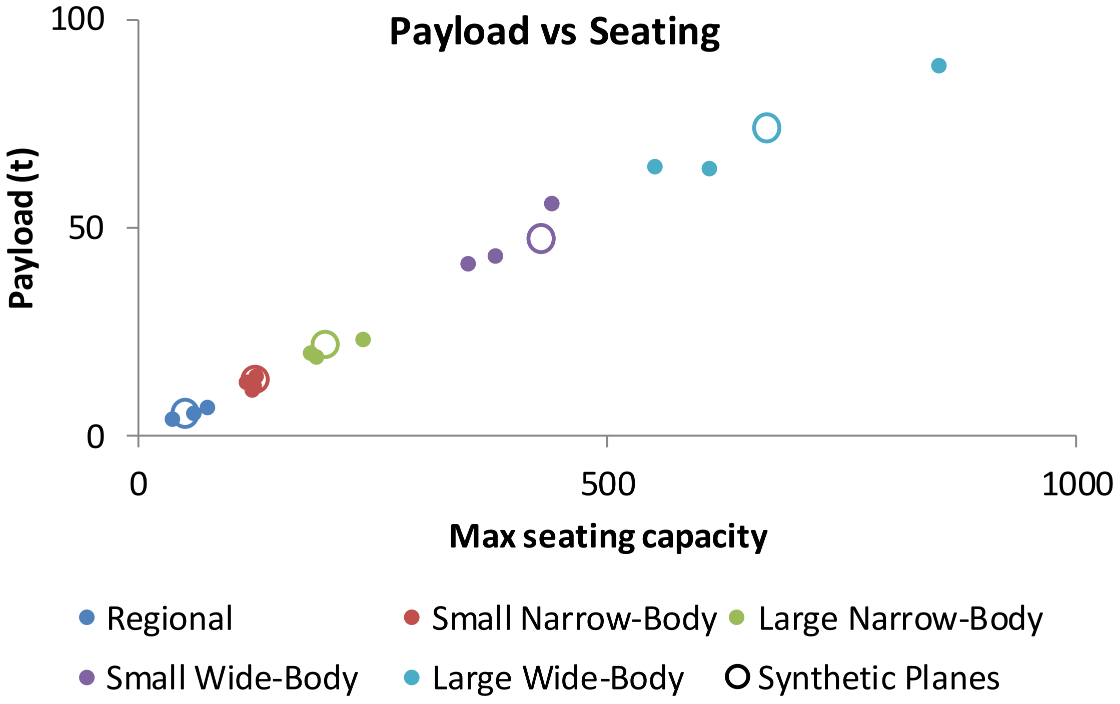


**Figure 4-8 The relationship between Aircraft Payload and maximum number of seats with synthetic plane characterization.**



Detailed characteristics of aircraft selected to analyze can be found in the Table 4-2.

**Table 4-2 Characteristics of synthetic plane models**

| Aircraft Category | Regional | Small Narrow-body | Large Narrow-body | Small wide-body | Large wide-body |
|---|---|---|---|---|---|
| **Seating group** | < 100, single aisle | 100 - 150, single aisle | 150 - 250, single aisle | 250 - 450 | > 450 |
| **Seating (one class)** | 50 | 125 | 200 | 430 | 670 |
| **OEW (t)** | 12 | 31 | 51 | 116 | 187 |
| **Thrust (kN)** | 42 | 158 | 275 | 631 | 1004 |
| **Range (km)** | 2600 | 4100 | 5600 | 10300 | 15100 |
| **Payload (t)** | 5 | 14 | 22 | 47 | 74 |

## 4.4.Capacity utilization

Capacity utilization (also defined as seat load factor) of a major airline on the analyzed market – Swiss International, has been increasing over the recent years. The 2014 press release states that system wide seat load factor for European network amounted 66% and for intercontinental routes 83% (Swiss International Air Lines, 2014). For the 2015 plane analysis, this work utilizes those numbers. Based on the past trends, forecasts for traffic developments in Europe and the estimates provided by United States Department of Transportation, it was calculated that by year 2050, seat load factor may change to over 80% for both European and intercontinental routes. However, an industry-wide practice is to utilize the weight of empty seats by loading an aircraft with additional freight (Belly Cargo). It is therefore not always an only goal for the airline to maximize revenues exclusively from sales of the tickets. Hence, the seat load factor given by the airlines is often just a theoretical value (Swiss Federal Statistical Office, 2005).

The standard weight of a passenger including luggage used by airliners is 100 kg (Airliners.net, 2014). If a plane with a maximum seating capacity of 500, carries onboard 400 passengers (80% seat load factor), the additional weight made available by missing passengers is filled with freight in the belly of the plane, allowing for additional 10 tons of weight to be carried. Therefore, the results of this work are calculated using the assumption that planes always travel fully loaded, which was observed to be a common practice in Switzerland.

## 4.5.Fuel production

The ecoinvent database has provided a fuel production dataset that was used in this thesis. That includes emissions connected with the production, combustion and evaporation of the fuel. Dataset reflects the kerosene production market in Switzerland. The same fuel production dataset was assumed to be valid also in year 2050.

## 4.6. Airport production

This thesis utilizes the data for the airport production from the paper of Spielmann (2007) described in the section 2. To correctly allocate airport construction among various synthetic plane models, a testing was done. One may expect that large plane models such as Boeing 747 or Airbus 380 can have higher allocation because they are bigger and require more infrastructure. However, smaller planes fly more often per PKM, and thus “need more airport". In the end though, the calculations showed that those two effects roughly cancelled each other out and it was decided to allocate the same amount of airport to all PKM, regardless of the plane size or flight length.

## 4.7.Manufacturing phase

Manufacturing of an aircraft is a first phase of an LCA, during which all necessary inputs are gathered and processed. Information about detailed material breakdown is not widely available. Aircraft manufacturers treat this data as confidential and collection of vital information to perform LCA is therefore difficult. However, one of the main literature sources described in the Chapter 2 of this work (Lopes, 2010), provides valuable resources used to examine environmental impact of an aircraft.

Mr. Lopez performed LCA of Airbus A330-200. He also mentions in his work the impossibility of finding specific information about weight compositions that are publicly accessible either online or in the literature. He was provided this information by TAP Portugal[4] engineers over a personal communication. Following this finding, he was challenged with determining materials that compose each structural part. This data was obtained by analyzing detailed manuals of the A330-200, expert opinions of engineers and mechanics personnel working in the hangars of TAP. In the later phase, obtained results were revised by TAP engineers. Those meticulous steps allow assuming that the data

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[4] TAP is a flag carrier of Portugal and a member of Star Alliance group.

presented in the work of Lopes is accurate and can be used as a base for further analysis (Lopes, 2010).

This section focuses on providing material breakdown for all determined synthetic plane models in year 2015 and 2050. The analysis was based on detailed information provided by Lopes' paper. However, in calculating the breakdown he uses manufacturer's empty weight of the A330-200, which is different than OEW used in this thesis. It includes all equipment considered to be an internal part of an aircraft but does not include items added by operator and the crew. Since the difference between those two measures was marginal, this thesis neglects it and calculations of material breakdown are based on operating empty weight instead of manufacturer's empty weight.

Disposal of materials used during manufacturing process is included in the ecoinvent 3.1 database that this work bases on. For the energy consumption during manufacturing phase and disposal of an airport, the data from Spielmann (2007) has been applied. The lifetime of 100 years per airport and disposal distance of 20 km has been employed.

### 4.7.1. 2015 plane

As the historical analysis indicated, the main difference in terms of material composition over the years 1968 – 2010 accounts for increasing share of carbon fiber reinforced plastic (CFRP) and decreasing share of aluminum. Figure 4-10 presents it in more details, with respect to the specific plane models of Boeing and Airbus. The oldest plane for which the data was available was manufactured in 1968, Boeing 747 "Jumbo Jet", does not have a significant share of composites in its structure. Nevertheless, it still remains a model that is widely used by the airlines all over the world. The structure of a newest plane model analyzed, Airbus A350, is 50% by weight composites.

Swiss aircraft fleet is represented by a variety of models. The most commonly used aircraft however is Airbus A320 family (Swiss International Air Lines, 2015). It is currently also the best-selling globally single-aisle jetliner family (Airbus Group, 2015). Nevertheless, its detailed material breakdown does not appear to be publicly available. Therefore, since material composition of A330 presented in the work of Lopes does not significantly differ from the general figures available for A320, to model current state of Swiss aircraft fleet, detailed values for the A330 were taken. They are assumed to reliably represent the Swiss fleet in year 2015 that composes of models both older and newer than A330.

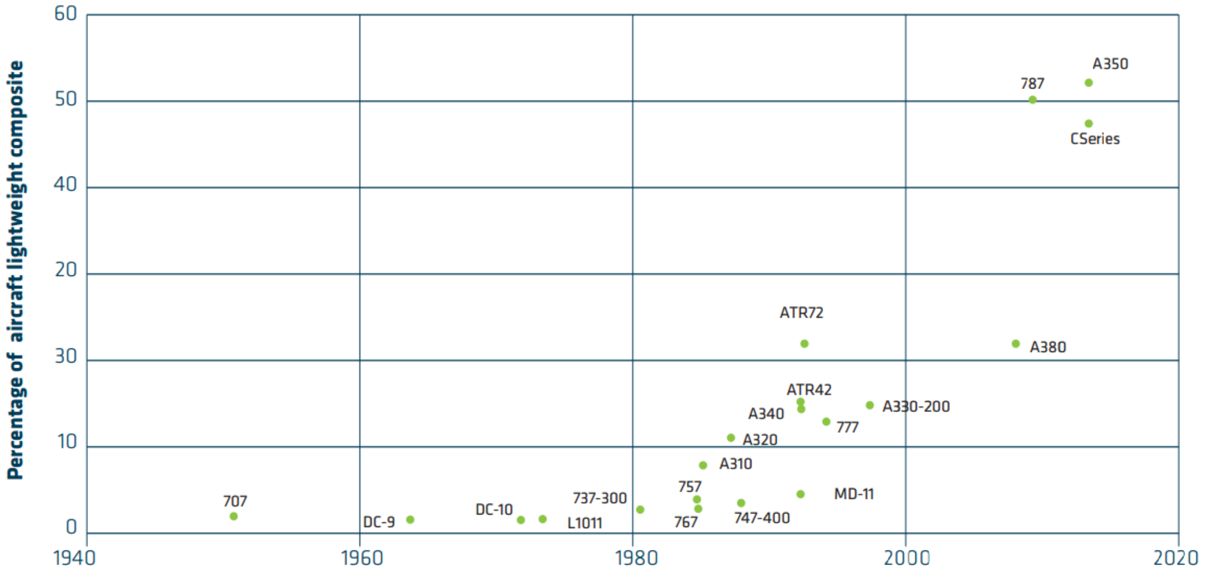
Number of kilograms of each material used, were based on the percentage breakdown of A330 presented in the paper of Lopes. Later they were adjusted according to the OEW of each of the five synthetic planes to obtain detailed material breakdown. Precise figures can be found in the Table A-1 of Appendix.

### 4.7.2. 2050 plane

High cost of aviation fuel and regulatory initiatives aiming to develop standards for greenhouse gas emissions, are main forces for civil aviation sector to implement lightweight materials. It is commonly recognized that the total weight of an aircraft influences fuel consumption and $CO_2$ emissions. They can be reduced by implementing composite materials into the airplane structure. Those steps are being incrementally introduced by the major aircraft manufacturers.

Air Transport Action Group in its report about aviation efficiency shows a steady rise in the use of composite materials by aviation industry. Figure 4-9 represents that development over last decades. Use of composite materials does not only provide weight savings, but also much better strength-to-weight ratio than metals. Carbon composites are only about 60% of the density of aluminum. Those materials are typically represented by strong, stiff fibers that can be formed into the very complex shapes.

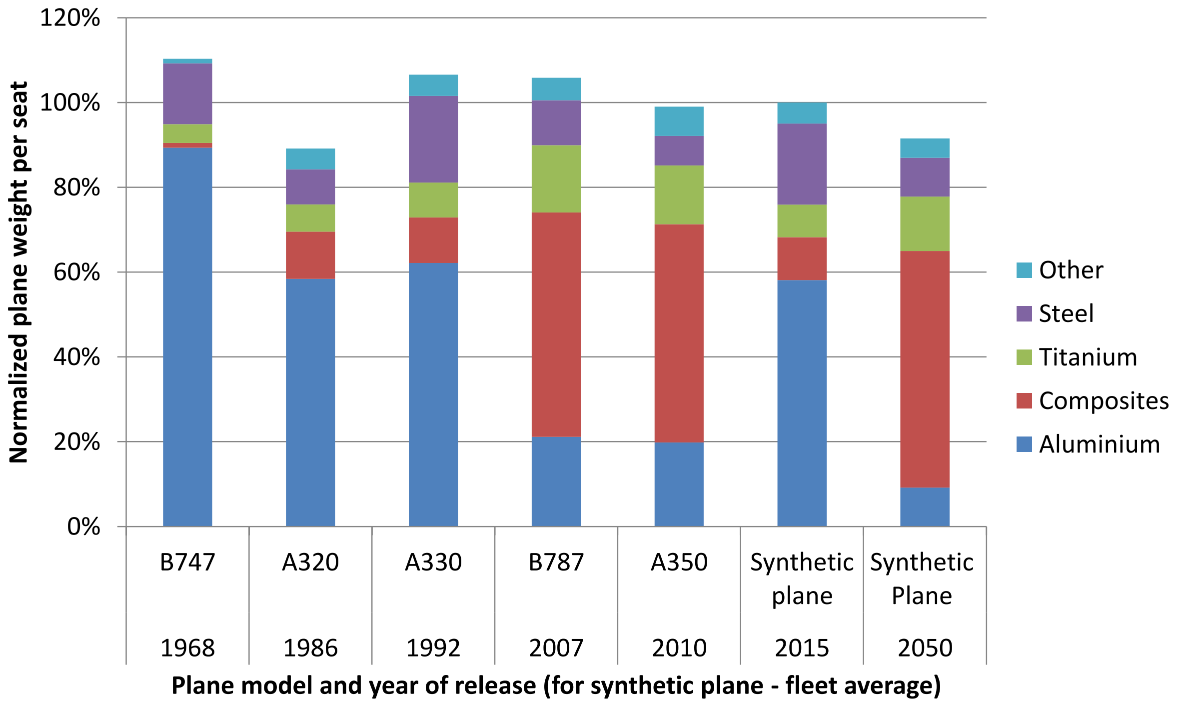
**Figure 4-9 Growth in the use of composites in commercial aircraft. Source: Air Transport Action Group (2010).**



Based on the past changes in material split, time series analysis was performed to determine how the plane that will represent Swiss fleet in year 2050 may look like. It was assumed that the average plane in operation in 2050 will have the same material composition as the most technically advanced plane available today (in 2015). That gave 61% share of composites, 10% share of aluminum, 14%

share of titanium, 10% share of steel and 5% of other materials. Figure 4-10 shows the contribution of each material in the structural operating empty weight of the analyzed aircraft over last decades as well as for synthetic plane in year 2015 and 2050. Regarding the changes in OEW, linear regression of the data available showed an average of 0.25% weight reduction per year since 1968. Extrapolating this data, the 2050 plane will have a weight of about 91.5% of plane from 2015. Results obtained in this work are in line with other studies that obtain similar numbers (Graham, 2014 and Timmis, 2015).

**Figure 4-10 Normalized plane material breakdown. Source: company presentations of Mitsubishi Heavy Industries (2011) and Airbus (2008).**



The manufacturing impacts (other than material breakdown) used in the analysis was obtained from the ecoinvent 3.1 database with respect to today's technology. It was assumed that the future material production can be modeled with today's datasets. Calculations of disposal impacts of materials used in the manufacturing process are included production dataset in the ecoinvent database. Additionally, this thesis assumes that 20% of the energy consumed in the production process is required for the end of life treatment of an aircraft. It can be argued here that this simplistic treatment of production and end of life is justified as the operating emissions and fuel consumption during the lifetime of the airplane completely overwhelm all production and end of life impacts. This was also found by others, including Howe, Lopes and Lewis. See chapter 5 for more information.

Weight increase results in higher induced drag that directly corresponds to higher fuel consumption. Lighter fuselage and engines allow for extended range due to the fuel economies. Weight savings therefore allow for reduced fuel consumption and lower environmental emissions. The use of composites and other light-weight materials in the modern airframes such as Airbus A380 or Boeing 787 significantly reduces aircraft's mass and in result increases the fuel efficiency. This thesis however does not recalculate the fuel consumption per km flown based on a lighter plane but rather evaluates how weight savings influence the amount of additional freight capacity the plane can carry.

## 4.8.Lifetime kilometers travelled and average flight distance

The environmental impacts per passenger kilometer of a manufacturing phase are influenced by a number of kilometers a given aircraft travels during its lifetime. As estimated in the chapter 4.2, it is to be 22 years. To determine distance flown per year, it is crucial to know the flight history of a plane. This data was gathered using website Flighradar24. Following steps were undertaken:

1. Firstly, a one-week flight plan of all planes from the Table 4-1 that are operated by Swiss carriers was taken. In total, 93 aircraft models that appear under various registration codes were analyzed. This was performed to ensure a high accuracy of results.
2. However, this data allowed only for determining a departure and arrival airport. The flight lengths were obtained from a Mileage Calculator for around 2,700 various flights that occurred in March 2015 (WebFlyer, 2015). An example of a flight history of an Embraer ERJ-190LR, registration code HB-JVN, in the second week of March 2015 can be found in Appendix in Table A-2.
3. Since the flight data was gathered only in the month of March, it had to be extrapolated to accurately represent a whole calendar year. Therefore, a traffic data from Swiss Statistics Office was analyzed in addition (Bundesamt für Statistik, 2015). It was discovered that March represents a relatively equal share in terms of the traffic movements in Switzerland. In months such as November or February number of arrivals and departures at the Swiss airports is usually lower than the annual average. From May until October, higher traffic movements can be observed. Therefore, results from March were extrapolated throughout the whole year taking into the consideration a slight difference in the incoming and outgoing flights.
4. By determining the length of around 2,700 flights of different aircraft models, it became feasible to calculate an average flight distance of each of the five synthetic plane models.
5. Number of kilometers flown per year was multiplied by the average lifetime of an aircraft. In such way, it was possible to estimate a number of kilometers flown per each aircraft model

described in the Table 4-1. Following this, a lifetime kilometers travelled was calculated of each of the five synthetic plane models. Table 4-3 presents the obtained results. Based on the historical data regarding traffic movements, it was assumed that synthetic planes in year 2050 will have the same characteristics.

**Table 4-3 Comparison of distances travelled by five synthetic plane types.**

| Aircraft type | Average flight length (km) | Distance per year (km) | Lifetime (years) | Lifetime kilometers travelled (km) |
|---|---|---|---|---|
| Regional | 460 | 518,000 | 22 | 11,400,000 |
| Small Narrow-body | 760 | 1,267,000 | 22 | 27,900,000 |
| Large Narrow-body | 1,500 | 1,885,000 | 22 | 41,700,000 |
| Small wide-body | 6,900 | 4,061,000 | 22 | 89,300,000 |
| Large wide-body | 8,100 | 3,947,000 | 22 | 86,800,000 |

It is worth mentioning that the large wide-body aircraft travels during its lifetime less than small wide-body one. It may stem from the fact that the largest plane types fly less often than the smaller ones, but they are able to carry more passengers on board.

## 4.9.Operating phase

Energy consumption and operating emissions are expected to be dependent on the aircraft size and distance travelled. They appear to be very large during the start phase, which in case of smaller aircraft occurs more often due to higher number of take-offs and landings. This work models environmental results of five generic plane models that travel on various distances.

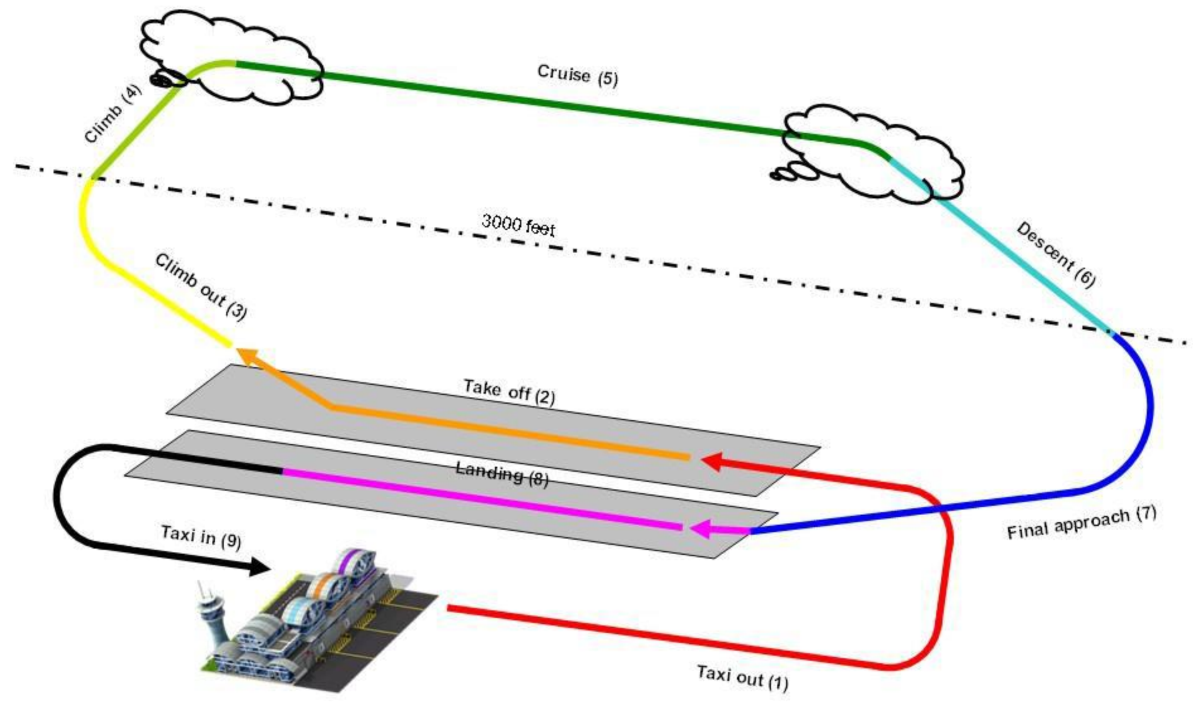
### 4.9.1. Landing and take-off

First cycle of aircraft operation is landing and take-off. It further breaks down into four phases: take-off, climb out, approach landing and taxi / ground idle. Following definitions are based on the report of International Civil Aviation Organization (ICAO, 1993).

| | |
|---|---|
| Take-off phase: | The phase of flight from the application of take-off power until reaching the first prescribed power reduction, or until reaching the VFR[5] pattern or 1000 feet (300 meters) above runway end elevation, whichever comes first or the termination (abort) of the takeoff. |
| Climb out phase: | Thrust setting from the point of throttle back to the mixing height altitude, or more generally 3000 feet (ca. 914 meters). |
| Approach landing phase: | The phase of flight from the point of transition from nose-low to nose-up attitude, immediately before landing, through touchdown and until aircraft exits landing runway, comes to a stop or when power is applied for takeoff in the case of a touch-and-go landing, whichever occurs first. |
| Taxi / Ground Idle: | The phase of flight in which movement of an aircraft on the surface of an aerodrome under its own power occurs, excluding take-off and landing. |

Figure 4-11 provides a graphic illustration of standard flying cycles.

**Figure 4-11 Standard flying cycles**



Source: (European Environment Agency, 2013)

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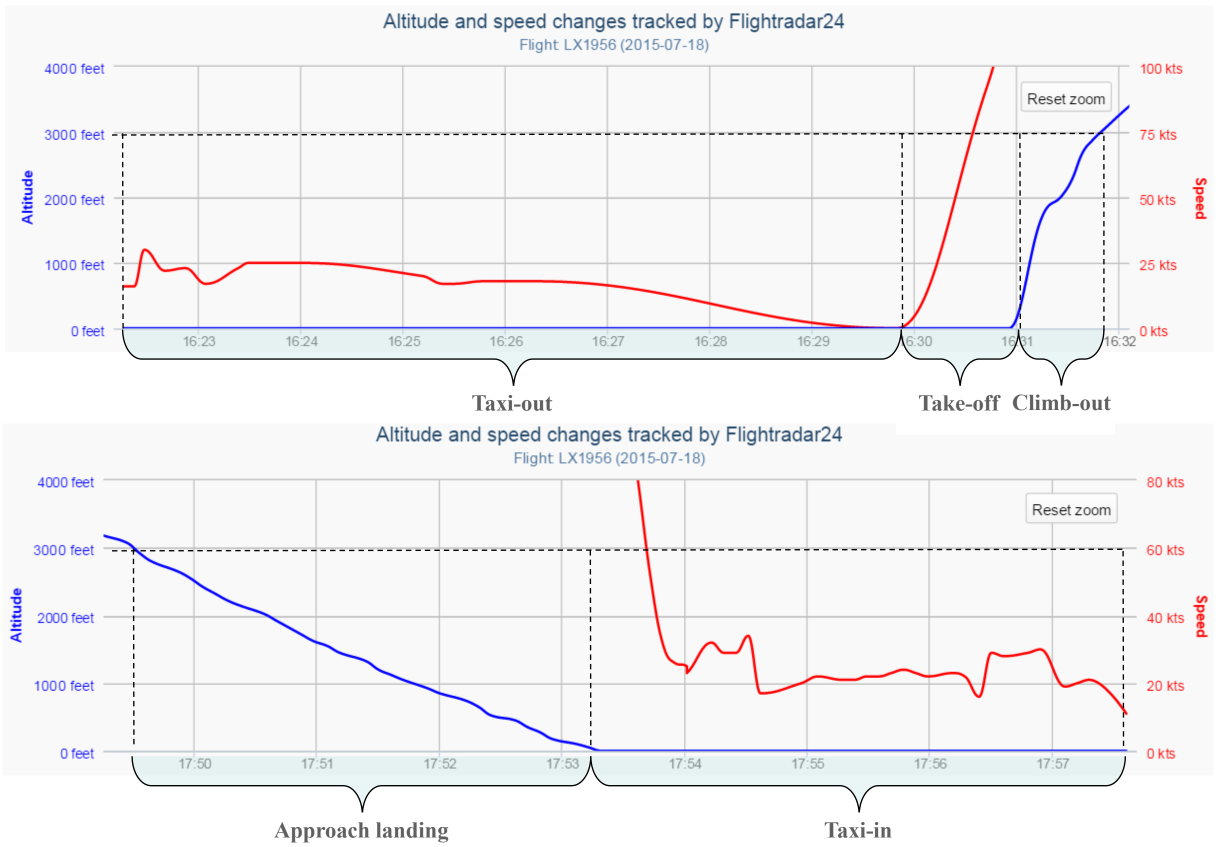
[5] Visual flight rules (VFR) are a set of regulations under which a pilot operates an aircraft in weather conditions generally clear enough to allow the pilot to see where the aircraft is going.

Majority of scientific papers in order to calculate emission inventories uses the ICAO reference times for LTO cycle that date back to year 1993. One of the goals of this paper is to perform a study of all current LTO phases in regard to the Zürich Airport (ZRH) and to compare them with ICAO reference times. The purpose of this is to develop an environmental assessment based on the precise LTO times that refer to the Swiss market, rather than taking a global average that is more than 20 years outdated.

Since LTO cycle occurs at the altitude below 914 meters, emissions emitted have more direct impact on human health. It is therefore necessary to develop a precise methodology to assess the local air quality (Flughafen Zürich AG, 2004).

This study completed an evaluation of the four times of LTO phases that occur in Zürich (ZRH) airport. Data comes from the third week of March and second week of July 2015. Assessed aircraft include models commonly used at ZRH airport: Airbus A319, A320, A321, A330, and A340. Calculations were based on the time and altitude estimates from FlighRadar24 (FlightRadar24, 2015b). This database provides precise changes of altitude across a given time-line, which allows defining how long each of the LTO phases last for. Figure 4-12 is a graphic illustration of altitude and speed changes. It concerns Airbus A321-111 that flew from Zürich (ZRH) to Barcelona (BCN) on 18 July, 2015 (FlightRadar24, 2015a).

**Figure 4-12 Altitude and speed changes of flight LX1956.**

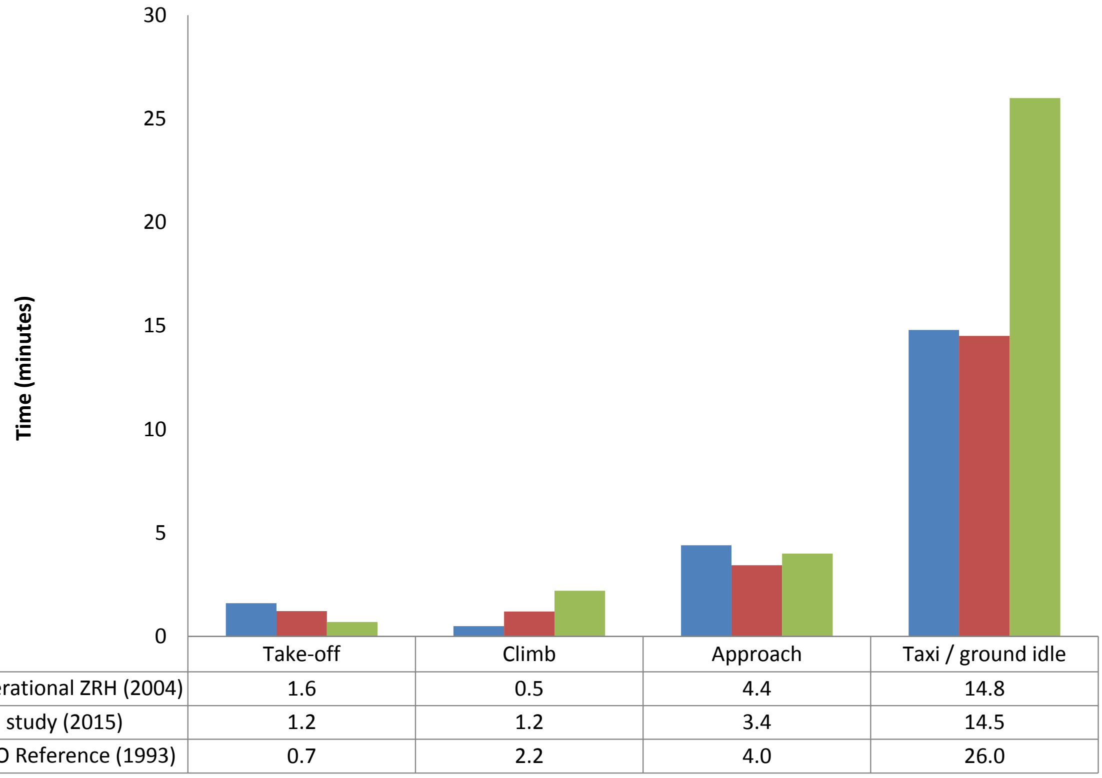


Source: Flightradar24

Following the method of gathering time length of each LTO phase, data for ZRH airport was collected and compared with ICAO reference cycle (ICAO, 1993) and study performed by Airport Zürich in 2004 (Flughafen Zürich AG, 2004). The data was gathered in the month of March 2015 and June 2015 and was assumed to be valid for the whole year. In total 20 flights operated by various aircraft models were analyzed. Current results show significant differences in time across different LTO stages. Take-off phase with thrust setting of 100%, is about 74% longer than the commonly used ICAO reference from 1993. Another important phase in terms of gaseous and smoke emissions is climb out phase with the thrust setting of 85%. Current results, gathered with the use of data from Flighradar24, show 45% time decrease of that phase. Aircraft during approach landing operates on 30% thrust setting, and the current data also show decrease in time. The biggest change in terms of minutes spent, can be observed during taxi / ground idle phase, which compared with 1993 data has decreased by 11 minutes and 30 seconds by year 2015. Although this phase has a thrust setting of only 7%, it does not necessarily mean that all environmental impacts are lower than those that operate at a higher setting. Despite the fact that greenhouse gas emissions are lower as less fuel is consumed, other emissions, such as NMVOCs and PM may be even higher at low thrust levels

(European Environment Agency, 2013). Figure 4-13 provides a graphic description of how the time spent on each LTO phase can vary depending on the source and time when the data was gathered. The data for Zurich Airport obtained from the 2004 report as well as analysis performed for this work in 2015, show significant variance between the ICAO standard.

**Figure 4-13 Difference in time in mode among different sources (time in minutes).**



| | Take-off | Climb | Approach | Taxi / ground idle |
|---|---|---|---|---|
| 🟦 Operational ZRH (2004) | 1.6 | 0.5 | 4.4 | 14.8 |
| 🟥 This study (2015) | 1.2 | 1.2 | 3.4 | 14.5 |
| 🟩 ICAO Reference (1993) | 0.7 | 2.2 | 4.0 | 26.0 |

The analysis of a current data shows decrease in time in most of the phases (except for take-off phase), which has a direct impact on the emissions that influence environment and human health. In case of ZRH specifically, significant effort was made to bring those times down over the years. Federal Office of Civil Aviation (FOCA) of Switzerland shares the environmental concerns and is fully committed towards a sustainable development of air transport (Federal Office of Civil Aviation, 2012). Therefore, it can be expected that the LTO times can tried to be shortened in the future. Literature also suggests other ground propulsion systems for taxi operations. Those new technologies can significantly cut down ground-movement-related fuel burn and emissions. Some new proposed solutions include: taxing with less than all engines, external tractors that could be attached to aircrafts for towing between gates and runaways or integrated on-board electric motors installed in the wheels that would eliminate the use of airplane engines during taxi-out and taxi-in phases (Guo, 2014). The use of those future technologies is however not analyzed in this thesis.

### 4.9.2. Climb, cruise, descent

Climb, cruise, descent phase refers to the aircraft activities at elevations above 3,000 feet (914 m). No upper height limit is given. According to the literature, it is the phase that is responsible for a vast majority of environmental impacts, as it is the phase in which the aircraft spends the majority of its operation time. Many variables have influence on the amount of pollutants emitted into the atmosphere. Some of them include: aircraft design, type of engine, seat load factor or weather conditions (Lewis, 2013), (Lopes, 2010).

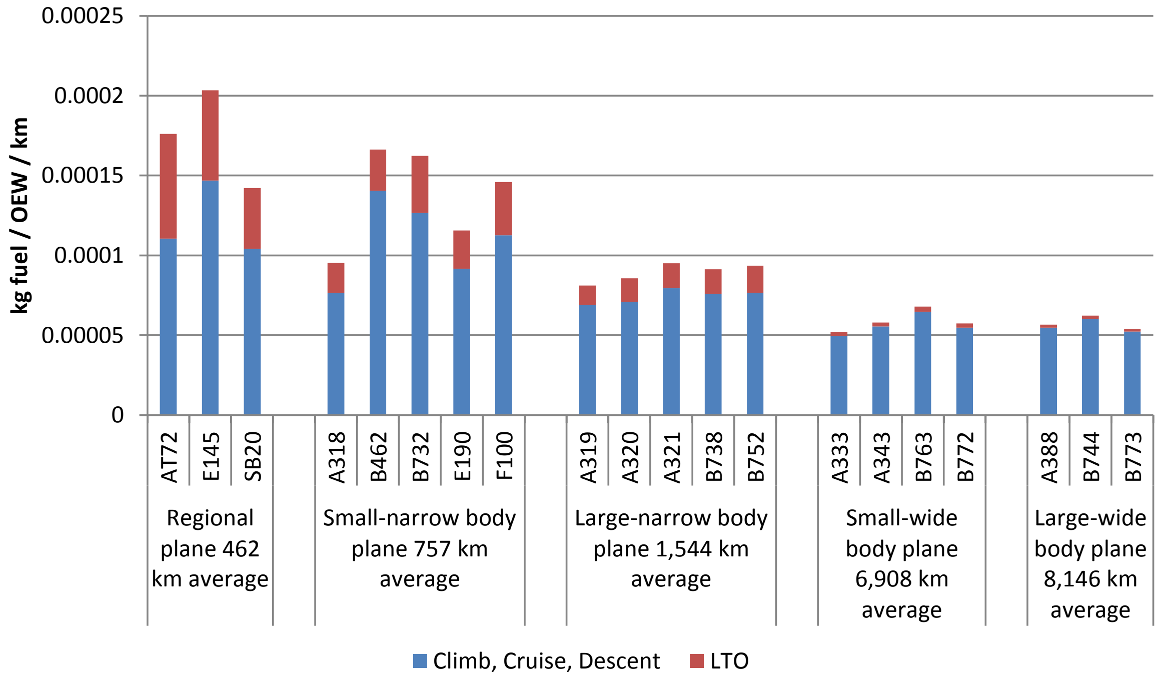
## 4.10. Operating emissions and fuel consumption

Environmental emissions from aviation come from burning of jet fuel and use of aviation gasoline. Committee on Aviation Environmental Protection (CAEP) operates under the ICAO technical council and formulates policies related to aircraft noise and emissions (ICAO, 2015b). Standards need to be met by the makers of aircraft engines.

European Environmental Agency (EEA) provides an inventory guidebook for estimating aircraft emissions. It calculates them over a defined flight length, plane type and phase of flight. It is considered to be a high quality estimation tool and this work utilizes it. However, many calculation parameters, such as the weight or seat load factor are unknown.

Firstly, planes representative of the synthetic planes studied in this analysis and described in the Table 4-1 were chosen from the EEA database. Following indicators were used for further analysis: amount of fuel burn, $CO_2$, $NO_x$, $SO_x$ and PM 2.5. Data was also available for carbon monoxide (CO) and hydrocarbons (HC) emissions. A preliminary analysis was performed to test the impact of CO and HC, but it has indicated that those indicators do not significantly contribute to environmental emission results and were excluded from the study in order to reduce computational requirements. By calculating the slope and intercept functions of the plot of fuel consumed divided by OEW versus flight distance it became possible to obtain parameterized data of total amount of emissions for both LTO and cruise phase on a given flight distance. Consequently, due to the small number of data points, it was assumed that within each synthetic plane category, emissions could be scaled according to the OEW. Figure 4-14 represents the results of fuel burn of previously determined five plane models during landing and take-off (LTO) cycle and climb, cruise, descent phase (CCD) with respect to the distances on which those planes fly.

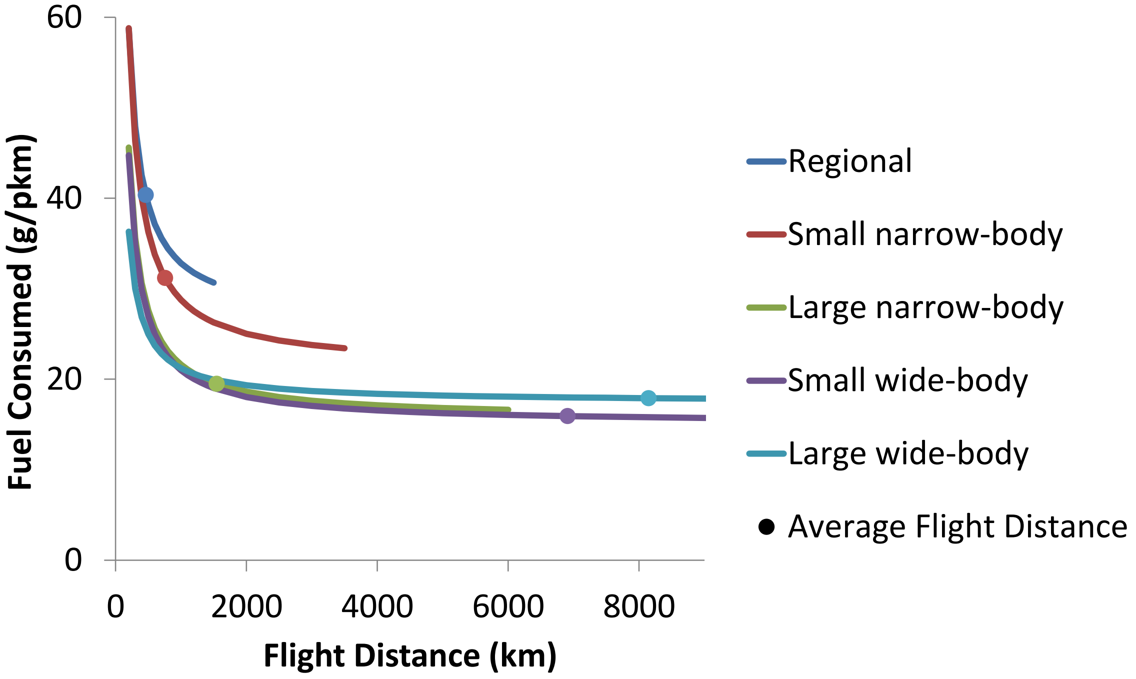
**Figure 4-14 Amount of fuel burn of given plane models per operating empty weight and kilometer.**



It can be observed that smaller planes have higher consumption of fuel per kg of OEW per km. In this regard, large planes are more efficient per kg of weight. Landing and take-off phase is more important for small planes since it represents a larger share of fuel consumption during a specified trip. It can be explained by the fact that small planes fly on shorter distances.  Planes with the code names: B722, CS100 and DO328 were excluded in this analysis because of inconsistent data that produced disrupted results.

By analyzing the data further, it is possible to plot a relationship between fuel consumed with respect to one passenger kilometer and flight distance. This dependence is shown in the Figure 4-15 below. Dots on the figure represent average flight distance (also given in the Figure 4-14) of each of the five plane categories. Small planes operate on the short, steep lines; large ones by flat lines. As a result, decreasing the flight distance for large aircraft such as small or large wide-body of a long trip does not significantly reduce the amount of fuel consumed per PKM. Cutting the flight length for large wide-body from 8,000 km to 4,000 does not influence fuel consumption which will stay below 20 g/PKM. On the other hand, models like regional or small narrow-body which perform shorter trips are very sensitive to the change of flight distance. Decreasing it for a small narrow-body plane would cause the consumption to almost double.

**Figure 4-15 Aircraft fuel consumption**



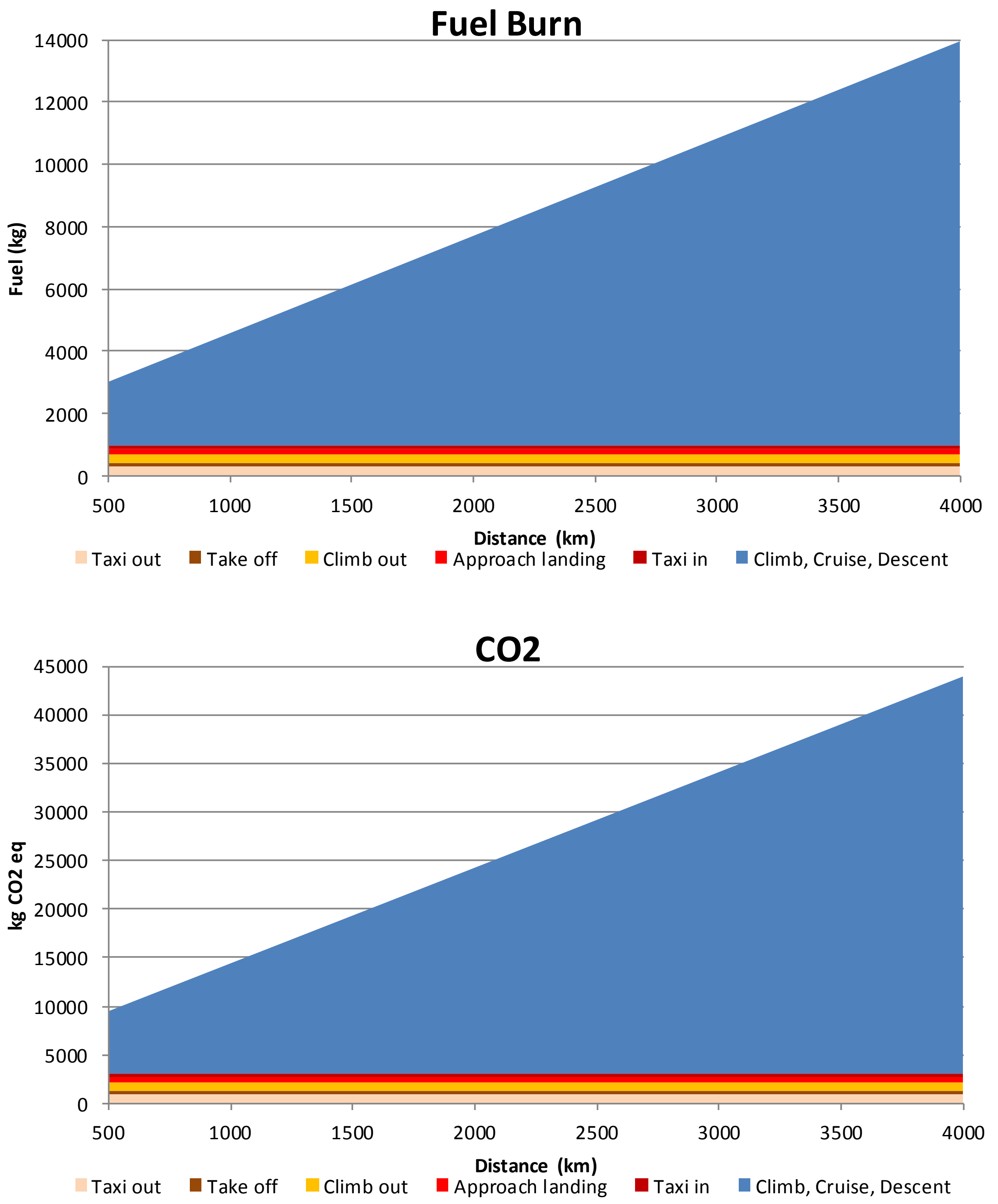
For calculation of total emissions of each of the five synthetic plane models the sum of emissions in each category was gathered and assigned to specific plane models. Regarding LTO cycle, a synthetic plane represents an average of emissions of all planes that belong to that category. For calculation of emissions during climb, cruise, descent (CCD) phase, a slope-intercept form was determined. Table 4-4 provides numbers for those functions that were used for further calculations. This methodology allows for precise estimations on the fuel consumption and emissions in a distance that can be parameterized.

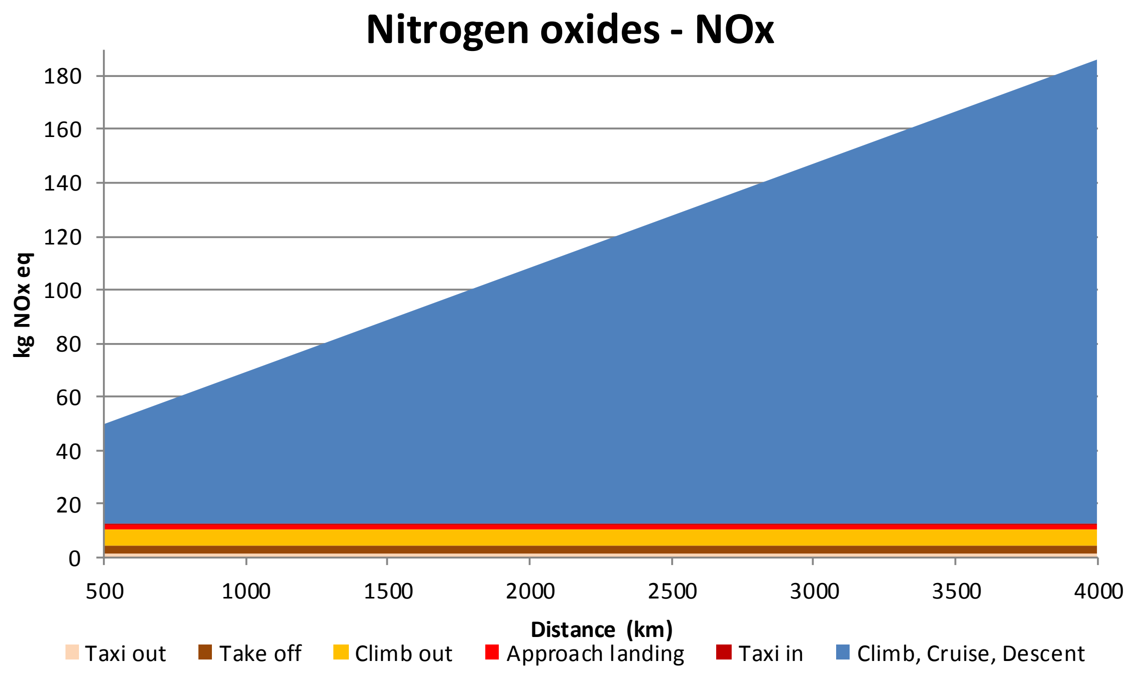
**Table 4-4 Slope and intercept functions for CCD phase of synthetic planes per given emissions.**

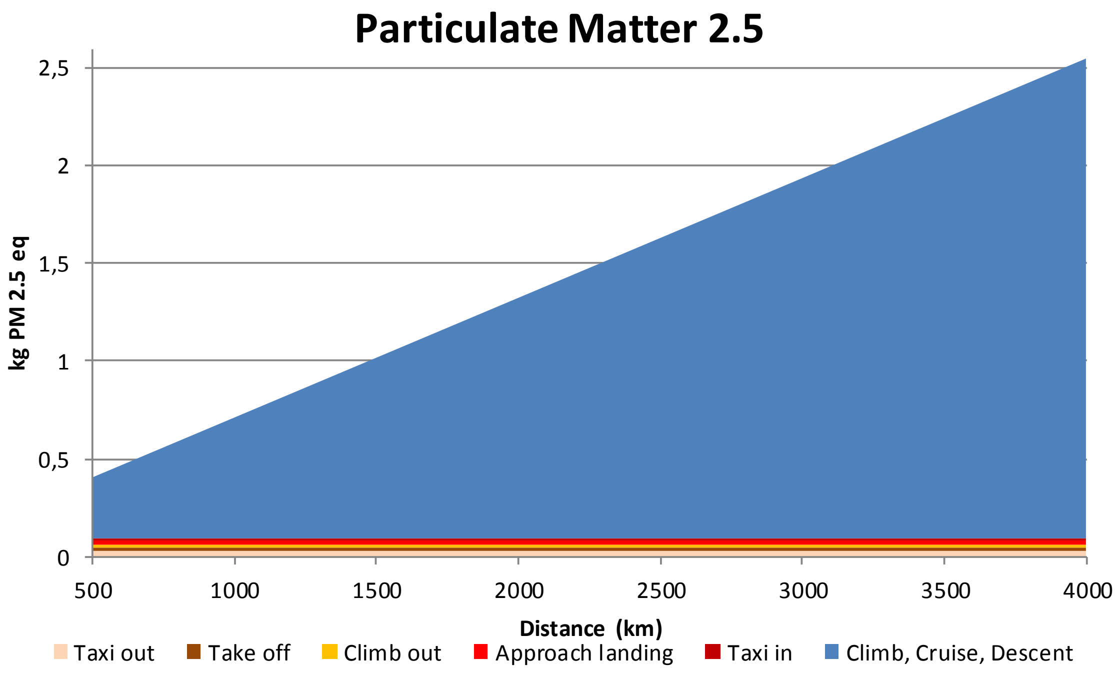
| | kg of fuel burn | | kg of $CO_2$ eq | | kg of $NO_x$ eq | | kg of $SO_x$ eq | | kg of PM 2.5 eq | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Slope | Intercept | Slope | Intercept | Slope | Intercept | Slope | Intercept | Slope | Intercept |
| **Regional** | 1.3E+00 | 1.0E+02 | 4.2E+00 | 3.2E+02 | 1.7E-02 | 1.9E+00 | 1.1E-03 | 8.4E-02 | 1.8E-04 | 1.9E-03 |
| **SNB** | 2.6E+00 | 4.1E+02 | 8.2E+00 | 1.3E+03 | 2.4E-02 | 8.8E+00 | 2.2E-03 | 3.4E-01 | 4.7E-04 | 7.2E-03 |
| **LNB** | 3.1E+00 | 4.8E+02 | 9.8E+00 | 1.5E+03 | 3.9E-02 | 1.8E+01 | 2.6E-03 | 4.0E-01 | 6.1E-04 | 5.2E-03 |
| **SWB** | 6.4E+00 | 1.0E+03 | 2.0E+01 | 3.2E+03 | 1.1E-01 | 5.0E+01 | 5.4E-03 | 8.7E-01 | 1.2E-03 | 8.8E-02 |
| **LWB** | 1.2E+01 | 6.4E+01 | 3.7E+01 | 2.0E+02 | 2.1E-01 | 6.7E+01 | 9.8E-03 | 5.4E-02 | 1.3E-03 | 7.2E-02 |

The use of defining the intercept and slope functions can be seen in the Figure 4-16. It shows four categories of emission factors from the European Environmental Agency (EEA) inventory guidebook. Results are presented for large narrow-body plane category to which belong two most commonly used civil, commercial aircraft: Airbus A320 and Boeing 737. LTO phase is additionally broken down into all its five phases. The CCD phase is responsible for the majority of emissions among all factors. The longer the flight distance is, the more marginal share of the LTO cycle impacts becomes.

**Figure 4-16 Parameterized results of fuel burn and emissions for Large narrow-body plane with respect to LTO and CCD phases**







### 4.10.1. 2050 forecast

ICAO Committee on Aviation Environmental Protection (CAEP) has created the Engine Emissions Database on exhaust emissions of all the aircraft engines registered since 1972. The data is provided by the engine manufacturers themselves who are responsible for the accuracy. It also provides the standards for emissions of smoke, unburnt hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) from turbojet and turbofan engines. The descriptions are also provided for the measurement techniques.

The databank takes into consideration all engines that entered production regardless of the numbers produced. It provides information about both engines that comply or do not comply with the emissions standards. Manufacturers provide the data voluntarily which later on goes through the approval and certification process. After the certification authority approves the data, it is submitted to the ICAO databank, where it is checked for format and consistency. It is available as an Excel file. Engines no longer in service or in production are specially marked. The data is updated regularly but the frequency depends on the availability of new data. ICAO claims it is updated at least one time per year. The database used in this thesis comes from February 2015 (ICAO, 2015a).

One of the limitations is that the data assesses the emissions only during the LTO cycle which occurs below 914 m (3,000 ft.). Values are calculated for the average throttle setting for each phase of the standard LTO. Those may vary and when assessing emissions for specific airport, the change of conditions should be taken under consideration. As mentioned before, the data is measured at the ground level (LTO) but this work assumes that the trend in improvement over time at LTO is also valid for the cruise phase. One of the reasons for this decision is fact that as of now, there is no dataset that would measure the emissions at cruise level in such detailed manner as the ICAO Engine Emissions Databank.

One of the most important steps in performing LCA was to estimate how fuel consumption and other emissions may change over the years until 2050. Time series data in the newest ICAO databank was gathered for all the engines produced since 1972 until 2012. It includes variables such as: engine type, rated output (kN), current engine status, testing dates, fuel flow and amount of nitrogen oxides, hydrocarbons and particulate matter[6] (PM) emitted. Given this data, a time series analysis on aircraft engine fuel consumption was performed which is shown on Figure 4-17.

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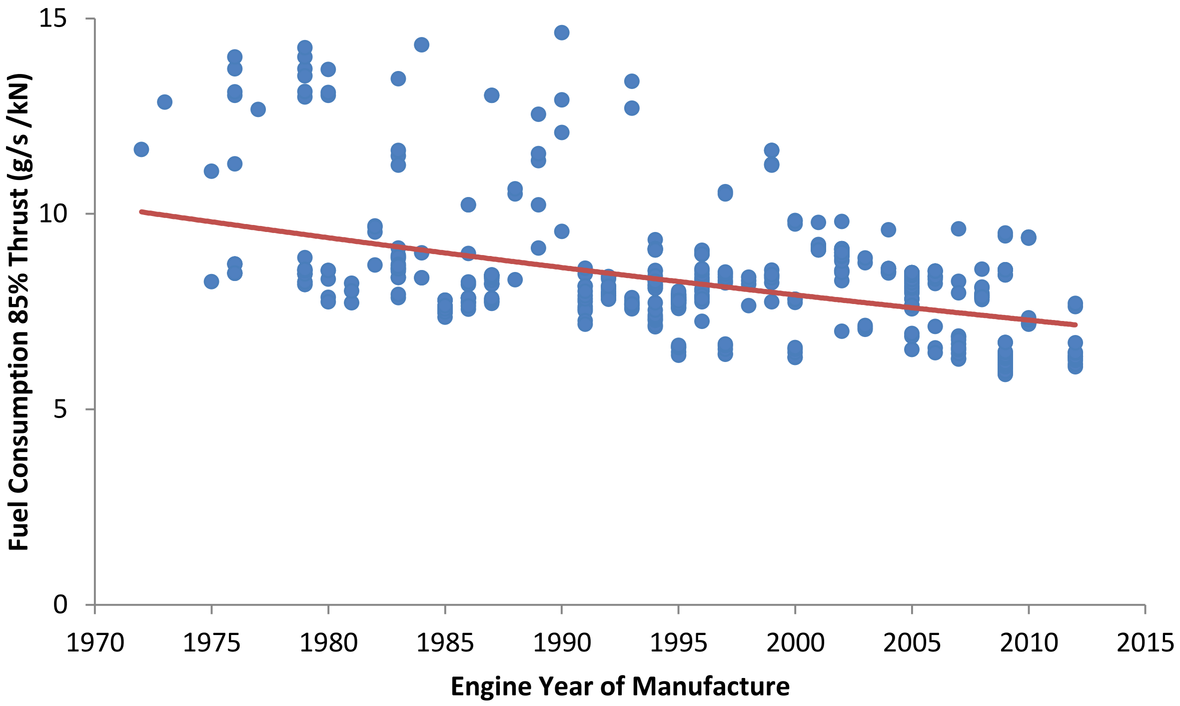
[6] ICAO in its emissions databank uses the term “smoke number” instead of “particulate matter”. For the simplification reason this work assumes the improvement in “smoke number” to be valid as well for “particulate matter”.

**Figure 4-17 Aircraft Engine Fuel Consumption from 1972 until 2012. Source: ICAO Engine Emissions Databank (2015).**



The fuel consumption per kN of thrust was plotted against the year when the engine was manufactured and tested for the first time. It is valid for 85% thrust setting, which is similar to the settings at which aircraft operate in cruise phase. Additionally, other variables such as engine type, rated output or different manufacturer were tested. However, none of these additional variables seemed to have a significant impact on the results.

Figure 4-18 shows how the $NO_x$ emissions were changing over the years. The amount of nitrogen oxides expressed in grams per second per kN of thrust was plotted against the year of manufacture. Similarly to Figure 4-17, a thrust setting of 85% was applied to reflect the cruise phase.

**Figure 4-18 Aircraft Engine NOx Emissions. Source: ICAO Engine Emissions Databank (2015).**

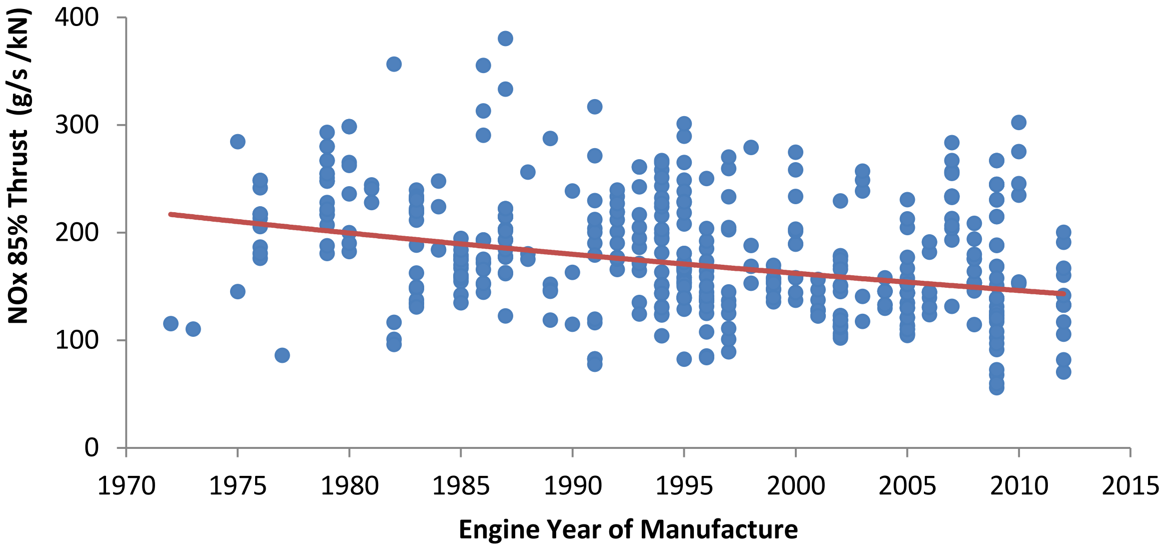
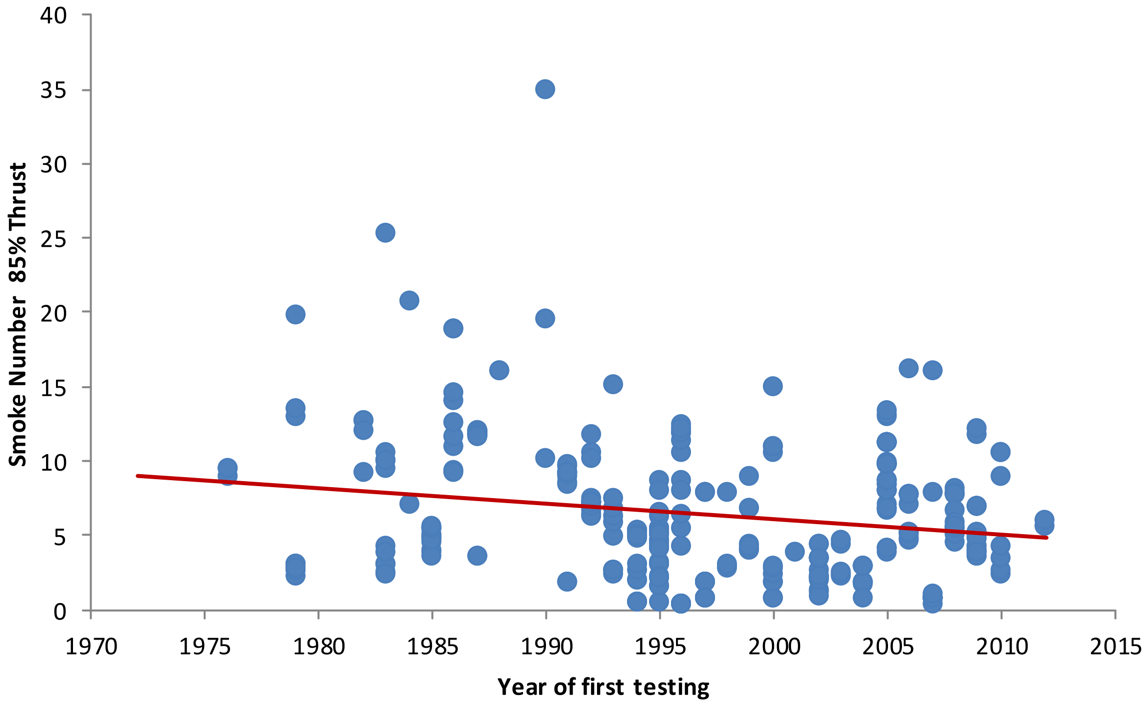


**Figure 4-19 Aircraft Engine Smoke Number Emissions. Source: ICAO Engine Emissions Databank (2015).**



Three of the presented time series analyses indicate that fuel consumption as well as nitrogen oxides and smoke emissions, have been declining since 1972 until 2012. The annual improvements between those times were calculated using least squares regression analysis and extrapolated until year 2050. Complete list of all emissions for which time series analysis was performed is presented in the Table 4-5. The base year is 2012, from which the forecast begins. All the impact categories are expected to have lower environmental burden in 2050.

**Table 4-5 Annual efficiency improvements. Base year 2012 = 100%.**

| Impact category name | **2015 value** | **2050 value** | **Annual change** |
|---|---|---|---|
| Fuel consumption | 97.6% | 73.8% | -0.8% |
| Carbon dioxide ($CO_2$) | 97.6% | 73.8% | -0.8% |
| Sulphur oxides ($SO_x$) | 97.6% | 73.8% | -0.8% |
| Nitrogen oxides ($NO_x$) | 97.0% | 68.4% | -1% |
| Particulate Matter 2.5 (PM) | 95.3% | 54.4% | -1.6% |

Historic rate of engine efficiency delivers fuel consumption improvement of 0.8% per year. According to the literature, investments in new technologies has enabled jet engine to improve at an average of 1% per year (Air Transport Action Group, 2010). Aspirational goal of global fuel efficiency improvement rate of 2 per cent per annum increases this rate up to 2%. ICAO states that it would require additional technological and operational improvements even beyond the base scenario (ICAO, 2013).

# 5. Results of Life Cycle Impact Assessment

This section will provide findings of Life Cycle Assessment for current 2015 and 2050 technologies. Subchapter 5.1 focuses on the climate change in terms of kg $CO_2$ emissions. Following subchapters expand the results to other environmental indicators, such as terrestrial acidification, photochemical oxidant formation and particulate matter formation.

Results are presented for all five synthetic plane categories defined in the section 4.3. All life cycle stages are included: airport construction, operation and disposal; manufacturing and disposal; fuel production; operation. In order to present findings in a consistent manner, they all are expressed in functional unit PKM. Extended results can be found in Appendix in Table A-3.

## 5.1.Global warming potential

The amount of carbon dioxide produced is strongly dependent on the combustion of kerosene in aircraft. This subsection shows potential impact of air transportation on climate change in terms of kg $CO_2$ eq per PKM as well as the breakdown of total emissions into various life cycle phases.

Figure 5-1 and Table 5-1 show the climate change impacts per passenger kilometer among five synthetic plane types in year 2015 and 2050.

**Figure 5-1 LCA results for 2015 and 2050 aircraft, Global warming potential**

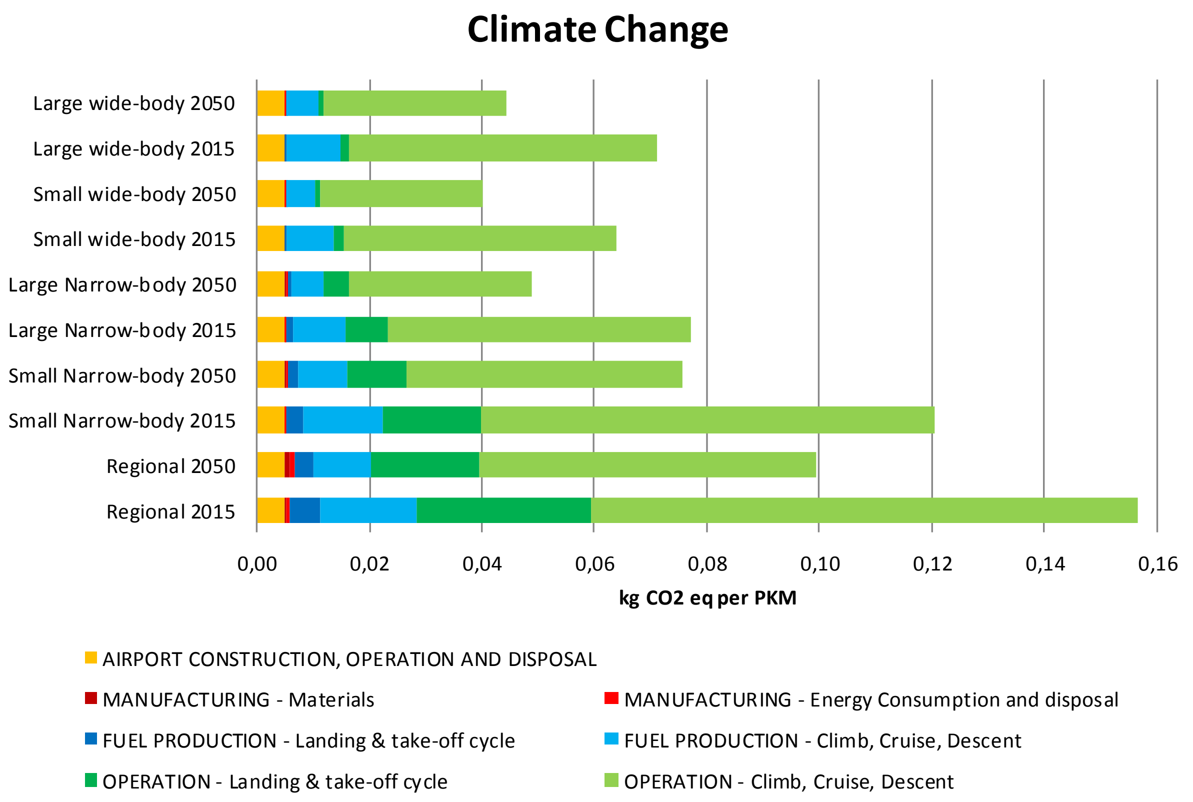


**Table 5-1 Total LCA results for 2015 and 2050 aircraft, Global warming potential**

| | kg CO2 eq per PKM |
|---|---|
| **Regional 2015** | **0,157** |
| Regional 2050 | 0,099 |
| **Small Narrow-body 2015** | **0,120** |
| Small Narrow-body 2050 | 0,076 |
| **Large Narrow-body 2015** | **0,077** |
| Large Narrow-body 2050 | 0,049 |
| **Small Wide-body 2015** | **0,064** |
| Small Wide-body 2050 | 0,040 |
| **Large Wide-body 2015** | **0,071** |
| Large Wide-body 2050 | 0,044 |

For the current scenario, the largest impact share is represented by the operation cycle in the cruise phase for all aircraft models. In the regional category it is 62% of total 157 g of $CO_2$ eq per PKM, and in the large wide-body one over 77% out of 71 g of $CO_2$ eq per PKM. Interestingly, landing and take-off cycle also share significant impact. In the lifetime of regional plane, it is responsible for almost 20% of climate change impact, in contrary to large-wide body where the share amounts only 2%. This difference is a result of various flight characteristics. Share of landing and take-off cycle in the total number of kilometers flown during a lifetime of an aircraft is more notable in case of smaller planes. That as well translates to the significantly smaller impact per PKM of large planes than regional planes during their lifetime. As already mentioned, big aircraft spend most of their operating time in the cruise phase which per km consumes less fuel than the LTO phase. Fuel consumption is directly correlated with the environmental emissions. Small planes operate more often in the LTO phase. As all five synthetic plane models share the same lifetime of 22 years, large planes show significantly smaller impact than small ones. An exception to this rule can be however observed in the case of small wide-body plane that shows smaller emissions than large wide-body plane, although the first one carries less passengers than the latter. This is due to the fact that many plane models that belong to the small wide-body category, despite their shorter average distance, travel more kilometers during their lifetime than the large models. That includes among others Boeing 787-8 or Airbus 350-900. Non-tailpipe emissions are also relevant from a climate change perspective. They hold between 18% and 21% share of the life cycle emissions depending on the aircraft type. Manufacturing phase represents marginal impact for all plane types.

Forecasts for year 2050 show decreased climate change impacts for all planes categories. The total amount g of $CO_2$ eq per PKM is expected to decrease on average 37% by then. Given the efficiency improvements, fuel production and operation phase are expected to have lower impacts. However, they will still be responsible for the majority of environmental burden in this category. Amount of $CO_2$ eq per PKM coming from the airport construction, operation and disposal phase assumed not to change and will stay at the 2015 levels. Important to notice is fact that the manufacturing phase shows increased significance. Impacts increase by over 200%, however they still do not go beyond 1% threshold. This rise is due to the light weighting process, which causes larger amount of composite materials to be used. They are mostly responsible for the higher contribution to the climate change.

## 5.2.Terrestrial acidification

Change of soil acidification that affects the growth condition of plants is determined by the terrestrial acidification. Following subsection shows the potential impact of air transportation on terrestrial acidification as well as the breakdown of total emissions into various life cycle phases.

Figure 5-2 and Table 5-2 show the terrestrial acidification impacts per passenger kilometer among five synthetic plane types in year 2015 and 2050.

**Figure 5-2 LCA results for 2015 and 2050 aircraft, Terrestrial acidification potential (TAP) in kg SO2 eq per PKM**

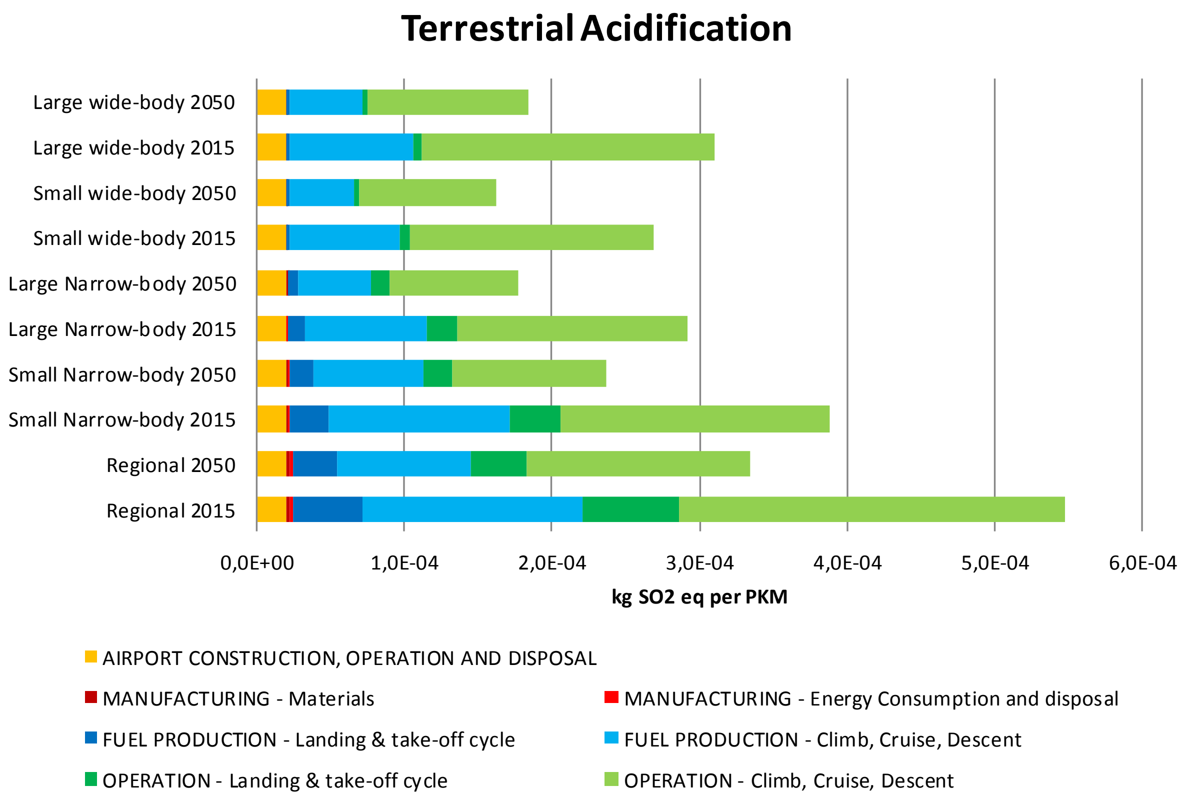


**Table 5-2 LCA results for 2015 and 2050 aircraft, Terrestrial acidification potential (TAP) in kg SO2 eq per PKM**

| | kg SO2 eq per PKM |
|---|---|
| **Regional 2015** | **5.48E-04** |
| Regional 2050 | 3.34E-04 |
| **Small Narrow-body 2015** | **3.88E-04** |
| Small Narrow-body 2050 | 2.36E-04 |
| **Large Narrow-body 2015** | **2.92E-04** |
| Large Narrow-body 2050 | 1.78E-04 |
| **Small Wide-body 2015** | **2.69E-04** |
| Small Wide-body 2050 | 1.62E-04 |
| **Large Wide-body 2015** | **3.10E-04** |
| Large Wide-body 2050 | 1.84E-04 |

Similarly to the climate change impact category, operation phase in year 2015 is responsible for the majority of the terrestrial acidification impacts. That share has however decreased to 60% for regional plane and 66% for large wide-body one. Fuel production phase has much higher impact on the change of soil acidification. It is responsible for between 29% and 38% of total $SO_2$ eq emitted depending on the aircraft category.

Expected efficiency improvements by year 2050 will have big influence on the terrestrial acidification. Total amount of kg $SO_2$ eq per PKM is expected to decline by approximately 40% for all plane categories. The largest change will occur in the operation and fuel production phases. Manufacturing is expected to have increased contribution in the acidification process, but not as drastic as in case of climate change potential. Higher use of carbon and glass fiber reinforced plastic does not significantly raise the amount of $SO_2$ produced. The future picture for air transportation in this category appears to be relatively optimistic.

## 5.3.Photochemical oxidant formation

Photochemical oxidants cause ground level ozone which in result can irritate the lining of the nose, airways and lungs. Since they are present on the ground level, environmental impacts coming from Operation in the Climb, Cruise, and Descent phase were neglected and excluded from the results.

Figure 5-3 and Table 5-3 show the photochemical oxidant formation impacts per passenger kilometer among five synthetic plane types in year 2015 and 2050.

**Figure 5-3 LCA results for 2015 and 2050 aircraft, Photochemical oxidant formation (POF)**

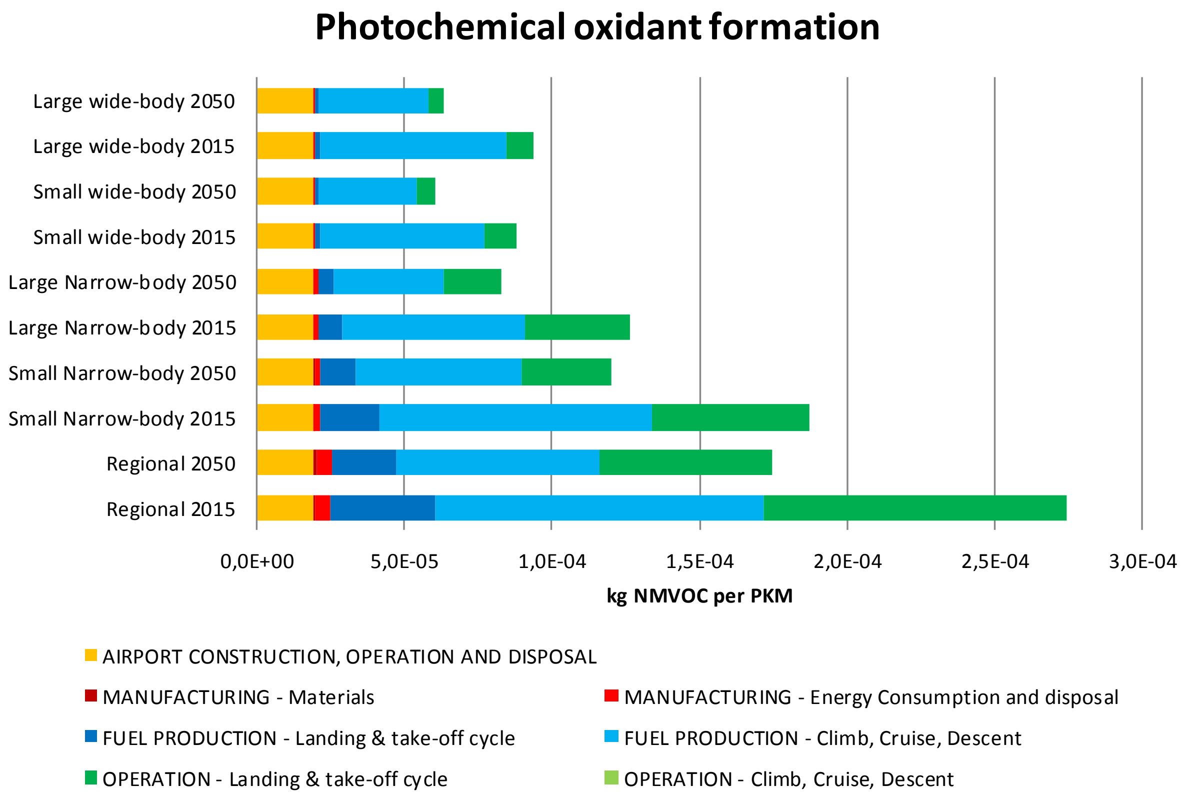


**Table 5-3 LCA results for 2015 and 2050 aircraft, Photochemical oxidant formation (POF)**

| | kg NMVOC per PKM |
|---|---|
| **Regional 2015** | **2.74E-04** |
| Regional 2050 | 1.74E-04 |
| **Small Narrow-body 2015** | **1.87E-04** |
| Small Narrow-body 2050 | 1.20E-04 |
| **Large Narrow-body 2015** | **1.26E-04** |
| Large Narrow-body 2050 | 8.31E-05 |
| **Small Wide-body 2015** | **8.83E-05** |
| Small Wide-body 2050 | 6.03E-05 |
| **Large Wide-body 2015** | **9.39E-05** |
| Large Wide-body 2050 | 6.34E-05 |

Since the emissions from the operation in the cruise phase are not taken under consideration, the fuel production for 2015 Aircraft is responsible for the majority of impacts. For regional plane it is 54% of total emissions and for large wide-body this number increases to 69%. NMVOC equivalent impacts are emitted also from the exhaust at low power settings during airport taxi and idle operations, which results in high impacts coming from the LTO phase. Due to the higher occurrence of landing and take-offs that regional planes perform, environmental burden coming from that phase is responsible for over 37% of total NMVOC equivalent impacts. This number decreases as the aircraft size increases and for the largest category amounts 10%.

Expected efficiency improvements by year 2050 cause the impacts to decrease, but not as drastically as for the other categories. Foremost, the operating emissions during LTO cycle and fuel production are expected to decrease by approximately 40%. On the other hand, the increased use of composites will cause the impacts from the manufacturing phase to increase by around 70%. They will however still stay below 1% level.

## 5.4.Particulate Matter (PM) Formation

As discussed in section 3.2.2, PM emissions from operation in the cruise phase were excluded from the analysis.

Figure 5-4 and Table 5-4 LCA results for 2015 and 2050 aircraft, Particulate matter formation (PMF) show the particulate matter formation impacts per passenger kilometer among five synthetic plane types in year 2015 and 2050.

**Figure 5-4 LCA results for 2015 and 2050 aircraft, Particulate matter formation (PMF)**

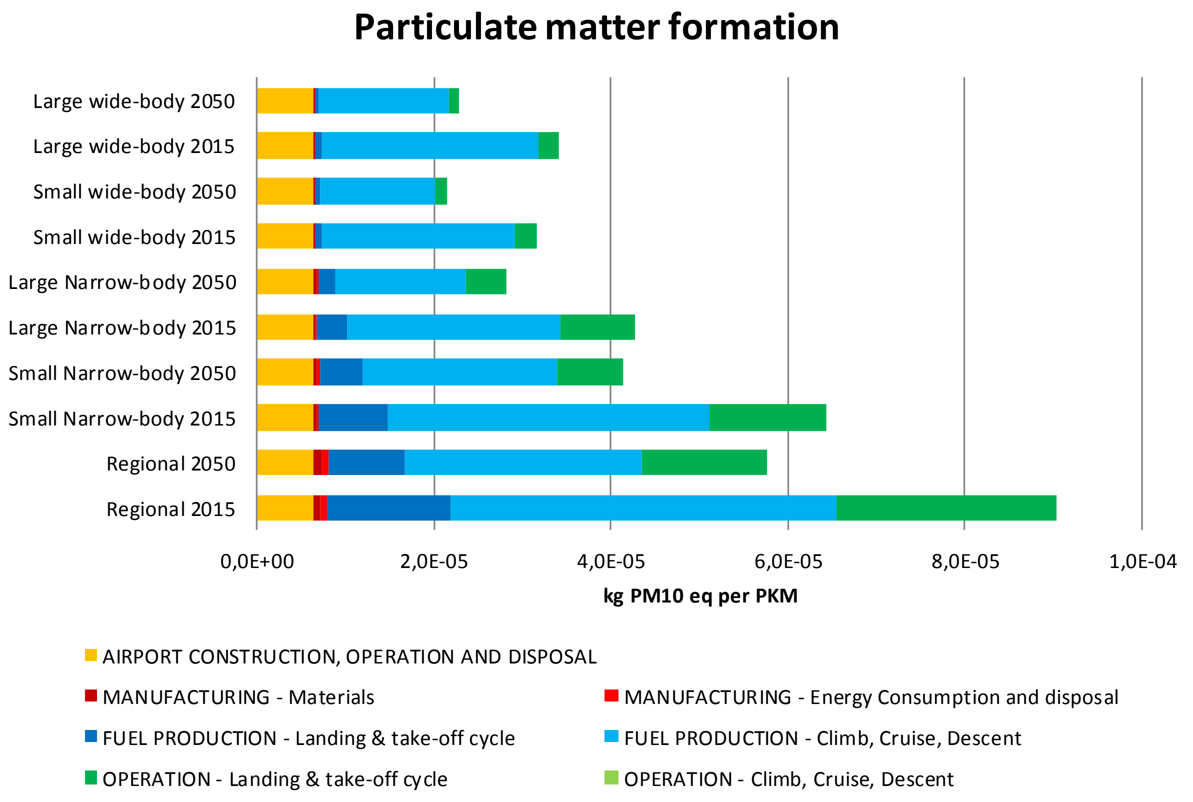


**Table 5-4 LCA results for 2015 and 2050 aircraft, Particulate matter formation (PMF)**

| | kg PM10 eq per PKM |
|---|---|
| **Regional 2015** | **9.03E-05** |
| Regional 2050 | 5.76E-05 |
| **Small Narrow-body 2015** | **6.43E-05** |
| Small Narrow-body 2050 | 4.13E-05 |
| **Large Narrow-body 2015** | **4.28E-05** |
| Large Narrow-body 2050 | 2.82E-05 |
| **Small Wide-body 2015** | **3.17E-05** |
| Small Wide-body 2050 | 2.15E-05 |
| **Large Wide-body 2015** | **3.41E-05** |
| Large Wide-body 2050 | 2.29E-05 |

For 2015 Aircraft, emissions created during fuel production are dominating category among all plane types. They are responsible for more than 60% of all the emissions during life cycle of a plane. Among smaller planes such as regional one, fuel produced for the LTO cycle has larger impact than in case of big aircraft such as large wide-body.

Efficiency improvements cause the emissions to decline. Thanks to the expected lower fuel consumption, impacts coming from the fuel production are to decline by around 40% for all plane types. Manufacturing process causes more particles to be emitted into the air, due to the increased use of composite materials. Amount of PM coming from the airport construction and operation is not expected to change, therefore its share in among all the categories slightly increases.

## 5.5.Sensitivity analysis

This section evaluates the sensitivity of the results to changes into the input parameters. Sensitivity was done to test the impact of uncertain or highly variable input values on LCA results. The examined parameters are presented in the Table 5-5 and include: plane lifetime, landing and take-off times, average flight lengths, rates of weight and fuel efficiency improvements and freight filling assumption (Belly Cargo). The change of environmental impact potential is shown in percentage values for each of the category. The figures below present results for two plane models: regional and large wide-body. The detailed results and complete figures can be found in Appendix.

**Table 5-5 Parameters tested in sensitivity analysis.**

| | Original Value | Higher Value | Lower Value |
|---|---|---|---|
| **Plane lifetime (years)** | 22.11 | 30 | 14 |
| **LTO Times** | This study (2015), see Figure 4-13 | ICAO Reference (1993), see Figure 4-13 | |
| **Average flight length (km)** | See Table 4-3 | 100% increase | 50% decrease |
| **Weight reduction rate (per decade)** | 2.5% | 5% | 1.25% |
| **Fuel efficiency and other exhaust emissions improvement rate (annual )** | Fuel consumption: 0.8% | Fuel consumption: 1.6% | Fuel consumption: 0.4% |
| | HC: 7.4% | HC: 14.8% | HC: 3.7% |
| | $NO_x$: 1% | $NO_x$: 2% | $NO_x$: 0.5% |
| | PM: 1.6% | PM: 3.2% | PM: 0.8% |
| **Freight filling assumption (Belly Cargo)** | Planes travel always fully loaded | Planes are loaded up to their statistical seat load factor | |

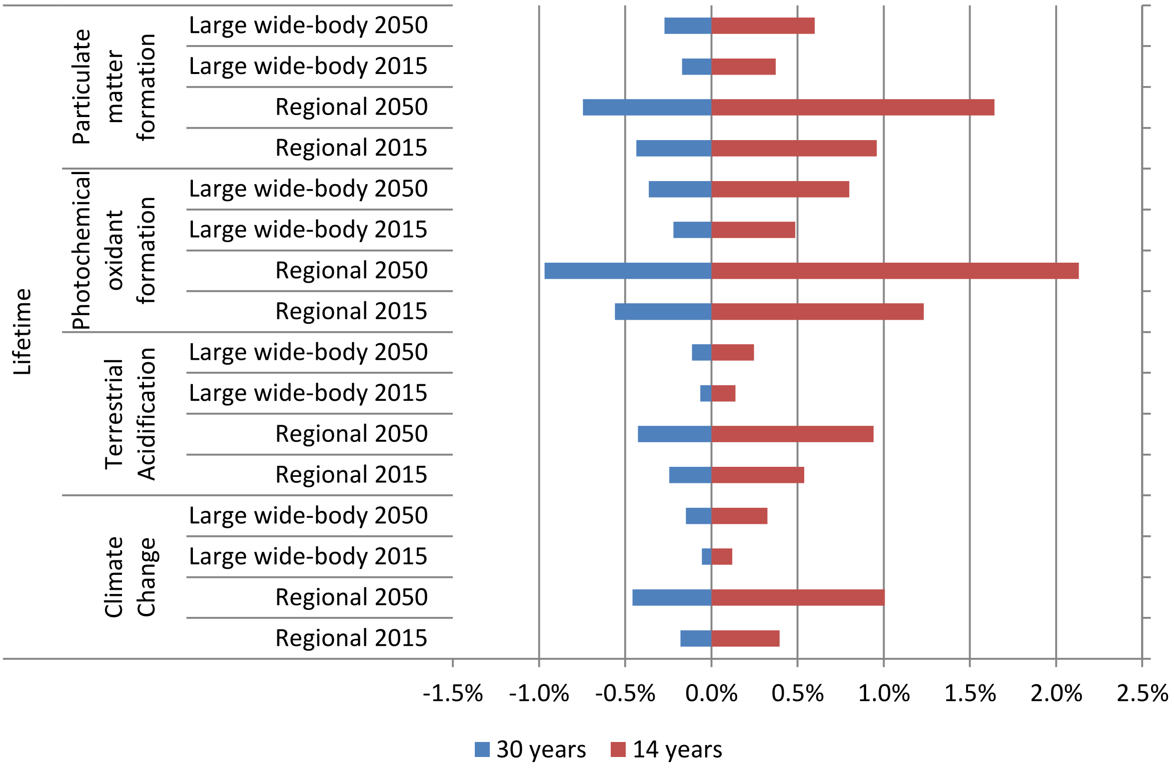
### 5.5.1. Aircraft lifetime

Figure 5-5 shows the results of the sensitivity analysis for the change of the aircraft lifetime. It can vary extremely, based on the various factors. One of them is the metal fatigue which is a natural limiting factor of the lifespan. The cracks on the metal build up every flying cycle, especially during LTO phase. Long haul aircraft that perform less take-offs and landings are exposed to fewer cycles than short haul aircraft that start and land more often. The lifetime of a plane can be stretched thanks to the special maintenance services and can reach sometimes 30 years (Aviation Stack Exchange, 2014). In many cases however, the decision to retire an aircraft is purely based on economics. The life ends typically when it becomes more expensive to maintain it than to purchase a new one. New aircraft are less expensive to operate and can replace the old fleet. The fuel costs benefits may outweigh the drawbacks of higher purchase price. Fuselage is the most vulnerable element to the fatigue, followed by the wings. This work however does not evaluate how do airlines determine the fatigue of various parts and treats the aircraft as a whole. Studies show that if entire global aircraft fleet was replaced with the most fuel efficient today's technology, the global $CO_2$ emissions from aviation could be reduced by 10% (Dray, 2014).

Although, typically an aircraft's lifetime is measured not in years but in pressurization cycles (Air & Space Magazin, 2008), this study uses the time measure. It is due to the availability of the data that allowed for estimating the average aircraft lifespan. Additionally, using the year basis gives more flexibility of extrapolating the results into the future. Therefore, a variation of +8 and -8 years is used in this sensitivity analysis.

As anticipated, the longer lifespan may reduce the environmental impacts per PKM. On the other hand, reduced lifetime will cause the results to increase. The most sensitive impact category to changes in the lifespan is photochemical oxidant formation. Depending on whether extending or reducing the amount of years of Regional plane in service, the results for that category change by -1%/2% respectively. The changes in the greenhouse gasses emissions are even less significant and regarding Regional plane they do not reach 1%. Reducing the lifetime of a long-haul aircraft such as large wide-body, will not increase Climate Change impacts even by 0.5%. The plane lifespan in this work is strictly connected with the lifetime kilometers flown based on the distances flown per year described in the section 4.8. Short-haul aircraft will be more sensitive to the lifetime changes since the amount of kilometers flown during their lifetime is approximately eight times smaller (in the base scenario) than of long-haul ones. Calculations performed in this study show that the Regional plane flies over 11 million kilometers during its lifespan, versus the Large wide-body that flies over 87 million. Overall, this small variation of the results allows to conclude that aircraft age does not have significant influence on environmental results. That strengthens the fact that methodology applied in the subchapter 4.2 of calculating plane’s lifetime was accurate enough for the purpose of this work.

**Figure 5-5 Sensitivity analysis: Change of the aircraft lifetime. Original value: 22 years.**



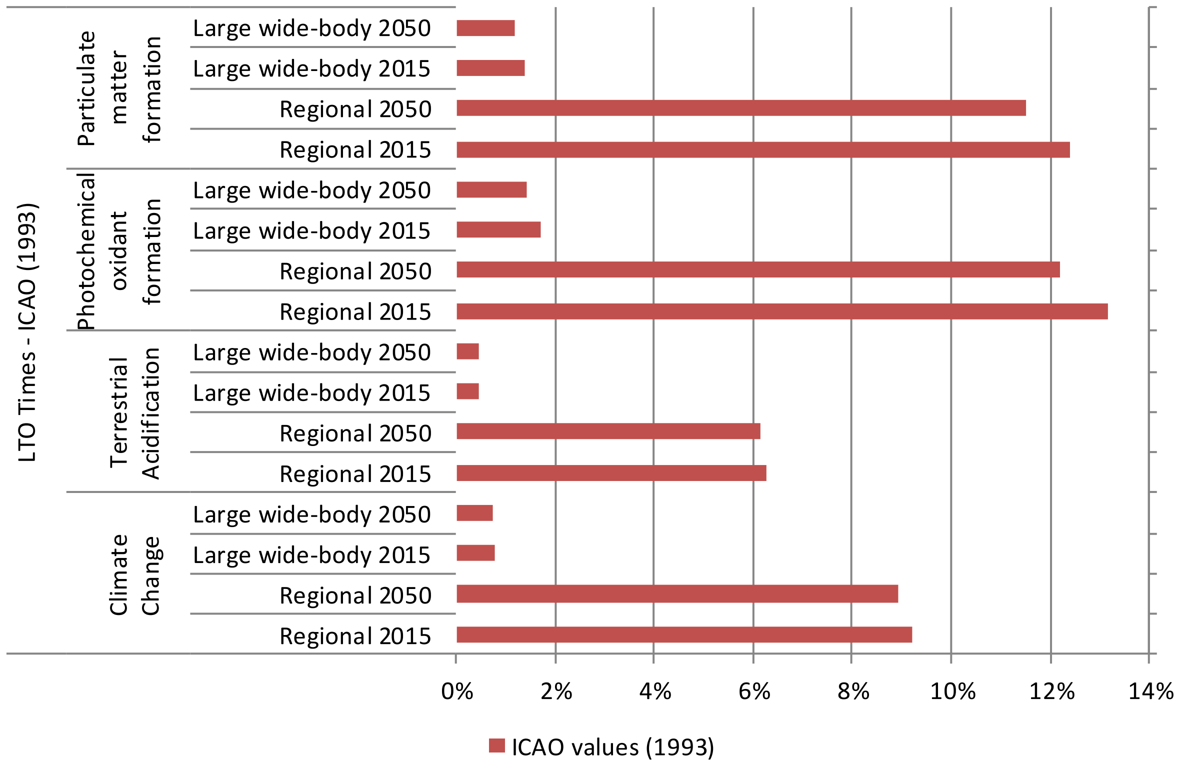
### 5.5.2. LTO times

This work also evaluates the sensitivity of using the ICAO defined LTO cycle and its influence on environmental impact categories. For emission results described in the chapter 5, original times-in-mode presented in the Figure 4-13 were used. As previously mentioned, they are based on own calculations of LTO modes, with the data coming from the Zurich international airport. Since the difference between values provided by ICAO and this study was significant, this section examines the use of the standard ICAO LTO times. The results for all four impact categories are shown in Figure 5-6 for Regional 2015/2050 and Large wide-body 2015/2050 plane.

The application of ICAO reference times for LTO cycle showed that calculated emissions were higher for all four impact categories. The most noticeable difference can be observed for the regional plane, as expected as it has the largest contribution from LTO life cycle phase. Large wide-body plane was least affected. In climate change impact category, Regional aircraft appears to be almost seven times more sensitive to the results than the largest one. By calculating with times provided by ICAO, the computed $CO_2$ emissions per PKM increase for the regional plane by around 9% both in year 2015 and 2050. Large wide-body is less sensitive to the change and shows the increase by only 1% in that category. Other three environmental indicators show even larger discrepancy between two aircraft types, with Regional one being the most affected by the change in LTO times. It is mainly due to the fact that small aircraft usually travel on shorter distances. They spend smaller proportion of flying time in the cruise phase than they do on the landing and taking off. Airports should try to reduce LTO times as they cause big environmental burdens. The uncertainty connected with this analysis comes from the fact that base values of LTO times from 2015 estimated for the purpose of this work were based on the values for Zurich Airport only. They may differ with respect to the airport, but this analysis was however considered to be out of scope for this thesis. The longer times spend on the LTO phases are directly correlated with the higher emissions produced by the tested aircraft categories. It is worth mentioning that in all cases the emissions calculated with using ICAO reference times are greater than those with using the times computed for this study. The overestimation of ICAO cycle is not unexpected and was mentioned in the literature already in the past (European Commission, 2001).

Although reference times for LTO cycle provided by ICAO database are useful baseline, they do not reflect real operations and can lead to inaccurate estimation of aircraft emissions (Celikel, 2004). This reference data should help to provide better understanding of the aircraft operation at a given airport. Due to the fact that focus of this work is Swiss market, the self-calculated values described in the Figure 4-13 are used throughout the work. Moreover, this sensitivity analysis confirms the discrepancy in the results between the official ICAO times and this paper. However, the provided methods of estimating environmental impacts are connected with uncertainties. In order to minimize the error of measuring the times, the more detailed operational modes than the four established by LTO, would be needed. It becomes greatly important when estimating the $NO_x$ emissions at the airport for the high engine thrust settings. Overestimation of CO, HC, $NO_x$ and PM emissions by the ICAO LTO reference cycle is reported widely in the literature. This sensitivity analysis confirms that using the LTO times from major Swiss airports calculated in this work, delivers lower values.

**Figure 5-6 Sensitivity analysis: Change of the LTO times to the reference cycle of ICAO (1993). Original values are presented in the Figure 4-13.**



### 5.5.3. Average flight lengths

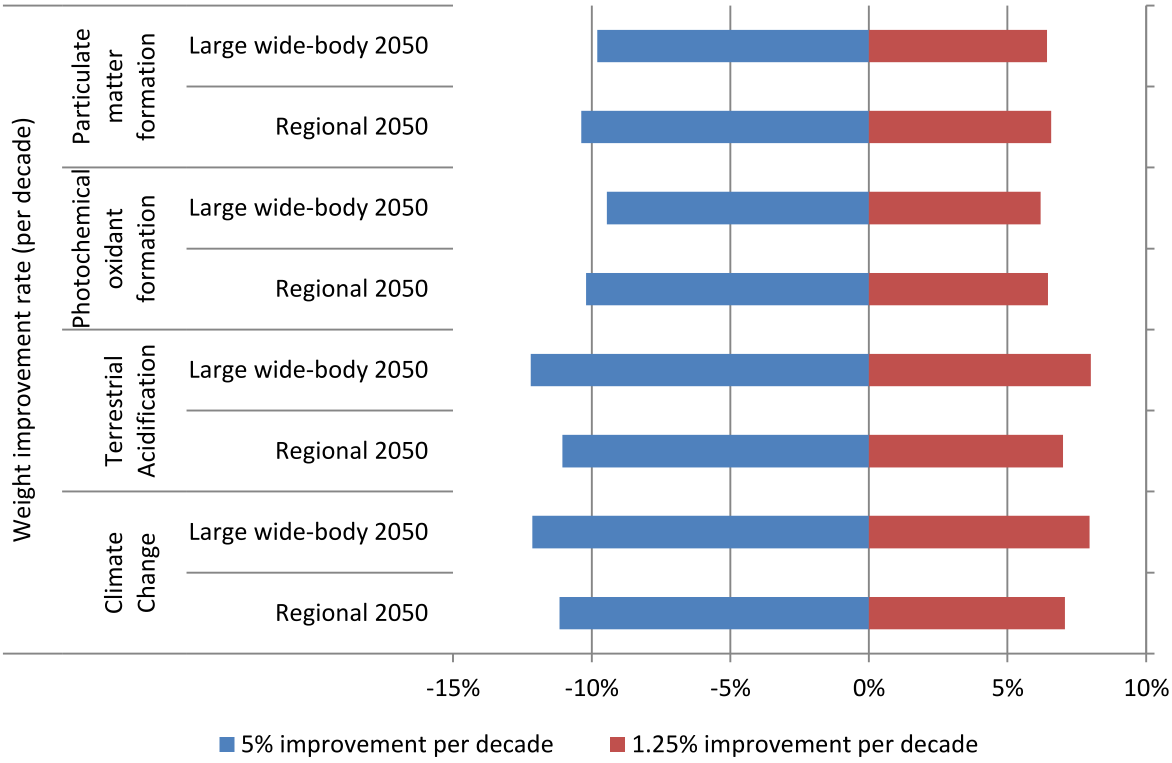
Figure 5-7 shows the sensitivity analysis of average flight lengths among two plane categories: regional and large-wide body. Results on the left side show how environmental impacts among all four impact categories would change if planes were to fly two times further as in the base case. Results on the right side show change in results in case when average flight distances would be cut in half. It was calculated that the regional plane travels on average 460 km per flight. Doubling this number to 920 km per flight changes the environmental results significantly. Being able to extend flight distance, results in cutting climate change emissions by over 16% for 2015 and 2050 regional plane. The most sensitive impact categories turn out to be photochemical oxidant and particulate matter formation, whose emissions cat be reduced by over 25% during regional plane's lifetime. On the other hand, decreasing the average flight distance by 50% would drastically grow environmental emissions. Climate change impact and terrestrial acidification would increase by over 30%, photochemical oxidant and particulate matter formation by around 50%. The least sensitive to change of flight length is large wide-body plane category. Climate change results would change just slightly by -1% and +2% for both current 2015 and 2050 plane. Small plane categories are the most sensitive ones to the change of flight distance. Their impact per PKM significantly changes, due to the fact that they share higher environmental impacts than large plane categories.

**Figure 5-7 Sensitivity analysis: Change of the average flight length distances. Original values are presented in the Table 4-3.**

### 5.5.4. Weight improvement rate

Figure 5-8 shows how different rates of weight improvement influence the LCA results. Linear regression of the data available, showed 0.25% weight reduction per year since 1968. Doubling this rate up to 0.5% per year allows for significant impact reduction until the year 2050. As the Figure below shows, environmental results in all evaluated impact categories are expected to decrease by roughly 10%. In case of slower weight improvement rate of 0.125% per year, emissions are expected to increase for the future 2050 plane. Compared with base case, aircraft would share more than 5% higher emissions in all impact categories. The sensitivity analysis shows that increased light-weighting of aircraft would lead to reduced impact per PKM in all categories, which has a significant effect on the environmental emissions produced during aircraft's lifetime.

**Figure 5-8 Sensitivity analysis: Change of weight improvement (decrease) rate (per decade). Original value: 2.5% weight decrease.**



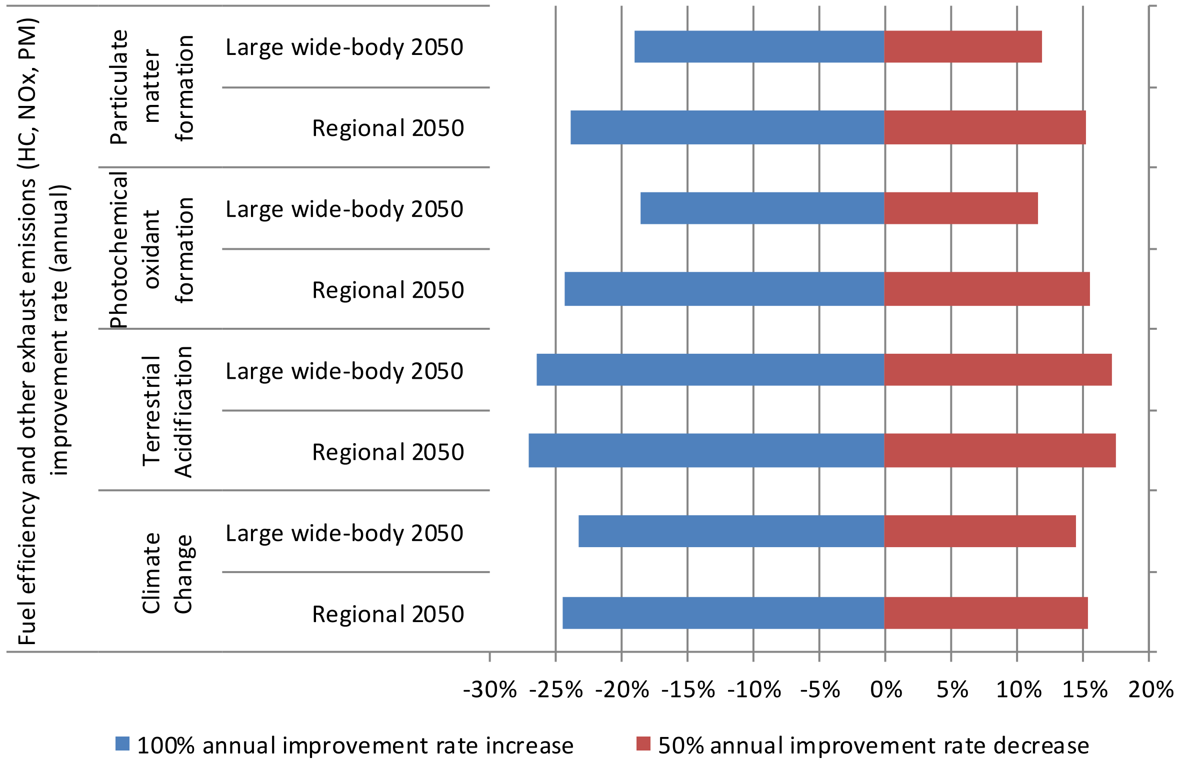
### 5.5.5. Fuel efficiency and other exhaust emissions improvement rate

Even greater fuel efficiency than before is driving the aviation industry forward. It not only corresponds directly to the distance the plane can fly or the amount of payload it can carry but also to the environmental performance. However, secondary effects of fuel efficiency such as weigh reduction are not considered in this thesis. Each ton of fuel saved, translates to approximately 3.15 tons less of carbon-dioxide emitted into the atmosphere. At the same time reducing fuel consumption decreases $NO_x$, CO, HC and PM emissions.

Aviation industry has been experiencing improved fuel efficiency since the beginning of operation. Based on the time series analysis performed in this thesis, fuel efficiency improvement rate per annum was calculated to be 0.8%. The upside scenario used in this sensitivity analysis assumes improvement rate of 1.6%. Other environmental emissions used to calculate the base case scenario had the following improvement rate values per annum: HC – 7.4%, $NO_x$ – 1%, PM – 1.6%. In a positive scenario tested in sensitivity analysis, all improvement rates increased twice; in a negative scenario – they were cut in half.

In this pace by year 2050 the aircraft tested in this thesis show very significant changes in terms of environmental performance. Both regional and large wide-body plane category due to the increased fuel efficiency, represent lower environmental impacts. A large improvement can be seen in the climate change category. Its impacts are estimated to decrease by almost 25% by year 2050 for both plane categories. Even more sensitive category is terrestrial acidification, which is highly correlated with the emissions of nitrogen oxides . Improvements in that category can go beyond 25%. On the other hand, reducing annual improvement rate by half would cause climate change emissions to increase by 2050 compared with the base case by around 15%. Other environmental indicators such as photochemical oxidant and particulate matter formation would increase by roughly 10%-15%.

**Figure 5-9 Sensitivity analysis: Change of fuel efficiency and other exhaust emissions improvement rate (per annum). Original values are presented in the Table 5-5.**



### 5.5.6. Freight filling assumption.

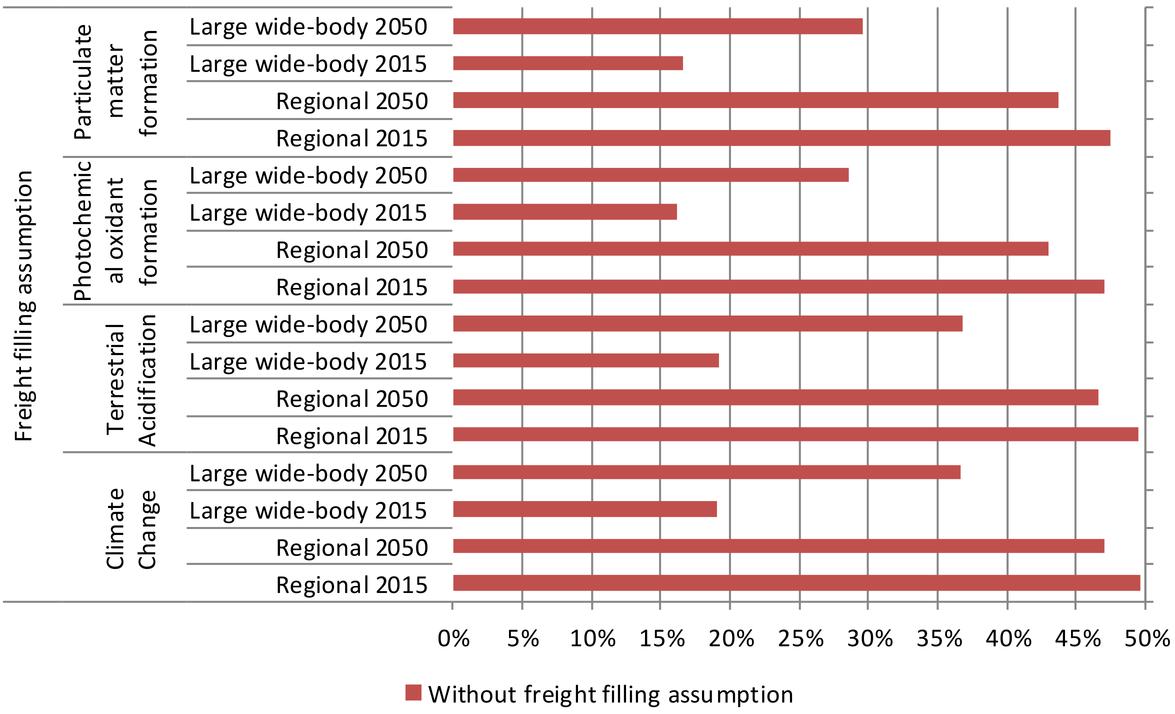
This thesis uses the assumption that the aircraft in Switzerland always travel fully loaded which is described in more details in the chapter 4.4 Capacity utilization. As the Figure 5-10 shows, the savings of environmental emissions caused by filling up the plane with cargo are very significant. Original results are calculated assuming that tested synthetic planes utilize left capacity by adding additional freight, and therefore decreasing the impact per PKM. This assumption is tested for sensitivity by changing the seat load factor to following values:

**Table 5-6 Seat load factors for 2015 and 2050 synthetic planes used in the sensitivity analysis.**

| Plane type | Seat load factor |
|---|---|
| Regional 2015 | 66% |
| Regional 2050 | 80% |
| Small Narrow-body 2015 | 66% |
| Small Narrow-body 2050 | 80% |
| Large Narrow-body 2015 | 66% |
| Large Narrow-body 2050 | 80% |
| Small wide-body 2015 | 83% |
| Small wide-body 2050 | 88% |
| Large wide-body 2015 | 83% |
| Large wide-body 2050 | 88% |

Applying those values increases very significantly environmental impacts for all plane categories. The most sensitive to the results is regional aircraft both in the year 2015 and 2050. The climate change burden by not utilizing empty space in this plane model and travelling with the seat load factor of 66% for 2015 model and 80% for 2050 one as the statistical data suggests, increases by almost 50% both in the year 2015 and 2050. Other three impact categories are very sensitive as well. The smallest sensitivity shows the largest of the tested planes – large wide-body one, but even here the impacts increase sometimes by 37% depending on the category. Figure 5-10 presents results for regional and large wide-body aircraft. Detailed figure for all five synthetic plane models can be found in the Figure A-6.

**Figure 5-10 Sensitivity analysis: Change of freight filling assumption. Tested value: no freight filling.**



# 6. Summary and conclusions

## 6.1.Comparison with other research papers

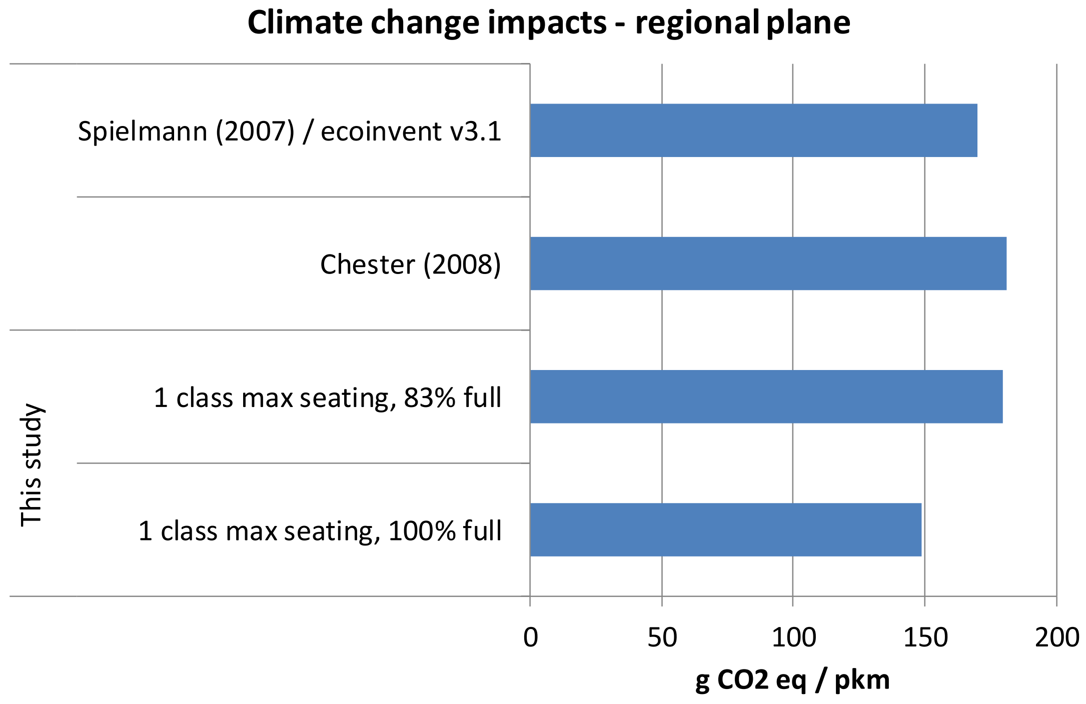
Results presented in this thesis can be compared with those presented by the other authors. As mentioned in the section 1.1.4 by the united strategy of ICAO partners, average decrease in fuel consumption of 1.5% per annum would result in the cutback of $CO_2$ emissions in year 2050 by 50% compared with 2005. Section 5.5.5 of this work, shows that original $CO_2$ emissions, assuming 1.6% efficiency improvement rate per year, may drop in 2050 by 52% compared with the year 2005. This result is very close to the one from the ICAO. It needs to be mentioned that it also includes improvements of other emissions and a weight reduction, which is already included in the 1.5% rate of ICAO.

The analysis of Timmis (2015) demonstrates reduction of $CO_2$ through the implementation of composite materials. The constructed scenario shows the 20% emission reduction until 2050. The results presented in this work forecast on average the 37% $CO_2$ emissions decrease by 2050. Although this result appears to be much higher than the one obtained by Timmis, it includes not only light-weighting due to the use of composites but also other assumed improvements.

Lynnette Dray (2013) estimates the average fuel improvement of aircraft ordered between 1970 and 2005 to be in the range of 0.4% and 1.6%. This thesis for the original case calculates the rate of 0.8% and the sensitivity analysis chapter tests the results when values are changed to 0.4% and 1.6% improvement rate per year. David Lee (2009), as the reference rate of fuel efficiency improvement uses 1.3% per annum until 2010, then 1% to 2020 and 0.5% until 2050. Summarizing, the assumptions in this work is in line with those of the above mentioned papers.

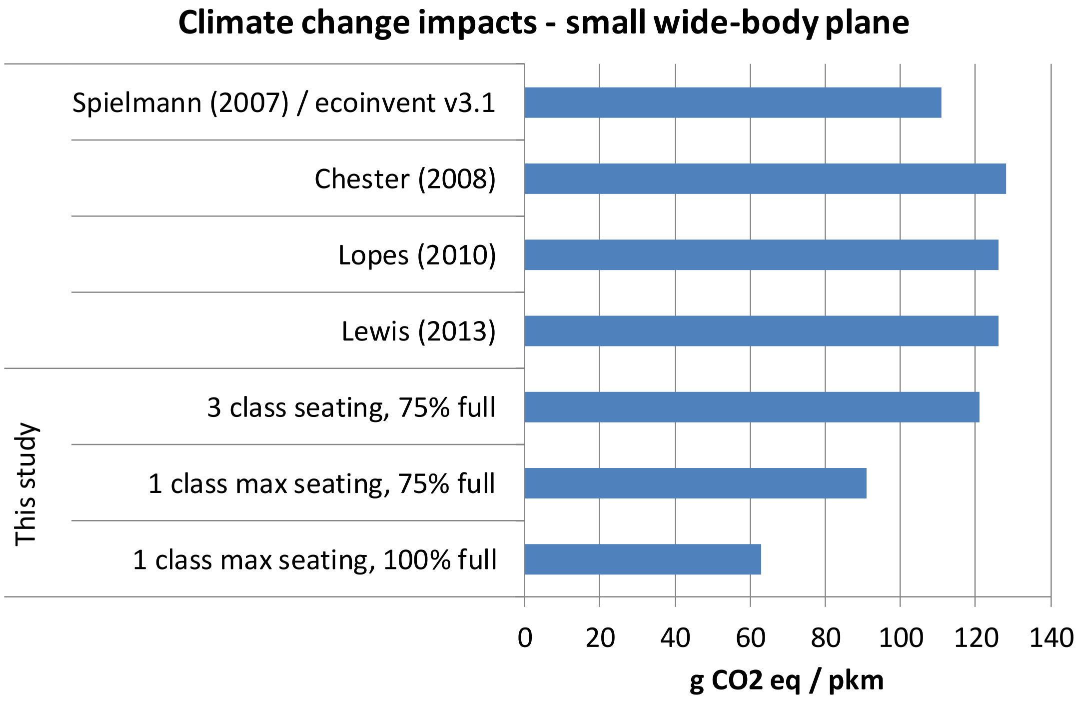
Figure 6-1 and Figure 6-2 present comparison of climate change results between this work and some of papers described in the section 2 Literature review. Spielmann (2007) and Chester (2008) also performed the analysis of an aircraft that fits into the regional plane category presented in this thesis. Spielmann assumes that the plane of that size travels on average 500 km. Chester computes a distance of 800 km. This thesis calculates an average flight length of 460 km (Table 4-3). Assuming 83% seat load factor of a regional plane authors calculate following results: Chester (2008) – 181 g $CO_2$ eq/PKM; Spielmann (2007) – 170 g $CO_2$ eq/ PKM. This thesis after adjusting results for the same seat load factor, shows 180 g $CO_2$ eq/ PKM for regional plane category. Therefore the difference between the above-mentioned research papers and this work does not exceed 6%.

**Figure 6-1 Climate change impacts compared with the other papers for regional plane.**



To compare results for the small wide-body plane (for example Boeing 777/787 or Airbus 330/340), more papers were available for testing. Spielmann for this category assumes an average flight length of 6000 km, Chester approximately 4400 km, Lopes 3507 km (for a A330-200, which is smaller than analyzed here A330-300), Lewis takes approximately 3000 km for A330-200 as well and this thesis calculates an average distance of 6900 km for many aircraft that fit into this category based on the real-life data. Results were normalized for a case when the seat load factor was 75% in a 3 class seating configuration. All five studies shows following results (in g $CO_2$ eq/PKM): Spielmann (2007) – 111; Chester (2008) – 128; Lopes (2010) – 126; Lewis (2013) – 126 and this study – 121. The maximum deviation of results from this work amounts 9%, which is considered not to be significant given the high number of characteristics that differentiate those studies making the comparison more challenging.

**Figure 6-2 Climate change impacts compared with the other papers for small wide-body plane.**



## 6.2.Uncertainties and limitations

This chapter serves as a summary of all previously mentioned uncertainties and limitations connected with this work. Major ones include:

- LCIA methods for atmospheric emissions – ReCiPe impact assessment is only valid for emissions that occur at ground level. It does not consider emissions that occur during the cruise phase. Because of existing uncertainty concerning the influence of emissions that occur in the cruise phase on the climate change, the ReCiPe method calculates impacts independently on the altitude.
- Material breakdown – it might be not accurate for all plane sizes. The weights of all five synthetic plane models were scaled based on the estimates provided by Lopes (2010). For the future forecast, they were adjusted assuming the 0.25% weight improvement rate per year, which was based only on five data points. Additionally, the engine size does not scale linearly with the number of seats. That fact was neglected in the analysis.
- Plane lifetime and flight distance – determining the lifetime of a plane and average distance travelled were done by using the data from platforms such as Flightradar24 and Planespotters. Aircraft lifetime was estimated based on the age when it is scrapped by major

European carriers. That result however, may not accurately reflect the global practices. Based on the calculations, it was concluded that the average lifetime of 22 years is the same for all five synthetic plane types. The average distances travelled were based on the flights analysis performed in 2015 of the Swiss market only. Furthermore, the estimation of lifetime kilometers was done by simply multiplying the average distance per year times the airplane's lifespan. Then the same distances and methodology was used for year 2050.

- Improvement rates – fuel consumption and emissions improvement rate were based only on the LTO data. That is described in the section 4.10.1. The other factors such as the influence of the airframe or variability in the emissions depending on the age of the age were also not considered.
- Belly Cargo – the additional weight made available by missing passengers is filled with freight, allowing for additional cargo. Therefore, the results of this work are calculated using the assumption that planes always travel fully loaded, which was observed to be a common practice in Switzerland. It was however assumed that the amount of the additional freight is limited by the mass and not by the volume.
- LTO times - another uncertainty is connected to the way LTO times used as a base case for the analysis. The values were based with regard to the Zurich Airport only. In addition, they reflect the state of 2015. Times spent in each of the LTO mode, may differ from airport to the airport and over the course of time.

## 6.3.Future work

This section tries to identify the tasks that may be performed in order to enhance the quality of the results. Improvements can be made in the following areas:

- Review datasets for future production of carbon fiber and other materials - this thesis uses current production datasets for the background data such as carbon fiber or jet fuel production. The new production conditions must be adjusted in order to better reflect possible future changes.
- Improve future light weight assumption – it was assumed that the weight improvement per year is 0.25% of an aircraft's operating empty weight. This number is based only on five data points, therefore a more reliable forecast should be projected using more input data. Additionally, the same improvement rate was taken to forecast 2050 emissions for all five synthetic plane models. That rate might be however different for various aircraft size and therefore should be improved.

- Evaluate use of other fuel sources – it must be also assessed what measures can the aviation industry take to minimize carbon dioxide emissions and local pollutants. The long-term development of GHG emitted by the commercial aircraft through the use of conventional jet A, LNG and liquid hydrogen ($LH_2$) should be evaluated. A further research is needed to also look at which production process of alternative fuels is the most sustainable one. Moreover, it might be interesting to assess the GHG emissions from various alternative fuels with respect to the five synthetic plane models presented in this thesis. Possible variables may include operating empty weight, flight length or number of LTO cycles during plane's lifetime. Furthermore, the analysis may include the emissions of all the pollutants included in this work ($CO_2$, $SO_2$, PM 10 and NMVOC). The fact that many studies present hydrogen as a very compelling alternative to jet fuel, makes the possible future work more interesting and needed. Another development that is worth paying attention to is the Airbus E-Fan, a prototype electric aircraft that had its first test flight in April 2014. The aircraft can carry onboard two passengers and is powered by lithium polymer battery packs which allow for two hour flight. The plane is able to cruise at the speed of 160 km/h, which is much lower compared with the cruising speed of for example A320 which is 828 km/h. E-Fan is constructed mainly from composite materials and its two electric motors with the total power of 60 kW, propel two eight-blade ducted fans producing 0.75 kN of thrust. There are plans to start production of this aircraft in 2017. Additionally, Airbus has announced that it hopes to develop a regional battery-powered plane able to carry between 70 and 90 people, within 15 to 20-year timeline.
- Extend analysis to include i.e. noise pollution – it is an area that has been regulated by ICAO already in the 1960s when the first Noise Standards were developed. An extended study may consider another local environmental impact – noise. With the projected growth in demand for commercial aviation, decision-makers and stakeholders look for ways to reduce aircraft noise. Further analysis may include only aircraft-related noise or other multiple noise sources at airports as well. Noise is measured in decibels and is scaled to mirror the human sensitivity to different frequencies. High noise levels may cause problems such as sleep disturbance, learning disruption or community annoyance. Apart from social factors, the economic ones may include the decrease of housing prices in the areas located close to the commercial airports. All the above mentioned factors, provide grounds that the noise pollution is a very important topic to be examined.
- Evaluate future LTO improvements – aviation seeks to reduce fuel burn in order to decrease its costs and to reduce the environmental impacts. Recent studies show various Aircraft Ground Propulsion Systems (AGPS) that are expected to significantly reduce fuel

consumption during taxi operations. Those innovative strategies include: using single engine for taxiing, tractors attached to aircraft for towing and on-board motors installed in the wheels. A comprehensive analysis should be performed that would provide a comparison between conventional and unconventional AGPS with regard to the environmental impacts. Expanding this analysis further, some of the systems could be powered by alternative energy sources such as from wind or solar farms, biodiesel or hydrogen.

## 6.4. Conclusion

The main objective of this thesis was to evaluate the environmental impacts of passenger air transport in Switzerland and how they may change until year 2050 given the technology improvements. The results presented here have met this objective and provide an assessment of life cycle impacts for various aircraft models.

Results of this study are similar to the literature values. The largest deviation from the result of other research papers does not exceed 9%. Cruise phase has proven to have the largest environmental impact in terms of GHG emissions. For regional plane category it is responsible for 62% of total 157 g of $CO_2$ eq per PKM, and in the large wide-body one for over 77% out of 71 g. Light-weighting demonstrated to have an impact on the results due to the fuel savings over the life-time. Aircraft production showed however very little relative impact. Environmental impacts per km decrease with the flight distance, what appears to be the case especially for small planes. Approach to divide analyzed planes into five synthetic plane models was validated. The LCA results between smallest and largest aircraft show significant differences. Given weight improvement rate of 0.25% per year and fuel efficiency and other emissions improvement rate of 0.8% per year, on average the environmental results will decrease by 30% in the year 2050.

Sensitivity analysis demonstrated that analyzed aircraft models are either insensitive or show small sensitivity to the change of following variables: plane’s lifetime and landing and take-off times. In case of flight length, only small regional aircraft show very high sensitivity to that factor which may change the $CO_2$ emissions by over 30%. Weight improvement rate presents moderate sensitivity. Fuel efficiency improvement rate and Belly Cargo assumption can change the results even up to 50% for a small plane and by 20% for the largest one.

An future research should also evaluate the use of the alternative fuel sources such as biomass, LNG or liquid hydrogen that may play significant role in the future.

# 6 - Summary and conclusions

The results demonstrate that the best way to lower environmental impacts is to decrease fuel consumption and increase the seat load factor of each flight. Lifetime of an aircraft is also an important factor. Production impacts of new aircraft are small, and new models have lower operation impacts. Therefore, from an environmental point of view, retiring current aircraft fleet sooner and introducing new models, may have a positive effect on the way to reduce $CO_2$ emissions as well.

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# A. Appendix

## Additional figures and tables

**Table A-1 Material breakdown of synthetic planes in 2015. All values in kg.**

| | Regional | Small narrow-body | Large narrow-body | Small wide-body | Large wide-body |
|---|---|---|---|---|---|
| Iron-nickel-chromium-alloy | 98 | 243 | 424 | 1021 | 1681 |
| Aluminum alloy | 6943 | 17261 | 30059 | 72428 | 119202 |
| Titanium | 915 | 2276 | 3963 | 9549 | 15715 |
| Nickel | 331 | 822 | 1431 | 3449 | 5677 |
| Chromium | 50 | 125 | 217 | 523 | 861 |
| Iron | 102 | 254 | 443 | 1067 | 1756 |
| Niobium + tantalum | 11 | 26 | 46 | 110 | 181 |
| steel | 2287 | 5685 | 9900 | 23854 | 39260 |
| GFRP | 119 | 295 | 514 | 1239 | 2039 |
| CFRP | 1093 | 2717 | 4731 | 11400 | 18761 |
| **Total (kg)** | **11948** | **29704** | **51728** | **124640** | **205133** |

**Table A-2 Flight history of an Embraer ERJ-190LR, registration HB-JVN, in the second week of March 2015.**

| Registration | Type | From | To | Distance (km) |
|---|---|---|---|---|
| HB-JVN | Embraer ERJ-190LR | Brindisi (BDS) | Bern (BRN) | 1090 |
| | | Bern (BRN) | Brindisi (BDS) | 1090 |
| | | Palma de Mallorca (PMI) | Bern (BRN) | 904 |
| | | Bern (BRN) | Palma de Mallorca (PMI) | 904 |
| | | Palma de Mallorca (PMI) | Bern (BRN) | 904 |
| | | Bern (BRN) | Palma de Mallorca (PMI) | 904 |
| | | Palma de Mallorca (PMI) | Bern (BRN) | 904 |
| | | Bern (BRN) | Palma de Mallorca (PMI) | 904 |
| | | Olbia (OLB) | Bern (BRN) | 687 |
| | | Bern (BRN) | Olbia (OLB) | 687 |
| | | Heraklion (HER) | Bern (BRN) | 1950 |
| | | Bern (BRN) | Heraklion (HER) | 1950 |
| | | Zakynthos (ZTH) | Bern (BRN) | 1500 |
| | | Bern (BRN) | Zakynthos (ZTH) | 1500 |
| | | Palma de Mallorca (PMI) | Bern (BRN) | 904 |
| | | Bern (BRN) | Palma de Mallorca (PMI) | 904 |
| | | Kos (KGS) | Bern (BRN) | 1960 |
| | | Bern (BRN) | Kos (KGS) | 1960 |
| | | Zurich (ZRH) | Bern (BRN) | 100 |
| | | London (LCY) | Zurich (ZRH) | 761 |
| | | Zurich (ZRH) | London (LCY) | 761 |
| | | London (LCY) | Zurich (ZRH) | 761 |
| | | Zurich (ZRH) | London (LCY) | 761 |
| | | Prague (PRG) | Zurich (ZRH) | 510 |
| | | Zurich (ZRH) | Prague (PRG) | 510 |

| | | | |
|---|---|---|---|
| | Budapest (BUD) | Zurich (ZRH) | 801 |
| | Zurich (ZRH) | Budapest (BUD) | 801 |
| | Vienna (VIE) | Zurich (ZRH) | 602 |
| | Zurich (ZRH) | Vienna (VIE) | 602 |
| | Florence (FLR) | Zurich (ZRH) | 455 |
| | Zurich (ZRH) | Florence (FLR) | 455 |
| **Total** | | | **29486** |

**Table A-3 Extended LCA results**

| | Synthetic plane type | **Regional 2015** | **Small Narrow-body 2015** | **Large Narrow-body 2015** | **Small wide-body 2015** | **Large wide-body 2015** |
|---|---|---|---|---|---|---|
| | Lifetime (years) | 22 | 22 | 22 | 22 | 22 |
| | Lifetime km | 11445407 | 27884434 | 41724315 | 89784852 | 87272089 |
| | Seat load factor | 66% | 66% | 66% | 83% | 83% |
| | Number of seats | 51 | 123 | 200 | 428 | 670 |
| | Kg of additional freight to carry | 1717 | 4187 | 6810 | 7279 | 11396 |
| | Seats occupied (including additional freight) | 51 | 123 | 200 | 428 | 670 |
| FUEL PRODUCTION - Landing & take-off cycle | Climate change (kg CO2 eq) | 0,005389615 | 0,003020427 | 0,001269117 | 0,000279369 | 0,000246528 |
| | Ozone depletion (kg CFC-11 eq) | 6,61036E-09 | 3,70455E-09 | 1,55657E-09 | 3,42646E-10 | 3,02367E-10 |
| | Terrestrial acidification (kg SO2 eq) | 4,7346E-05 | 2,65335E-05 | 1,11488E-05 | 2,45416E-06 | 2,16567E-06 |
| | Freshwater eutrophication (kg P eq) | 5,51156E-07 | 3,08877E-07 | 1,29783E-07 | 2,8569E-08 | 2,52106E-08 |
| | Marine eutrophication (kg N eq) | 1,08769E-06 | 6,09557E-07 | 2,56122E-07 | 5,63799E-08 | 4,97522E-08 |
| | Human toxicity (kg 1,4-DB eq) | 0,000839071 | 0,000470229 | 0,00019758 | 4,3493E-05 | 3,83802E-05 |
| | Photochemical oxidant formation (kg NMVOC) | 3,55545E-05 | 1,99253E-05 | 8,37219E-06 | 1,84296E-06 | 1,62631E-06 |
| | Particulate matter formation (kg PM10 eq) | 1,39409E-05 | 7,81268E-06 | 3,28272E-06 | 7,22619E-07 | 6,37673E-07 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 5,94499E-07 | 3,33167E-07 | 1,39989E-07 | 3,08157E-08 | 2,71932E-08 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 3,64643E-05 | 2,04352E-05 | 8,58641E-06 | 1,89011E-06 | 1,66792E-06 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 3,03296E-05 | 1,69972E-05 | 7,14184E-06 | 1,57212E-06 | 1,38731E-06 |
| | Ionising radiation (kBq U235 eq) | 0,002585231 | 0,001448805 | 0,000608756 | 0,000134005 | 0,000118252 |
| | Agricultural land occupation (m2a) | 6,54777E-05 | 3,66948E-05 | 1,54183E-05 | 3,39402E-06 | 2,99504E-06 |
| | Urban land occupation (m2a) | 6,34119E-05 | 3,55371E-05 | 1,49319E-05 | 3,28693E-06 | 2,90054E-06 |
| | Natural land transformation (m2) | 1,28735E-05 | 7,21453E-06 | 3,03139E-06 | 6,67295E-07 | 5,88852E-07 |
| | Water depletion (m3) | 1,51719E-05 | 8,50259E-06 | 3,5726E-06 | 7,86431E-07 | 6,93984E-07 |
| | Metal depletion (kg Fe eq) | 0,000176684 | 9,90163E-05 | 4,16045E-05 | 9,15833E-06 | 8,08174E-06 |
| | Fossil depletion (kg oil eq) | 0,012385806 | 0,006941206 | 0,002916542 | 0,000642014 | 0,000566543 |
| FUEL PRODUCTION - Climb, Cruise, Descent | Climate change (kg CO2 eq) | 0,016897608 | 0,014002858 | 0,009376798 | 0,008417218 | 0,00953234 |
| | Ozone depletion (kg CFC-11 eq) | 2,07249E-08 | 1,71745E-08 | 1,15006E-08 | 1,03237E-08 | 1,16914E-08 |
| | Terrestrial acidification (kg SO2 eq) | 0,00014844 | 0,00012301 | 8,23721E-05 | 7,39425E-05 | 8,37385E-05 |
| | Freshwater eutrophication (kg P eq) | 1,72799E-06 | 1,43197E-06 | 9,58896E-07 | 8,60767E-07 | 9,74802E-07 |
| | Marine eutrophication (kg N eq) | 3,41013E-06 | 2,82594E-06 | 1,89235E-06 | 1,69869E-06 | 1,92374E-06 |
| | Human toxicity (kg 1,4-DB eq) | 0,002630671 | 0,002180007 | 0,001459808 | 0,001310418 | 0,001484023 |
| | Photochemical oxidant formation (kg NMVOC) | 0,000111471 | 9,23749E-05 | 6,18574E-05 | 5,55272E-05 | 6,28835E-05 |
| | Particulate matter formation (kg PM10 eq) | 4,37076E-05 | 3,622E-05 | 2,42542E-05 | 2,17721E-05 | 2,46565E-05 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 1,86388E-06 | 1,54458E-06 | 1,0343E-06 | 9,28458E-07 | 1,05146E-06 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 0,000114323 | 9,47385E-05 | 6,34402E-05 | 5,6948E-05 | 6,44925E-05 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 9,50898E-05 | 7,87998E-05 | 5,27671E-05 | 4,73671E-05 | 5,36424E-05 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Ionising radiation (kBq U235 eq) | 0,008105259 | 0,006716737 | 0,004497759 | 0,004037478 | 0,004572368 |
| | Agricultural land occupation (m2a) | 0,000205287 | 0,000170119 | 0,000113917 | 0,00010226 | 0,000115807 |
| | Urban land occupation (m2a) | 0,00019881 | 0,000164752 | 0,000110323 | 9,90334E-05 | 0,000112153 |
| | Natural land transformation (m2) | 4,03613E-05 | 3,34469E-05 | 2,23972E-05 | 2,01052E-05 | 2,27688E-05 |
| | Water depletion (m3) | 4,75672E-05 | 3,94184E-05 | 2,6396E-05 | 2,36947E-05 | 2,68338E-05 |
| | Metal depletion (kg Fe eq) | 0,000553941 | 0,000459045 | 0,000307392 | 0,000275935 | 0,000312491 |
| | Fossil depletion (kg oil eq) | 0,038832184 | 0,032179793 | 0,021548702 | 0,019343503 | 0,021906152 |
| OPERATION - Landing & take-off cycle | Climate change (kg CO2 eq) | 0,031065128 | 0,017409405 | 0,00731505 | 0,001610251 | 0,001420961 |
| | Ozone depletion (kg CFC-11 eq) | 0 | 0 | 0 | 0 | 0 |
| | Terrestrial acidification (kg SO2 eq) | 6,53513E-05 | 3,44773E-05 | 2,17583E-05 | 6,66087E-06 | 5,77876E-06 |
| | Freshwater eutrophication (kg P eq) | 0 | 0 | 0 | 0 | 0 |
| | Marine eutrophication (kg N eq) | 3,97433E-06 | 2,07778E-06 | 1,37946E-06 | 4,33977E-07 | 3,7606E-07 |
| | Human toxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Photochemical oxidant formation (kg NMVOC) | 0,000102578 | 5,36529E-05 | 3,5529E-05 | 1,11625E-05 | 9,6733E-06 |
| | Particulate matter formation (kg PM10 eq) | 2,47811E-05 | 1,32225E-05 | 8,42443E-06 | 2,58486E-06 | 2,22471E-06 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Ionising radiation (kBq U235 eq) | 0 | 0 | 0 | 0 | 0 |
| | Agricultural land occupation (m2a) | 0 | 0 | 0 | 0 | 0 |
| | Urban land occupation (m2a) | 0 | 0 | 0 | 0 | 0 |
| | Natural land transformation (m2) | 0 | 0 | 0 | 0 | 0 |
| | Water depletion (m3) | 0 | 0 | 0 | 0 | 0 |
| | Metal depletion (kg Fe eq) | 0 | 0 | 0 | 0 | 0 |
| | Fossil depletion (kg oil eq) | 0 | 0 | 0 | 0 | 0 |
| OPERATION - Climb, Cruise, Descent | Climate change (kg CO2 eq) | 0,097395859 | 0,080710883 | 0,054046805 | 0,048515882 | 0,054943388 |
| | Ozone depletion (kg CFC-11 eq) | 0 | 0 | 0 | 0 | 0 |
| | Terrestrial acidification (kg SO2 eq) | 0,000262203 | 0,000182449 | 0,000155351 | 0,000165593 | 0,000198491 |
| | Freshwater eutrophication (kg P eq) | 0 | 0 | 0 | 0 | 0 |
| | Marine eutrophication (kg N eq) | 1,64518E-05 | 1,12074E-05 | 9,81535E-06 | 1,06314E-05 | 1,28031E-05 |
| | Human toxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Photochemical oxidant formation (kg NMVOC) | 0 | 0 | 0 | 0 | 0 |
| | Particulate matter formation (kg PM10 eq) | 0 | 0 | 0 | 0 | 0 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 0 | 0 | 0 | 0 | 0 |
| | Ionising radiation (kBq U235 eq) | 0 | 0 | 0 | 0 | 0 |
| | Agricultural land occupation (m2a) | 0 | 0 | 0 | 0 | 0 |
| | Urban land occupation (m2a) | 0 | 0 | 0 | 0 | 0 |
| | Natural land transformation (m2) | 0 | 0 | 0 | 0 | 0 |
| | Water depletion (m3) | 0 | 0 | 0 | 0 | 0 |
| | Metal depletion (kg Fe eq) | 0 | 0 | 0 | 0 | 0 |
| | Fossil depletion (kg oil eq) | 0 | 0 | 0 | 0 | 0 |
| RING - | Climate change (kg CO2 eq) | 0,000293004 | 0,000128983 | 8,95544E-05 | 4,41751E-05 | 4,70744E-05 |
| | Ozone depletion (kg CFC-11 eq) | 2,28854E-11 | 1,00743E-11 | 6,99474E-12 | 3,45035E-12 | 3,6768E-12 |
| | Terrestrial acidification (kg SO2 eq) | 2,80583E-06 | 1,23515E-06 | 8,57579E-07 | 4,23024E-07 | 4,50788E-07 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Freshwater eutrophication (kg P eq) | 2,61531E-07 | 1,15128E-07 | 7,9935E-08 | 3,94301E-08 | 4,2018E-08 |
| | Marine eutrophication (kg N eq) | 9,61715E-08 | 4,23355E-08 | 2,9394E-08 | 1,44994E-08 | 1,5451E-08 |
| | Human toxicity (kg 1,4-DB eq) | 0,00022741 | 0,000100108 | 6,95062E-05 | 3,42858E-05 | 3,6536E-05 |
| | Photochemical oxidant formation (kg NMVOC) | 8,14271E-07 | 3,58449E-07 | 2,48876E-07 | 1,22765E-07 | 1,30822E-07 |
| | Particulate matter formation (kg PM10 eq) | 8,0079E-07 | 3,52514E-07 | 2,44755E-07 | 1,20732E-07 | 1,28656E-07 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 2,56325E-08 | 1,12836E-08 | 7,83438E-09 | 3,86452E-09 | 4,11815E-09 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 3,54332E-05 | 1,5598E-05 | 1,08299E-05 | 5,34213E-06 | 5,69274E-06 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 3,11652E-05 | 1,37192E-05 | 9,52538E-06 | 4,69865E-06 | 5,00703E-06 |
| | Ionising radiation (kBq U235 eq) | 7,20064E-05 | 3,16978E-05 | 2,20082E-05 | 1,08561E-05 | 1,15686E-05 |
| | Agricultural land occupation (m2a) | 9,49738E-06 | 4,18082E-06 | 2,9028E-06 | 1,43188E-06 | 1,52586E-06 |
| | Urban land occupation (m2a) | 2,91202E-06 | 1,28189E-06 | 8,90035E-07 | 4,39034E-07 | 4,67849E-07 |
| | Natural land transformation (m2) | 3,15936E-08 | 1,39078E-08 | 9,65633E-09 | 4,76324E-09 | 5,07587E-09 |
| | Water depletion (m3) | 2,48626E-06 | 1,09447E-06 | 7,59905E-07 | 3,74844E-07 | 3,99445E-07 |
| | Metal depletion (kg Fe eq) | 6,58703E-05 | 2,89966E-05 | 2,01327E-05 | 9,93101E-06 | 1,05828E-05 |
| | Fossil depletion (kg oil eq) | 7,80066E-05 | 3,43391E-05 | 2,38421E-05 | 1,17608E-05 | 1,25326E-05 |
| MANUFACTURING - Energy Consumption and disposal | Climate change (kg CO2 eq) | 0,000775095 | 0,000318145 | 0,000212617 | 9,8806E-05 | 0,000101651 |
| | Ozone depletion (kg CFC-11 eq) | 8,65341E-11 | 3,55186E-11 | 2,37372E-11 | 1,1031E-11 | 1,13486E-11 |
| | Terrestrial acidification (kg SO2 eq) | 2,29072E-06 | 9,40247E-07 | 6,28369E-07 | 2,92012E-07 | 3,0042E-07 |
| | Freshwater eutrophication (kg P eq) | 2,60679E-07 | 1,06998E-07 | 7,15069E-08 | 3,32303E-08 | 3,41871E-08 |
| | Marine eutrophication (kg N eq) | 1,00427E-07 | 4,12213E-08 | 2,75482E-08 | 1,28021E-08 | 1,31707E-08 |
| | Human toxicity (kg 1,4-DB eq) | 0,000198524 | 8,1486E-05 | 5,44572E-05 | 2,53071E-05 | 2,60357E-05 |
| | Photochemical oxidant formation (kg NMVOC) | 5,01881E-06 | 2,06002E-06 | 1,37671E-06 | 6,39778E-07 | 6,58198E-07 |
| | Particulate matter formation (kg PM10 eq) | 6,94433E-07 | 2,85036E-07 | 1,9049E-07 | 8,85235E-08 | 9,10723E-08 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 2,16513E-08 | 8,88695E-09 | 5,93917E-09 | 2,76002E-09 | 2,83948E-09 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 8,28921E-06 | 3,40238E-06 | 2,27381E-06 | 1,05667E-06 | 1,0871E-06 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 7,32254E-06 | 3,0056E-06 | 2,00865E-06 | 9,33448E-07 | 9,60324E-07 |
| | Ionising radiation (kBq U235 eq) | 0,000363245 | 0,000149097 | 9,9642E-05 | 4,63051E-05 | 4,76383E-05 |
| | Agricultural land occupation (m2a) | 1,40644E-05 | 5,77283E-06 | 3,858E-06 | 1,79287E-06 | 1,84449E-06 |
| | Urban land occupation (m2a) | 2,46776E-06 | 1,01291E-06 | 6,76931E-07 | 3,1458E-07 | 3,23637E-07 |
| | Natural land transformation (m2) | 1,22448E-07 | 5,02597E-08 | 3,35886E-08 | 1,56091E-08 | 1,60585E-08 |
| | Water depletion (m3) | 2,58566E-07 | 1,06131E-07 | 7,09274E-08 | 3,2961E-08 | 3,391E-08 |
| | Metal depletion (kg Fe eq) | 9,99245E-06 | 4,10149E-06 | 2,74103E-06 | 1,2738E-06 | 1,31047E-06 |
| | Fossil depletion (kg oil eq) | 0,000243354 | 9,98866E-05 | 6,67544E-05 | 3,10217E-05 | 3,19149E-05 |
| AIRPORT CONSTRUCTION, OPERATION AND DISPOSAL | Climate change (kg CO2 eq) | 0,004899246 | 0,004899246 | 0,004899246 | 0,004899246 | 0,004899246 |
| | Ozone depletion (kg CFC-11 eq) | 5,80108E-10 | 5,80108E-10 | 5,80108E-10 | 5,80108E-10 | 5,80108E-10 |
| | Terrestrial acidification (kg SO2 eq) | 1,95685E-05 | 1,95685E-05 | 1,95685E-05 | 1,95685E-05 | 1,95685E-05 |
| | Freshwater eutrophication (kg P eq) | 2,57977E-06 | 2,57977E-06 | 2,57977E-06 | 2,57977E-06 | 2,57977E-06 |
| | Marine eutrophication (kg N eq) | 9,97423E-07 | 9,97423E-07 | 9,97423E-07 | 9,97423E-07 | 9,97423E-07 |
| | Human toxicity (kg 1,4-DB eq) | 0,002516326 | 0,002516326 | 0,002516326 | 0,002516326 | 0,002516326 |
| | Photochemical oxidant formation (kg NMVOC) | 1,89585E-05 | 1,89585E-05 | 1,89585E-05 | 1,89585E-05 | 1,89585E-05 |
| | Particulate matter formation (kg PM10 eq) | 6,39338E-06 | 6,39338E-06 | 6,39338E-06 | 6,39338E-06 | 6,39338E-06 |
| | Terrestrial ecotoxicity (kg 1,4-DB eq) | 2,50046E-07 | 2,50046E-07 | 2,50046E-07 | 2,50046E-07 | 2,50046E-07 |
| | Freshwater ecotoxicity (kg 1,4-DB eq) | 8,00035E-05 | 8,00035E-05 | 8,00035E-05 | 8,00035E-05 | 8,00035E-05 |
| | Marine ecotoxicity (kg 1,4-DB eq) | 7,48833E-05 | 7,48833E-05 | 7,48833E-05 | 7,48833E-05 | 7,48833E-05 |
| | Ionising radiation (kBq U235 eq) | 0,001792631 | 0,001792631 | 0,001792631 | 0,001792631 | 0,001792631 |

| | | | | | |
|---|---|---|---|---|---|
| Agricultural land occupation (m2a) | 0,0003453 | 0,0003453 | 0,0003453 | 0,0003453 | 0,0003453 |
| Urban land occupation (m2a) | 0,000292092 | 0,000292092 | 0,000292092 | 0,000292092 | 0,000292092 |
| Natural land transformation (m2) | 1,80027E-06 | 1,80027E-06 | 1,80027E-06 | 1,80027E-06 | 1,80027E-06 |
| Water depletion (m3) | -0,000506324 | -0,000506324 | -0,000506324 | -0,000506324 | -0,000506324 |
| Metal depletion (kg Fe eq) | 0,000319006 | 0,000319006 | 0,000319006 | 0,000319006 | 0,000319006 |
| Fossil depletion (kg oil eq) | 0,001480025 | 0,001480025 | 0,001480025 | 0,001480025 | 0,001480025 |

**Figure A-1 Sensitivity analysis: Change of the aircraft lifetime. Original value: 22 years.**

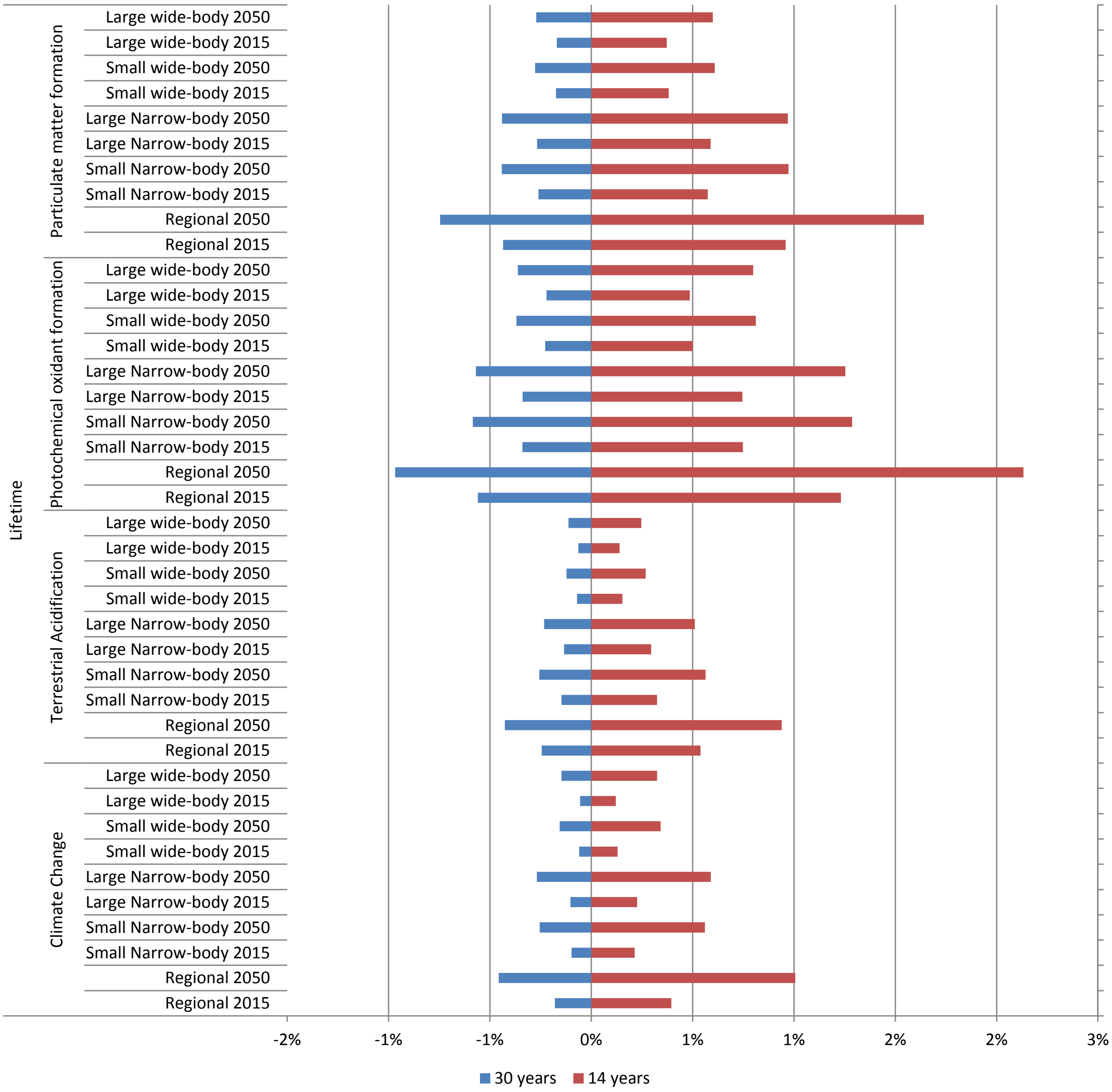

**Figure A-2 Sensitivity analysis: Change of the LTO times to the reference cycle of ICAO (1993). Original values are presented in the Figure 4 8.**

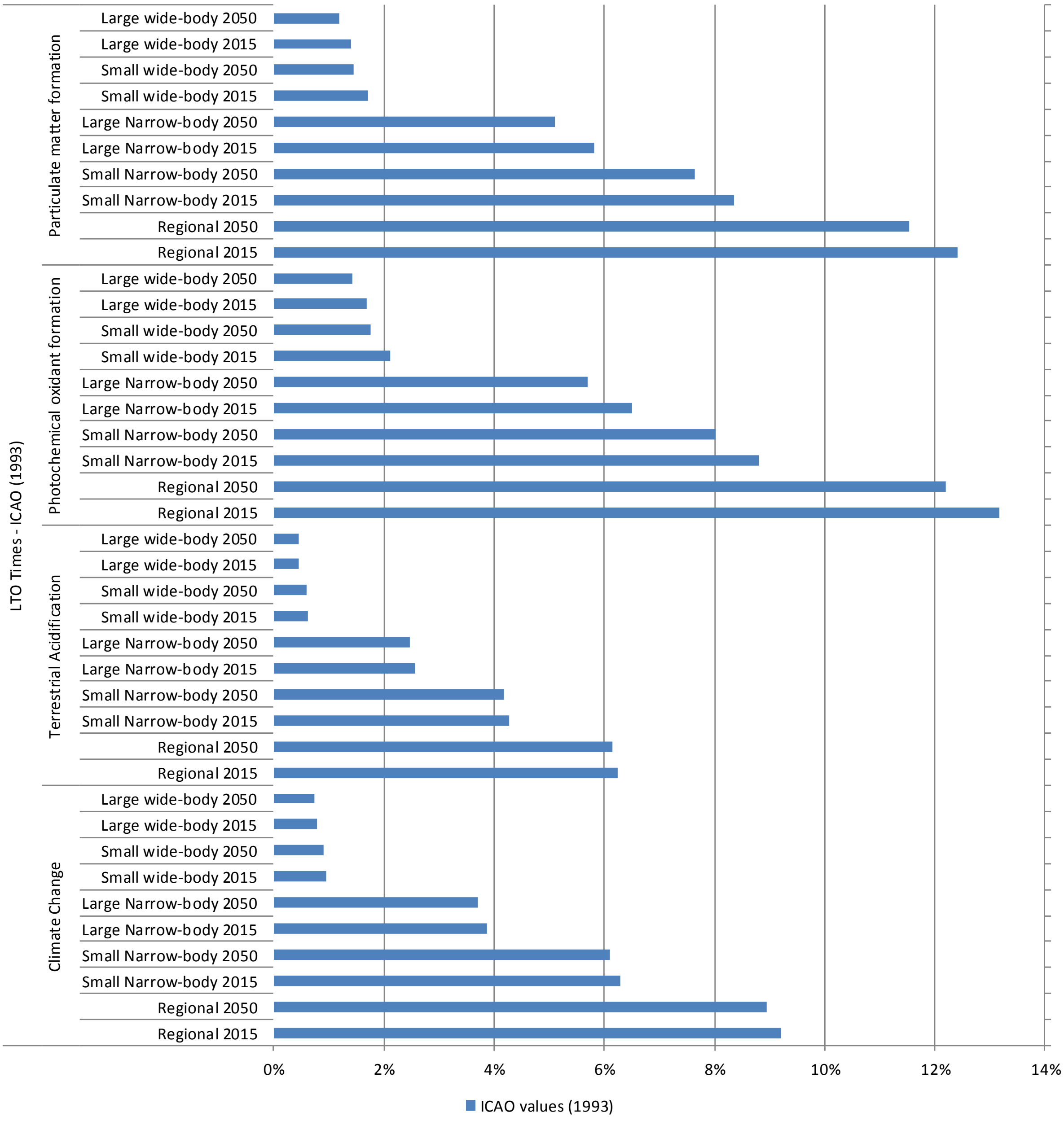

**Figure A-3 Sensitivity analysis: Change of the average flight length distances. Original values are presented in the Table 4 3.**

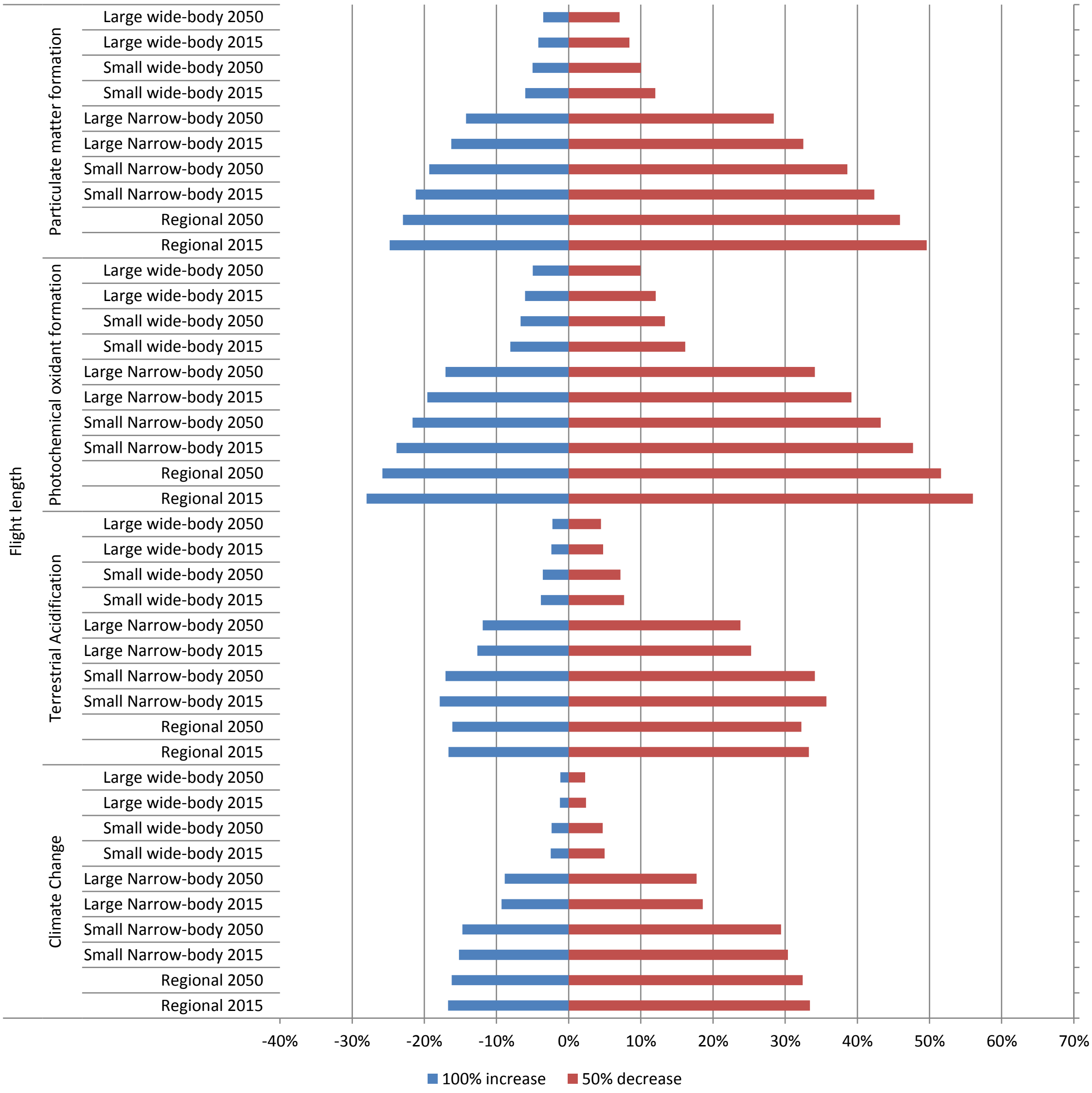

**Figure A-4 Sensitivity analysis: Change of weight improvement (decrease) rate (per decade). Original value: 2.5% weight decrease.**

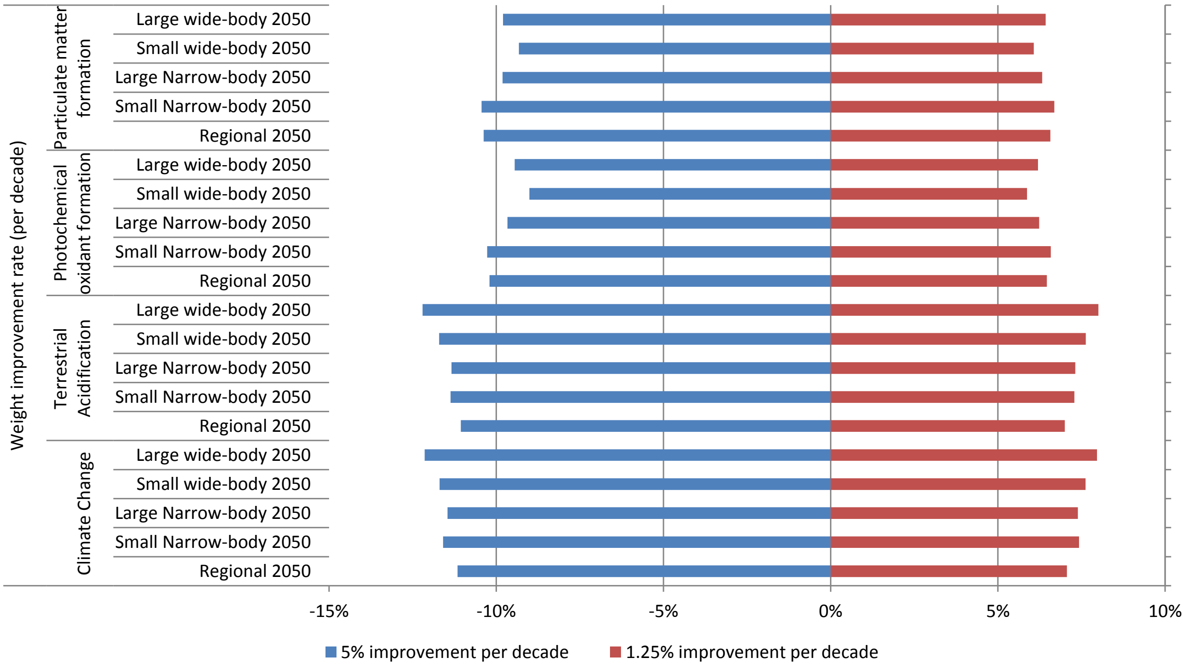

**Figure A-5 Sensitivity analysis: Change of fuel efficiency improvement rate (per annum). Original value: 0.8% improvement p.a.**

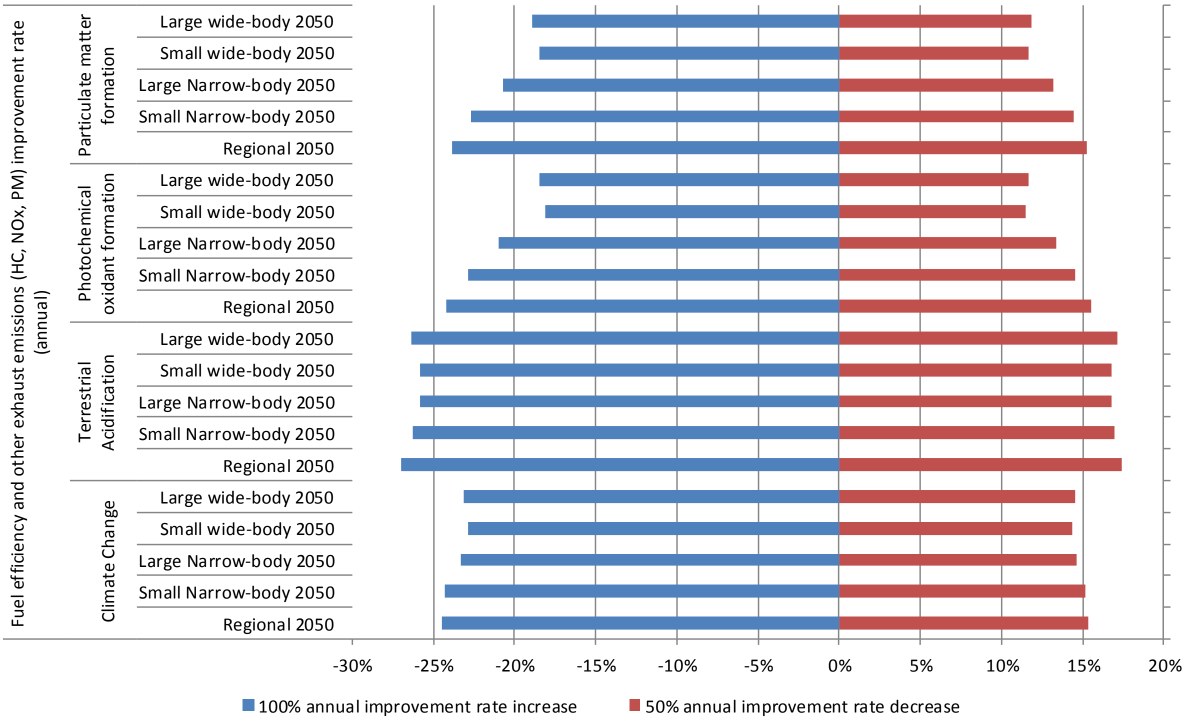

**Figure A-6 Figure 5 10 Sensitivity analysis: Change of freight filling assumption. Tested value: no freight filling.**

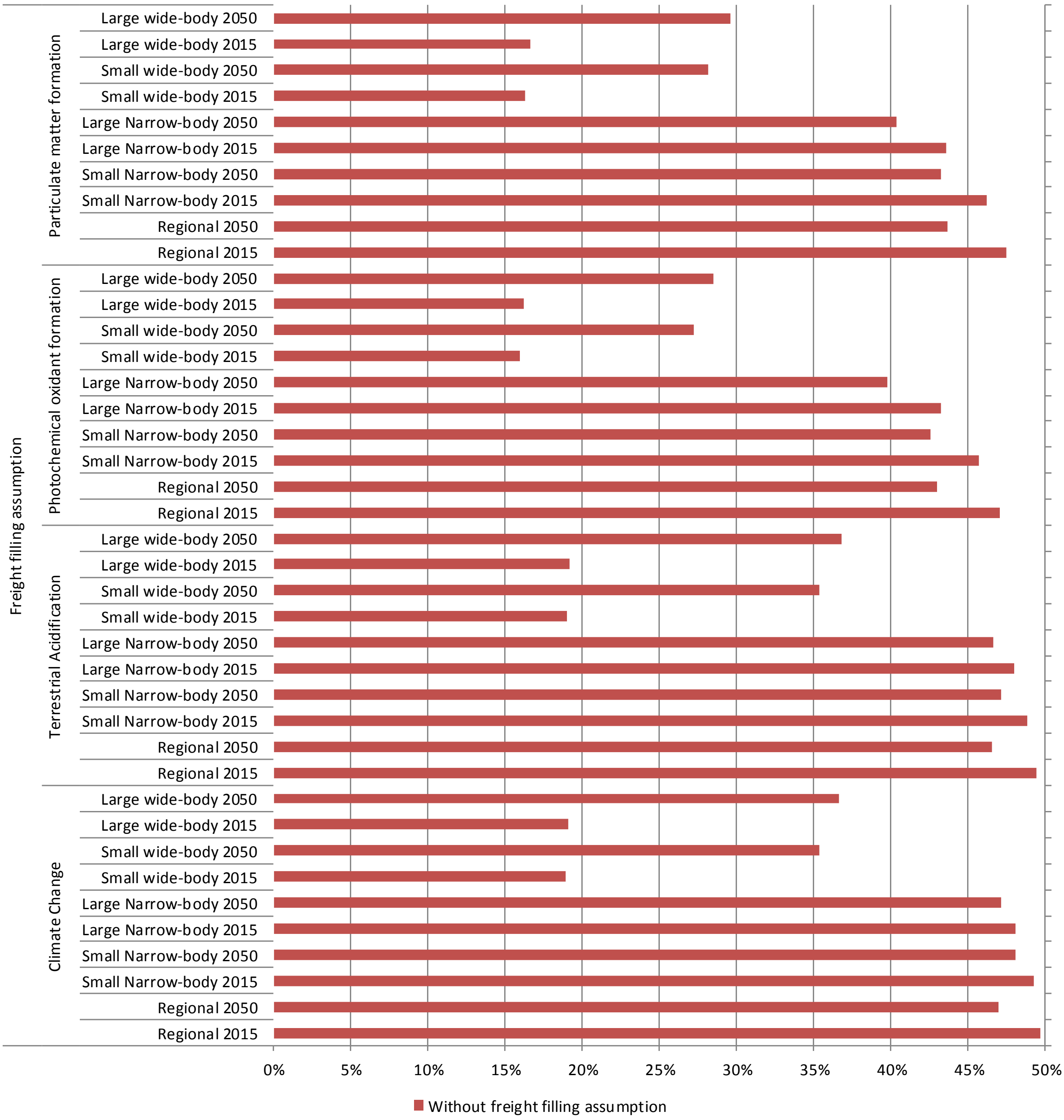

**Table A-4 Sensitivity analysis - detailed results for changes in: lifetime, LTO times and flight length.**

| | | Lifetime | | | LTO Times - ICAO (1993) | | Flight length | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Original value 22,11 | Higher value 30 years | Lower value 14 years | Original value Flightradar 24 (2015) | Higher value ICAO (1993) | Original value 100% | Higher value 100% increase | Lower value 50% decrease |
| Climate Change | Regional 2015 | 0,157 | 0,156 | 0,157 | 0,157 | 0,171 | 0,157 | 0,131 | 0,209 |
| | Regional 2050 | 0,099 | 0,099 | 0,100 | 0,099 | 0,108 | 0,099 | 0,083 | 0,132 |
| | Small Narrow-body 2015 | 0,120 | 0,120 | 0,121 | 0,120 | 0,128 | 0,120 | 0,102 | 0,157 |
| | Small Narrow-body 2050 | 0,076 | 0,075 | 0,076 | 0,076 | 0,080 | 0,076 | 0,065 | 0,098 |
| | Large Narrow-body 2015 | 0,077 | 0,077 | 0,077 | 0,077 | 0,080 | 0,077 | 0,070 | 0,092 |
| | Large Narrow-body 2050 | 0,049 | 0,049 | 0,049 | 0,049 | 0,051 | 0,049 | 0,045 | 0,058 |
| | Small wide-body 2015 | 0,064 | 0,064 | 0,064 | 0,064 | 0,064 | 0,064 | 0,062 | 0,067 |
| | Small wide-body 2050 | 0,040 | 0,040 | 0,040 | 0,040 | 0,041 | 0,040 | 0,039 | 0,042 |
| | Large wide-body 2015 | 0,071 | 0,071 | 0,071 | 0,071 | 0,072 | 0,071 | 0,070 | 0,073 |
| | Large wide-body 2050 | 0,044 | 0,044 | 0,045 | 0,044 | 0,045 | 0,044 | 0,044 | 0,045 |
| Terrestrial Acidification | Regional 2015 | 5,48E-04 | 5,47E-04 | 5,51E-04 | 5,48E-04 | 5,82E-04 | 5,48E-04 | 4,57E-04 | 7,30E-04 |
| | Regional 2050 | 3,34E-04 | 3,33E-04 | 3,37E-04 | 3,34E-04 | 3,54E-04 | 3,34E-04 | 2,80E-04 | 4,42E-04 |
| | Small Narrow-body 2015 | 3,88E-04 | 3,88E-04 | 3,89E-04 | 3,88E-04 | 4,05E-04 | 3,88E-04 | 3,19E-04 | 5,27E-04 |
| | Small Narrow-body 2050 | 2,36E-04 | 2,36E-04 | 2,38E-04 | 2,36E-04 | 2,46E-04 | 2,36E-04 | 1,96E-04 | 3,17E-04 |
| | Large Narrow-body 2015 | 2,92E-04 | 2,91E-04 | 2,93E-04 | 2,92E-04 | 2,99E-04 | 2,92E-04 | 2,55E-04 | 3,65E-04 |
| | Large Narrow-body 2050 | 1,78E-04 | 1,77E-04 | 1,78E-04 | 1,78E-04 | 1,82E-04 | 1,78E-04 | 1,56E-04 | 2,20E-04 |
| | Small wide-body 2015 | 2,69E-04 | 2,69E-04 | 2,69E-04 | 2,69E-04 | 2,71E-04 | 2,69E-04 | 2,59E-04 | 2,90E-04 |
| | Small wide-body 2050 | 1,62E-04 | 1,62E-04 | 1,62E-04 | 1,62E-04 | 1,63E-04 | 1,62E-04 | 1,56E-04 | 1,74E-04 |
| | Large wide-body 2015 | 3,10E-04 | 3,10E-04 | 3,11E-04 | 3,10E-04 | 3,12E-04 | 3,10E-04 | 3,03E-04 | 3,25E-04 |
| | Large wide-body 2050 | 1,84E-04 | 1,84E-04 | 1,85E-04 | 1,84E-04 | 1,85E-04 | 1,84E-04 | 1,80E-04 | 1,93E-04 |
| Photochemical oxidant formation | Regional 2015 | 2,74E-04 | 2,73E-04 | 2,78E-04 | 2,74E-04 | 3,11E-04 | 2,74E-04 | 1,98E-04 | 4,28E-04 |
| | Regional 2050 | 1,74E-04 | 1,73E-04 | 1,78E-04 | 1,74E-04 | 1,96E-04 | 1,74E-04 | 1,29E-04 | 2,64E-04 |
| | Small Narrow-body 2015 | 1,87E-04 | 1,87E-04 | 1,89E-04 | 1,87E-04 | 2,04E-04 | 1,87E-04 | 1,43E-04 | 2,77E-04 |
| | Small Narrow-body 2050 | 1,20E-04 | 1,20E-04 | 1,22E-04 | 1,20E-04 | 1,30E-04 | 1,20E-04 | 9,42E-05 | 1,72E-04 |
| | Large Narrow-body 2015 | 1,26E-04 | 1,26E-04 | 1,27E-04 | 1,26E-04 | 1,35E-04 | 1,26E-04 | 1,02E-04 | 1,76E-04 |
| | Large Narrow-body 2050 | 8,31E-05 | 8,26E-05 | 8,41E-05 | 8,31E-05 | 8,78E-05 | 8,31E-05 | 6,89E-05 | 1,11E-04 |
| | Small wide-body 2015 | 8,83E-05 | 8,81E-05 | 8,87E-05 | 8,83E-05 | 9,01E-05 | 8,83E-05 | 8,11E-05 | 1,03E-04 |
| | Small wide-body 2050 | 6,03E-05 | 6,00E-05 | 6,08E-05 | 6,03E-05 | 6,13E-05 | 6,03E-05 | 5,62E-05 | 6,83E-05 |
| | Large wide-body 2015 | 9,39E-05 | 9,37E-05 | 9,44E-05 | 9,39E-05 | 9,55E-05 | 9,39E-05 | 8,83E-05 | 1,05E-04 |
| | Large wide-body 2050 | 6,34E-05 | 6,32E-05 | 6,39E-05 | 6,34E-05 | 6,43E-05 | 6,34E-05 | 6,03E-05 | 6,98E-05 |
| Particulate matter formation | Regional 2015 | 9,03E-05 | 8,99E-05 | 9,12E-05 | 9,03E-05 | 1,02E-04 | 9,03E-05 | 6,79E-05 | 1,35E-04 |
| | Regional 2050 | 5,76E-05 | 5,72E-05 | 5,86E-05 | 5,76E-05 | 6,43E-05 | 5,76E-05 | 4,44E-05 | 8,41E-05 |
| | Small Narrow-body 2015 | 6,43E-05 | 6,41E-05 | 6,47E-05 | 6,43E-05 | 6,97E-05 | 6,43E-05 | 5,07E-05 | 9,15E-05 |
| | Small Narrow-body 2050 | 4,13E-05 | 4,11E-05 | 4,17E-05 | 4,13E-05 | 4,45E-05 | 4,13E-05 | 3,33E-05 | 5,73E-05 |
| | Large Narrow-body 2015 | 4,28E-05 | 4,27E-05 | 4,30E-05 | 4,28E-05 | 4,53E-05 | 4,28E-05 | 3,58E-05 | 5,67E-05 |
| | Large Narrow-body 2050 | 2,82E-05 | 2,81E-05 | 2,85E-05 | 2,82E-05 | 2,97E-05 | 2,82E-05 | 2,42E-05 | 3,62E-05 |
| | Small wide-body 2015 | 3,17E-05 | 3,16E-05 | 3,18E-05 | 3,17E-05 | 3,22E-05 | 3,17E-05 | 2,98E-05 | 3,55E-05 |
| | Small wide-body 2050 | 2,15E-05 | 2,14E-05 | 2,16E-05 | 2,15E-05 | 2,18E-05 | 2,15E-05 | 2,04E-05 | 2,36E-05 |
| | Large wide-body 2015 | 3,41E-05 | 3,41E-05 | 3,43E-05 | 3,41E-05 | 3,46E-05 | 3,41E-05 | 3,27E-05 | 3,70E-05 |
| | Large wide-body 2050 | 2,29E-05 | 2,28E-05 | 2,30E-05 | 2,29E-05 | 2,31E-05 | 2,29E-05 | 2,21E-05 | 2,45E-05 |

**Table A-5 Sensitivity analysis - detailed results for changes in: weight improvement rate; fuel efficiency and other emissions improvement rate; freight filling assumption.**

| | | Weight improvement rate (per decade) | | | Fuel efficiency and other exhaust emissions (HC, NOx, PM) improvement rate (annual) | | | Freight filling assumption (FFA) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Original value 2,50% | Higher value 5% | Lower value 1.25% | Original value 0,8% | Higher value 100% increase | Lower value 50% rate decrease | With FFA | Without FFA |
| Climate Change | Regional 2015 | | | | | | | 0,157 | 0,235 |
| | Regional 2050 | 0,099 | 0,088 | 0,106 | 0,099 | 0,075 | 0,115 | 0,099 | 0,146 |
| | Small Narrow-body 2015 | | | | | | | 0,120 | 0,180 |
| | Small Narrow-body 2050 | 0,076 | 0,067 | 0,081 | 0,076 | 0,057 | 0,087 | 0,076 | 0,112 |
| | Large Narrow-body 2015 | | | | | | | 0,077 | 0,114 |
| | Large Narrow-body 2050 | 0,049 | 0,043 | 0,053 | 0,049 | 0,037 | 0,056 | 0,049 | 0,072 |
| | Small wide-body 2015 | | | | | | | 0,064 | 0,076 |
| | Small wide-body 2050 | 0,040 | 0,036 | 0,043 | 0,040 | 0,031 | 0,046 | 0,040 | 0,055 |
| | Large wide-body 2015 | | | | | | | 0,071 | 0,085 |
| | Large wide-body 2050 | 0,044 | 0,039 | 0,048 | 0,044 | 0,034 | 0,051 | 0,044 | 0,061 |
| Terrestrial Acidification | Regional 2015 | | | | | | | 5,48E-04 | 8,19E-04 |
| | Regional 2050 | 3,34E-04 | 2,97E-04 | 3,57E-04 | 3,34E-04 | 2,44E-04 | 3,92E-04 | 3,34E-04 | 4,89E-04 |
| | Small Narrow-body 2015 | | | | | | | 3,88E-04 | 5,78E-04 |
| | Small Narrow-body 2050 | 2,36E-04 | 2,09E-04 | 2,54E-04 | 2,36E-04 | 1,74E-04 | 2,76E-04 | 2,36E-04 | 3,48E-04 |
| | Large Narrow-body 2015 | | | | | | | 2,92E-04 | 4,32E-04 |
| | Large Narrow-body 2050 | 1,78E-04 | 1,57E-04 | 1,91E-04 | 1,78E-04 | 1,32E-04 | 2,07E-04 | 1,78E-04 | 2,60E-04 |
| | Small wide-body 2015 | | | | | | | 2,69E-04 | 3,20E-04 |
| | Small wide-body 2050 | 1,62E-04 | 1,43E-04 | 1,74E-04 | 1,62E-04 | 1,20E-04 | 1,89E-04 | 1,62E-04 | 2,19E-04 |
| | Large wide-body 2015 | | | | | | | 3,10E-04 | 3,70E-04 |
| | Large wide-body 2050 | 1,84E-04 | 1,62E-04 | 1,99E-04 | 1,84E-04 | 1,36E-04 | 2,16E-04 | 1,84E-04 | 2,52E-04 |
| Photochemical oxidant formation | Regional 2015 | | | | | | | 2,74E-04 | 4,03E-04 |
| | Regional 2050 | 1,74E-04 | 1,57E-04 | 1,86E-04 | 1,74E-04 | 1,32E-04 | 2,02E-04 | 1,74E-04 | 2,49E-04 |
| | Small Narrow-body 2015 | | | | | | | 1,87E-04 | 2,73E-04 |
| | Small Narrow-body 2050 | 1,20E-04 | 1,08E-04 | 1,28E-04 | 1,20E-04 | 9,27E-05 | 1,38E-04 | 1,20E-04 | 1,71E-04 |
| | Large Narrow-body 2015 | | | | | | | 1,26E-04 | 1,81E-04 |
| | Large Narrow-body 2050 | 8,31E-05 | 7,51E-05 | 8,83E-05 | 8,31E-05 | 6,57E-05 | 9,42E-05 | 8,31E-05 | 1,16E-04 |
| | Small wide-body 2015 | | | | | | | 8,83E-05 | 1,02E-04 |
| | Small wide-body 2050 | 6,03E-05 | 5,48E-05 | 6,38E-05 | 6,03E-05 | 4,93E-05 | 6,72E-05 | 6,03E-05 | 7,67E-05 |
| | Large wide-body 2015 | | | | | | | 9,39E-05 | 1,09E-04 |
| | Large wide-body 2050 | 6,34E-05 | 5,74E-05 | 6,74E-05 | 6,34E-05 | 5,17E-05 | 7,08E-05 | 6,34E-05 | 8,15E-05 |
| Particulate matter formation | Regional 2015 | | | | | | | 9,03E-05 | 1,33E-04 |
| | Regional 2050 | 5,76E-05 | 5,17E-05 | 6,14E-05 | 5,76E-05 | 4,39E-05 | 6,64E-05 | 5,76E-05 | 8,28E-05 |
| | Small Narrow-body 2015 | | | | | | | 6,43E-05 | 9,40E-05 |
| | Small Narrow-body 2050 | 4,13E-05 | 3,70E-05 | 4,41E-05 | 4,13E-05 | 3,19E-05 | 4,73E-05 | 4,13E-05 | 5,92E-05 |
| | Large Narrow-body 2015 | | | | | | | 4,28E-05 | 6,14E-05 |
| | Large Narrow-body 2050 | 2,82E-05 | 2,54E-05 | 3,00E-05 | 2,82E-05 | 2,24E-05 | 3,19E-05 | 2,82E-05 | 3,96E-05 |
| | Small wide-body 2015 | | | | | | | 3,17E-05 | 3,68E-05 |
| | Small wide-body 2050 | 2,15E-05 | 1,95E-05 | 2,28E-05 | 2,15E-05 | 1,75E-05 | 2,40E-05 | 2,15E-05 | 2,75E-05 |
| | Large wide-body 2015 | | | | | | | 3,41E-05 | 3,98E-05 |
| | Large wide-body 2050 | 2,29E-05 | 2,06E-05 | 2,43E-05 | 2,29E-05 | 1,85E-05 | 2,56E-05 | 2,29E-05 | 2,96E-05 |