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Analysis of eco-efficiency among European airlines based on a conceptual framework of life cycle assessment

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Ph.D. Thesis

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Analýza eko-efektivnosti v evropských leteckých společnoste na základě koncepčního rámce posuzování životního cyklu

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Disertační práce

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Eng. Ticiano Costa Jordão

ABSTRACT

The impact of aviation on climate change is mainly related to emissions of carbon dioxide (CO_2), nitrogen oxide (NO_x) and water vapour (H_2O) released by aircraft engines, which in turn occur largely at higher altitudes. Among these greenhouse gases, CO_2 deserves more attention since it corresponds to about 70% of aircraft engine emissions, while H_2O consists in little less than 30% and NO_x is released in much lower concentrations that represent together with other gases less than 1% of overall engine emissions.

The inclusion of CO_2 emissions from international aviation in the European Union Emissions Trading Scheme (EU ETS) in 2012 has forced commercial airlines based in Europe to restructure their flight operations in a more eco-efficient manner, i.e., by reducing their overall fuel consumption and CO_2 emissions while avoiding loss of competitiveness and even increasing the amount of passengers flown.

The purpose of this research is to highlight and demonstrate that some opportunities for increasing eco-efficiency of airlines within the context of climate change mitigation are available and manageable by commercial airlines based in Europe despite the complexity and problems of the European civil aviation scenario. These opportunities are shown by means of a simplified life cycle analysis conceptual framework oriented to climate change mitigation in their flight operations. In order to achieve this goal, author estimates the average fuel consumption and CO_2 emissions per passenger-kilometre in different perspectives of analysis based on data provided by three largest European airlines in terms of total passengers carried per year. These airlines are Deutsche Lufthansa AG, Air France (a subsidiary of the Air France-KLM group), and British Airways (a subsidiary of the International Airlines Group).

Different approaches are adopted and compared in the estimation of fuel consumption and CO_2 emissions and also for testing proposed hypotheses that aim to validate the eco-efficiency opportunities. By using these approaches and hypotheses, the study compares the possible reductions in fuel consumption and CO_2 emission from suggested changes in aircraft choice for hub-to-hub flights for short-haul, medium-haul and long-haul distances. It also estimates the fuel cost and the climate change cost per passenger for different flight alternatives.

Keywords: airlines, climate change, eco-efficiency, life cycle assessment, greenhouse gas emissions, carbon dioxide emissions, environment protection.

ABSTRAKT

Dopady civilního leteckého provozu na změny klimatu jsou spojovány převážně s emisemi oxidu uhličitého (CO_2), oxidů dusíku (NO_x) a vodní páry (H_2O (g)), které jsou vypouštěny motory letadel převážně ve vysokých nadmořských výškách. Z uvedených skleníkových plynů nejvíce pozornosti si zasluhuje oxid uhličitý, který tvoří cca 70 % z celkových emisí. Vodní pára se podílí méně než 30 % a oxidy dusíku, společně s dalšími plyny, se podílí cca 1 %.

Začlenění emisí CO_2, produkovaných mezinárodním leteckým provozem do Evropského systému emisního obchodování (EU ETS) v roce 2012, donutilo komerční letecké společnosti se sídlem v Evropě restrukturalizovat letecký provoz „ekologičtějším“ způsobem. Ten spočívá v realizaci opatření s cílem snižovat celkovou spotřebu leteckého paliva, a tím i emisí CO_2, aniž by došlo ke ztrátě konkurenční schopnosti dotčených subjektů případně ve zvyšování počtu přepravovaných osob při dodržení stávajících spotřeb leteckého paliva.

Navzdory komplexnosti a problémovosti možného vývoje civilního leteckého provozu v Evropě, v kontextu se zmírňováním jeho dopadů na změny klimatu, existují reálné způsoby pro zvyšování „ekologické účinnosti“ leteckého provozu. Některé z možných přístupů k řešení této problematiky jsou naznačeny i v předložené práci.

Možnosti řešení jsou zobrazeny pomocí analýzy zjednodušeného životního cyklu koncepčního rámce orientovaného na zmírňování dopadů leteckého provozu na změny klimatu. Autor odhaduje průměrnou spotřebu paliva a produkovaných emisí CO_2/na osobu a km z různých pohledů a s využitím dat, která byla poskytnuta třemi největšími evropskými aerolinkami (Deutsche Lufthansa AG, Air France a British Airways). V práci jsou porovnávány různé varianty odhadu spotřeby paliva a emisí CO_2 za různých podmínek leteckého provozu, navrhovány a testovány různé hypotézy mající za cíl vyhodnotit ekologickou účinnost jednotlivých variant. Jsou rovněž srovnávány různé varianty a způsoby snížení spotřeby paliva a emisí CO_2 pro lety na krátké, střední a dlouhé vzdálenosti s různými typy letadel. Pro různé letové varianty jsou rovněž odhadovány náklady leteckého provozu, které se odvíjí od spotřeby paliva a vyvolaných nákladů, souvisejících s emisním příspěvkem oxidu uhličitého, ke zhoršení klimatu.

Klíčová slova: letecké společnosti, změna klimatu, ekologická účinnost, posuzování životního cyklu, emise skleníkových plynů, emise oxidu uhličitého, ochrana životního prostředí.

CONTENT

LIST OF ABBREVIATIONS AND ACRONYMS

NO_x	Nitrogen Oxides
CO_2	Carbon Dioxide
CH_4	Methane
N_2O	nitrous Oxide
SO_x	Sulphur Oxides
CO	Carbon Monoxide
HC	Hydrocarbon
H_2O	Water
O_3	Ozone
SO_2	Sulphur Dioxide
VOC	Volatile Organic Compounds
NMVOC	Non-Methane Volatile Organic Compounds
HAP	Hazardous Air Pollutants
PM	Particulate Matter
PM_{10}	Respirable Particulate Matter
$PM_{2.5}$	Fine Particulate Matter
GHG	Greenhouse Gases
EU ETS	European Union Emissions Trade Scheme
LCA	Life Cycle Assessment
LCC	life Cycle Costing
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
IPCC	Intergovernmental Panel on Climate Change
ICAO	International Civil Aviation Organization
CO_{2eq}	Carbon Dioxide Equivalent
ASK	Available Seat-Kilometres
RTK	Revenue Tonne-Kilometre
RPK	Revenue Passenger-Kilometres
FTK	Freight Tonne-Kilometres
GDP	Gross Domestic Product

LTO	Landing and Take-Off Cycle
UTLS	Upper Troposphere and Lower Stratosphere
ACI	Airports Council International
RF	Radiative Forcing
RFI	Radiative Forcing Index
ATM	Air Traffic Management
GVA	Gross Value Added
IATA	International Air Transport Association
PLF	Passenger Load Factor
PFF	Passenger-to-Freight Factor
UNFCCC	United Nations Framework Convention on Climate Change
EF	Emission Factor
SAGE	System for Assessing Aviation's Global Emissions
PAX	Passenger
Y PAX	Economy Equivalent Passenger
PAX.km	Passenger-Kilometres
Y-SEATS	Economy Equivalent Seats
PN	Petri Nets
CPN	Coloured Petri Nets
TPN	Timed Petri Nets
NN	Neural Network
ANN	Artificial Neural Network
KSOFMs	Kohonen’s Self-Organizing Feature Maps
FLNNs	Fuzzy Logic Neural Networks
ECASK	Environmental Cost per Available Seat Kilometre
$GVACO_{2e}$	Gross Value Added per Carbon Dioxide Equivalent
PRASK	Passenger Revenue per Available Seat Kilometre
CASK	Cost per Available Seat Kilometre
GCD	Great Circle Distance
FRA	Frankfurt International Airport
CDG	Paris Charles de Gaulle International Airport

LHR	London Heathrow International Airport
DME	Moscow Domodedovo International Airport
SVO	Moscow Sheremetyevo International Airport
JFK	New York John Kennedy International Airport
BA	British Airways
AF	Air France
LH	Lufthansa

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INTRODUCTION

The global airline industry has been playing a key role in the world economy growth through its contribution to the expansion of business and tourism opportunities, besides facilitating social cohesion, cultural exchange, humanitarian aid and political gathering in important international events. Currently, the world's airlines carry over three billion passengers a year and 50 million tonnes of freight. It provides 63 million jobs and contributes to 3.5% of the world's gross domestic product (GDP) which corresponds to about $2.7 trillion when considering direct and indirect employment as well as induced jobs and economic activities such as those observed in retail outlets, service industries (e.g. banks and restaurants) and in the tourism industry. This is expected to increase to 105 million jobs and $6 trillion in GDP in 2034 [1].

The sector has a history of strong growth in traffic volumes, and consequently, has been raising serious environmental concerns. Since 1970, when the corresponding number of passengers flown was 383 million, it has grown at an annual average rate of more than 6% [2].

Today, the global aviation system comprises over 50,000 routes connecting 3,883 commercial airports through 1,402 airlines operating more than 26,000 aircraft, carrying over 3.5 billion passengers on nearly 35 million flights a year. Based on current industry growth rates, it is expected that air transport will carry over 5.8 billion passengers, support 99 million jobs and $5.9 trillion in economic activity in 2034 [1].

Nowadays environmental and social externalities of air transport are recognized as a fundamental aspect of business strategy and therefore are considered critical factors to control for the achievement of financial success [3]. Thus air transport companies have the obligation of taking environmental impacts of their activities into account, whether due to a serious social commitment or to a desire to avoid paying fines for not adhering to existing laws. Some of the most important externalities generated from commercial flights are the impacts on air quality and their contributions to climate change through fuel consumption and engine emissions [4; 5]. The reduction of fuel consumption became a major global target among airlines worldwide due to the recent surge in oil prices. The aircraft emissions have also gained more relevance worldwide, but particularly in the European Union, where apart from the emissions of nitrogen oxides (NO_x) and its concerns related to ground level ozone formation, measurements and reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) at higher altitudes became a major regional target due to their contribution to man-made climate change.

It has been observed that total emissions controlled under the Kyoto Protocol fell in the European Union by 5.5% from 1990 to 2003, while in the same period greenhouse gas emissions from international aviation increased by 73%, corresponding to an annual growth of 4.3% per year [6].

Aviation produces around 2% of the world's manmade emissions of carbon dioxide (CO_2), according to the United Nations Intergovernmental Panel on Climate Change [7]. Moreover, it is responsible for 12% of CO_2 emissions from all transport sources, compared to 74% from road transport [8]. There has been massive investment in new technology and coordinated action to implement new operating procedures. However, as long as aviation grows to meet increasing demand, particularly in fast-growing emerging markets, the IPCC forecasts that its share of global manmade CO_2 emissions will increase to around 3% in 2050 [7]. IPCC points out that in terms of CO_2 (g C per tonne-km), aviation emits 1 to 2 orders of magnitude more carbon than other forms of transport [9]. Air transport has limitations of cost and weight to compete in the transport of heavy goods but is still the most recommended alternative for transport of perishable freight and high-value goods.

The major concern in the reduction of greenhouse gas emissions by civil aviation has been embraced by government authorities across the European Union and resulted in the inclusion of the sector in the EU Emissions Trade Scheme (EU ETS) from January 2012, when all intra-community flights became subject to emission restrictions with allocated annual emission allowances that airlines will have to comply with. This regulation has faced a strong rejection by European and non-European airlines due to expected significant increases in costs with the acquisition of carbon credits to meet their annual emission allowances. European commercial airlines more than ever before perceive a need to restructure its flight operations in order to reduce their overall fuel consumption and CO_2 emissions while avoiding loss of competitiveness and even increasing the amount of passengers flown.

Other environmental impacts caused by air transport sector are associated with airport operations, which became more relevant with the perceived significant increase in air passenger traffic and the associated need for investments in new runways and new airport terminals. These impacts are related to local air pollution, noise generation, light disturbance, waste generation, water consumption, groundwater contamination and energy consumption. In this research, environmental impacts associated with air transport sector are highlighted separately according to air operations and ground operations. However, a special focus will be given to air operations; i.e. to the fuel consumption and emissions released during the flights.

A good understanding of life cycle assessment (LCA) can prove to be a valuable asset in the measurement and control of environmental impacts during the lifespan of an aircraft. Previous research has shown that most of environmental impacts of aircraft come from the consumption of kerosene and its airborne emissions; i.e. the fuel burn process [10]. This is clearly the case of GHG emissions which in turn is largely represented by CO_2 released at high altitudes during the cruise stage of flights. Therefore, the most effective way to improve environmental performance of airlines is to undertake initiatives that jointly contribute to reduction of aircraft emissions. For this reason, a life cycle assessment can be simplified for an effective action by airlines and be focused on the flight operations. In fact, fuel consumption and emissions per passenger for each kilometre flown can vary significantly between the same origin and destination according to the total distance flown and total fuel carried, the type of aircraft and engines used, the seat configuration, the passenger load factor, among other factors that will be explained in detail in further chapters.

It is demonstrated in the following chapters that some opportunities for increasing eco-efficiency of flight operations are available and manageable by European commercial airlines despite the complexity and problems of the European civil aviation scenario. Initially, author addresses eco-efficiency from a purely environmental view as ecological efficiency. Further, author follows the same perspective of eco-efficiency as defined by Kicherer, Schaltegger, Tschochohei and Pozo [11]. In this extended view, eco-efficiency is seen as a linkage between economic and environmental issues and thus the comparison is expressed in terms of environmental impact caused per monetary unit earned or spent. Moreover, eco-efficiency in the context of this research is considered solely in terms of average fuel consumption per passenger-km and GHG emissions per passenger-km in different phases of flight, particularly carbon emissions. The associated costs to fuel consumption and GHG emissions are also considered and estimated. Estimations of emissions are provided within a simplified life cycle analysis conceptual framework that takes in account different phases of flight operation as described in chapter 2.3. When substantial differences are perceived in this aspect among flights chosen by air passengers from the same departure airport to the same arrival airport, air passengers may find valid arguments to claim for fees and taxes charged by airlines that are more proportional to their real contributions in terms of fuel consumption and GHG emissions. Airlines in turn may also identify opportunities to reduce their overall fuel consumption, their contributions to GHG emissions as well as the associated costs related to jet fuel and government fees on carbon emissions. A subsequent wave of marketing and sales initiatives oriented to attract air passengers to more eco-efficient flights may emerge among airlines. In the methodological part of this research, among other actions that can be taken by airlines to achieve these goals, author focuses in the optimization of aircraft fleet deployed by each airline in their flight operations. Other alternatives for reductions in fuel consumption and emissions during flights are briefly addressed and recommended for further research. These alternatives may take longer time to be implemented and will depend on the collaboration among airports, governments and the manufacturers of aircraft and its components. They comprise the acquisition of more fuel-efficient aircraft, change in aircraft seat configuration, use of more fuel-efficient engines, use of biofuels for aviation, and the negotiation of air passenger duty and airport taxes that could be charged proportionally to the actual contribution of air passengers to GHG emissions for each flight.

The dissertation is organized into four parts and the conclusions. Part 1 provides a literature review within three chapters. Part 2 is divided into three main chapters and presents the research objectives and hypotheses in detail and explains the methodology proposed. Part 3 come up with research findings and discuss the outcomes of results obtained and highlights opportunities for further research. Part 4 provides conclusions to the research undertaken by author.

Chapter 1.1 highlights the key contributions of the European civil aviation sector for the regional and national economic development and the environmental aspects and impacts associated with airport and aircraft operations. A special attention is given to the contribution of civil commercial aviation to climate change and to the way European airlines have been addressing this global issue. The main features of the EU ETS as a market-based climate change mechanism that includes the civil aviation sector are explained and fuel efficiency alternatives for airlines are highlighted. Chapter 1.2 explains the three methodological tiers for estimating emissions from flights as recommended by Intergovernmental Panel on Climate Change (IPCC) and the most common emission calculation methodologies used worldwide. The estimations of carbon emissions provided in this research are mainly based on the methodology of International Civil Aviation Organization (ICAO). Chapter 1.3 demonstrates the valuable contribution that Life Cycle Assessment can bring to European airlines in terms of eco-efficiency improvements of all its operations. Recommended computational, graphical and mathematical tools for LCA are highlighted. Chapter 2.1 presents in detail the main objectives of this research and illustrates several steps that were undertaken to identify opportunities for climate change mitigation among European airlines by means of reduction in fuel consumption under different flight conditions.

Chapter 2.2 presents a LCA oriented to climate change mitigation. Initially an LCA focused on the emissions of carbon dioxide equivalent (CO_{2eq}) is performed for two aircraft types regularly used by European airlines – Airbus A330-200 and Boeing 777-200. Author defines the goal, the scope and the functional unit used as well as the key indicators in the life cycle inventory that can be used as a reference for climate change mitigation of aircraft operations.

In Chapter 2.3 a simplified life cycle analysis conceptual framework is defined for estimating the fuel consumption and GHG emissions from flight operations of aircraft used by largest European airlines. Estimations are presented in terms of distance flown for different aircraft types and also per chosen flight routes among main competing airlines. In the part 3 the results in terms of eco-efficiency obtained by calculations presented in the part 2 are commented and compared. Chapter 3.2 provides recommendations for further research in other alternatives for emission reductions involving the engagement of governments and airports in Europe by rewarding airlines and air passengers with reduced taxes and fees for flights that are considered more eco-efficient than the benchmark of the same flight route.

1 TEORETICAL PART

1.1 THE MAIN EFFECTS AND CHALLENGES ASSOCIATED TO THE EXPANSION OF AIRLINE INDUSTRY

Commercial aviation has been playing a major role as a vital enabler and a beneficiary in the globalization process of business, supply chains and individuals. Back in 1950 there were just over 30 million passenger departures. Since then the market has grown almost 80 times. Besides the significant increase in number of passengers and number of flights perceived during the last decades, other indicators also confirm this trend: Available Seat-Kilometres (ASK), Revenue Passenger-Kilometres (RPK), and the freight Tonne-Kilometres (FTK). ASK is the number of seats available for sale multiplied by the distance flown. RPK is the number of revenue passengers carried multiplied by the distance flown. A revenue passenger consists in a passenger for whose transportation an air carrier receives commercial remuneration. FTK corresponds to the number of revenue tonnes of cargo (freight and mail) carried multiplied by the distance flown [12].

Travel distances have grown such that RPK flown are over 160 times as large today as in 1950 and FTK flown are over 200 times as large [13]. The expansion of international trade perceived since that time has been largely due to improvements in aircraft technology and in airline operational efficiency, which in turn contributed to a reduction in the costs of air transport.

The air transport sector, particularly the airline industry has a wide array of aspects and impacts that need to be carefully addressed and controlled facing the high increase in air passenger traffic observed in the last decade.

It has been observed that the increase in the air passenger traffic has not been followed in the same proportion by investments in the aviation infrastructure, thus causing many constraints that led to increasing congestion and flight delays, mishandled baggage, and dissatisfied customers due to perceptions of poor service in general. One of the main suggested alternatives for airports to meet the massive increase in the air passenger traffic has been the expansion of airport operations by building new terminals and runways. However, this alternative solution may result in the increase in large scale of environmental impacts. In some countries, the voices of important stakeholders have led to the delay and even cancellation of some airport expansion projects. To address these concerns, airports may be required to implement projects that would minimize the environmental impacts of their operations. An alternative to runway expansion is to cap the existing facilities and shift the short-haul traffic to alternate modes such as train or automobile. Although there is not a common definition that distinguish flight length in terms of distance and time, a definition currently used by Deutsche

Lufthansa AG is adopted in this study, which categorizes the flights as follows: short-haul for less than 800 km, medium-haul between 800 and 3,000 km, long-haul for more than 3,000 km [14].

The improvement of national high-speed networks observed in some European countries has enabled trains to challenge airlines on shorter trips. Examples are illustrated by the Eurostar service between London and Paris, the high-speed rail link between Madrid and Barcelona, and also the high-speed railroads Paris-Lyon, Paris-Brussels and Hamburg-Berlin. Such transport links offered by railroad industry resulted in the reduction of services provided by airlines for these routes [15]. The deregulation of European railroad industry enforced on the 1st of January 2010 has extended the range of market share of railroad industry for short routes, thus causing an additional deceleration in the growth scale of airport and airlines operations.

1.1.1 Key contributions for the regional and national development

There are currently more than 130 airlines, a network of over 450 airports and some 60 air navigation service providers across the civil aviation industry in Europe. These numbers demonstrate the high contribution in economic growth and social benefits provided by air transport sector to the citizens in Europe.

The air transport sector has some positive social and economic impacts which can be translated into job generation, business efficiency enhancement and tourism development. In this context, airports play an important role in the European Union. Thus, restricting airport capacity or burdening air travel demand with high taxes and fees could have severe economic or social consequences. Studies suggest that failure to increase capacity to meet demand could reduce GDP at a national or regional level by 2.5 to 3%**,** taking all impacts into account, although this will be heavily dependent upon the level of restriction applied [16; 17; 18; 8].

Table 1 highlights some key socio-economic contributions of airport activities for the regional and national economic development.

Table 1 Key contribution of the European airport sector for the regional and national economic development [16].

Key socio-economic contributions of air transport sector for the regional and national economic development in Europe
• Airports support employment directly on-site and in the surrounding area but also indirectly in the chain of suppliers providing goods and services. In addition, the incomes earned in these direct and indirect activities generate demand for goods and services in the economy, which supports further employment.
• Nearly two-thirds (64%) of employment comes from airlines, handling agents and aircraft maintenance, with the remainder split between airport operators (14%), in-flight catering, restaurants and bars and retailing (12%), air traffic control and control agencies (6%), freight (1%) and other activities such as fuel companies and ground transport operators (3%).
• The European airports on average support around 950 on-site jobs per million passengers (workload units) per annum currently.
• For every 1,000 on-site jobs supported by European airports there are around 2,100 indirect/induced jobs supported nationally, 1,100 indirect/induced jobs supported regionally, or 500 indirect/induced jobs supported sub-regionally.
• Given that there are 950 on-site jobs created per million passengers, it can be concluded that for every million passengers (workload units), European airports support around 2,950 jobs nationally, 2,000 jobs regionally, or 1,425 jobs sub-regionally.
• Airports can make a substantial contribution to the overall economy of the areas that they serve, when the combined effect of their direct, indirect and induced impact is taken into account. Estimates vary in the range 1.4 - 2.5% of GDP, excluding tourism impacts.

Due to the significant socio-economic and environmental impacts inherent to their operations, airports worldwide are increasingly being managed within the framework of sustainable development guiding principles mainly as a response to the pressure received by their various stakeholders. The *World Commission on Environment and Development* defined sustainable development in 1987 in the Brundtland Report as *"meeting the needs of the present without compromising the ability of future generations to meet their own needs".* This new paradigm is reinforced by the "Triple Bottom Line" (TBL) approach, a term also known as "*people, profit, planet*" [19 p. 90-100]. This concept according to John Elkington means that "for an organization to be sustainable – a long run perspective –, it must be financially secure, it must minimize (or ideally eliminate) its negative environmental impacts and, finally, it must act in conformity with societal expectations".

Table 2 and table 3 list the key social and economic themes that have to be addressed and reported to different groups of stakeholders by airports and airlines, respectively.

Table 2 Recommended social issues to be reported by airports and airlines [20; 21].

Sector Theme	Examples of information	TBL dimension	Targeted stakeholder
Health and Safety	Tightening security for passengers and employees. Quantitative measures of various types of injuries.	Social	Employees and Customers
Community Investment and Development	Continued and Increased communication and collaboration with the community. Amount of resources invested in community activities (e.g., sponsorships and donations for the local community). Provision of details about employee volunteering programme.	Social	Society, Government and Employees
Customer Care	Quality of airport and airlines responses to enquiries from customers, provisions of customer service training	Social	Customers
Labour/Sustainable and Human Resources	Information on training and professional development of employees, breakdown of demographics (% of women, minorities, and disabled persons employed). Notes on future benefits and incomes of employees.	Social	Employees
Surface Access/Transportation	Implemented measures to make the use of public transport a more convenient choice for those travelling to and from the airport. Measurement of such initiatives (e.g., overall annual public transport mode share and transport mode used by passengers and staff by year).	Social	Customers and Employees

* Note: Triple Bottom line (TBL) dimensions consist of: economic, social and environmental dimensions.

Table 3 Main Economic themes covered by sustainability reports in the air transport sector [20; 21].

Sector Theme	Examples of information	TBL dimension	Targeted stakeholder
Traffic/Operational Figures	**Airports**: Information on the number of takeoffs and landings, passenger volumes. **Airlines**: passenger load factor, available seat-kilometres, revenue passenger-kilometres, and passenger revenue per available seat-kilometre.	Economic	Investors
Income-Generation and Distribution	Information on how much income is generated and from which sources the generated income came from. Detail on the distribution and purpose for which the income was spent (e.g., community investment, renewal of aircraft fleet, renovations, airport expansion etc.). Contribution in Direct Gross Domestic Product (value added) from flight and airport operations to the regions served.	Economic	Investors and Government
Sourcing/Supply Chain	Policy, practices, and proportion of spending on locally-based suppliers at significant locations of operation. Initiatives to only purchase from "green" suppliers and to provide "sustainable" services and products to customers.	Economic	Supplier
Airport Expansion/Construction	Information on new runways being constructed and additional terminals being built.	Economic	Investors, Society and Government

* Note: Triple Bottom line (TBL) dimensions consist of: economic, social and environmental dimensions.

Previous research conducted in 2009 among various airlines around the world has shown that airlines from Asia were better reporting on social issues than airlines from other continents, whilst airlines from Europe showed in average a more balanced distribution in the information provided across the three TBL dimensions [22 pp. 1453-1455]. In the community investment and development perspective, a proactive dialogue with local stakeholders can be maintained with surveys, newsletters, sustainability reports and volunteerism programmes undertaken by their employees. Within the customer care perspective, it is noteworthy for airlines and airports to improve punctuality and manage properly any flight delays and cancellations that may occur, avoid overbooking, enforce effective baggage handling, and deliver high quality on-board product, cabin staff service, and airport hub services.

1.1.2 Main environmental impacts associated with airline industry

The air transport sector has been increasingly placed in the environmental agenda. The main emissions from combustion process of aircraft engines are presented in table 4. Fuel consumption considerations are a priority for airlines because profit margins are narrow and the price of fuel has steadily increased at a time when airfares have been decreasing in response to competition. Fuel burn rates and emissions vary according to the different modes of aircraft operation, namely idle, taxi, take-off, approach and landing. The take-off phase requires full engine thrust, and thus incur higher fuel burn rate. As the aircraft ascends to higher altitudes the drag decreases and so does the rate of fuel use.

Table 4 Emissions from combustion processes of aircraft engines [23; 24].

Gas	Source
CO_2	Carbon dioxide is the product of complete combustion of hydrocarbon fuels like gasoline, jet fuel, and diesel. Carbon in fuel combines with oxygen in the air to produce CO_2.
NO_x	Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x.
HC	Hydrocarbons are emitted due to incomplete fuel combustion. They are also referred to as volatile organic compounds (VOCs). Many VOCs are also hazardous air pollutants.
H_2O	Water vapour is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produce H_2O.
CO	Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel.
SO_x	Sulphur oxides are produced when small quantities of sulphur, present in essentially all hydrocarbon fuels, combine with oxygen from the air during combustion.
Particulates	Small particles that form as a result of incomplete combustion, and are small enough to be inhaled, are referred to as particulates. Particulates can be solid or liquid.
O_3	O_3 is not emitted directly into the air but is formed by the reaction of VOCs and NO_x in the presence of heat and sunlight. Ozone forms readily in the atmosphere and is the primary constituent of smog. For this reason it is an important consideration in the environmental impact of aviation.

Over very long distances the fuel use per kilometre increases because of the greater amount of fuel that has to be carried during the early stages of flight [25]. Even in short-haul flights, most part of fuel is burned during the cruise stage. However, in these flights, the shares of fuel burned during the landing and take-off phases (LTO) become more significant in proportion to the total amount of fuel burned during the aircraft operations than the shares observed for medium or long-haul flights [26 p. 65].

Landing and take-off cycle (LTO) includes all aircraft operations near the airport that take place below the altitude of 1000 m. Refer to section 1.2.1 for further explanations.

As aircraft emissions are directly proportional to fuel used, the bulk of aircraft emissions occur at higher altitudes during the cruise phase. Aircraft engine emissions are roughly composed of about 70% CO_2, a little less than 30% H_2O, and less than 1% each of NO_x, CO, SO_x, VOC, particulates, and other trace components including hazardous air pollutants (HAPs).

Little or no N_2O emissions occur from modern gas turbines [9 p. 3]. Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines [7].

Aircraft emissions are considered air quality pollutants or greenhouse gases, depending on whether they occur near the ground or at high altitude, respectively. However, aircraft are not the only source of aviation emissions. Emissions are also originated from vehicles that provide access to airports, shuttle services offered between terminals and to the aircraft, ground equipment that provide services to aircraft, stationary airport power sources, and auxiliary power units providing electricity and air conditioning to aircraft parked at airport terminal gates.

Aircraft emissions with an impact on air quality are estimated to be primarily released as nitrogen oxides (NO_x) and to a considerably minor degree as carbon monoxide (CO), non-methane hydrocarbons (NMVOC), sulphur dioxide (SO_2) and primary particulate matter (PM10). Numerous studies undertaken in the last three decades have focused on the different implications of NO_x emissions from aircraft [27]. Nitrogen oxide (NO_x) emissions from aviation contributes to ozone formation at ground level, and increase the deposition of oxidised nitrogen, thus increasing ecosystem exposure to acidification and eutrophication [28 p. 64]. Moreover, these emissions also expect to increase ozone in the upper troposphere and lower stratosphere region (UTLS), where pollutants have a much longer lifetime than at Earth´s surface. Thus, excess nitric oxide and ozone accumulate to larger and more persistent perturbations at UTLS than at Earth´s surface with an enhanced radiative forcing.

In fact, the presence of ozone in the UTLS acts as a greenhouse gas, absorbing some of the infrared energy emitted by the Earth [29]. Still, NO_x emissions in the atmosphere also reduce the lifetimes of methane. As a result of chemical processes in the atmosphere, emissions of NO_x can indirectly both damp and enhance the greenhouse effect [30 p. 64]

Since the lifetime of ozone is much shorter (100-200 days) than that of methane (10-12 years), the resulting increase of ozone originated from NOx emissions is limited to a regional scale, while the reduction of methane by reactions with NO_x will be perceived much long after NO_x emissions were originated [30].

More recent research has raised concern related to the effects of oxides of nitrogen and sulphur (NO_x and SO_x) emissions from aircraft at cruise altitude when these gases mix with ammonia released from farming and form harmful fine particulate matter ($PM_{2.5}$) that when inhaled and trapped in the lungs may cause cardiovascular and respiratory illnesses [31 p. 7736]. Therefore, researchers of that study recommended that cruise emissions be explicitly considered in the development of policies, technologies and operational procedures designed to mitigate air quality impacts of air transportation.

The International Civil Aviation Organization (ICAO) has been establishing since 1996 standards limiting the emissions of NO_x and other gases from aircraft engines [32 p. 2]. However, these regulations have been mainly limited to altitude lower than 1,000 km. The impacts of gases emitted by civil aviation sector are highlighted in table 5.

Table 5 Impacts on atmosphere caused by gas emissions from aviation [23; 24].

Gas	Impact
CO_2	Long-lived GHG. Contributes to global warming.
O_3	Lifetime weeks to months. Product of NO_x emissions plus photochemistry. The effect of O_3 is high at subsonic cruise levels and causes radio-active reactions at those levels.
CH_4	Lifetime of ~10 years. Aircraft NO_x destroys ambient CH_4.
H_2O	The effect is small because of its small addition to natural hydrological cycle. Triggers contrails, but actual contrail content is from the atmosphere.
Sulphate	Scatters solar radiation to space. Impact is one of cooling.
Soot	Absorbs solar radiation from space. Impact is one of warming.
Contrails	Reflect solar radiation, have cooling effect; but reflect some infrared radiation down to earth, that has a warming effect; but net effect is one of warming.
Cirrus	Contrails can grow to larger cirrus clouds (contrail cirrus), which can be difficult to distinguish from natural cirrus. Generally warming effects.

In the context of this research, a particular attention is given to carbon dioxide (CO_2) emissions due to its major contribution to global warming. Increasingly it has been claimed that impacts on the atmosphere caused by air passenger transport shall be internalized in the pricing of flight tickets, either aggregated to fuel surcharge or charged separately as carbon tax on domestic and international flights to be collected by a central body of the European Union (e.g. Association of European Airlines or the European Aviation Safety Agency). Because all core services provided by airlines depend on a regular and solid cooperation with airports, it is also noteworthy to highlight the main environmental aspects and impacts associated with airport operations as presented in table 6.

Table 6 Main environmental aspects and impacts associated with airport operations and expansion.

Environmental Aspect	Environmental Impact
Water consumption	Degradation of human health, ecosystem quality and natural resources
Energy and fuel consumption	Air pollution, global warming
Emissions of CO_2	Global warming
Emissions of VOC	Photochemical smog (increase in ground level ozone)
Emissions of NO_x and SO_x	Acidification and eutrophication
Waste generation	Odour (if applicable), global warming (if biodegradable), air pollution (if incinerated), aesthetical/visual impact, degradation of human health and ecosystem (if improperly disposed off).
Waste water (nitrates, phosphates)	Acidification and eutrophication, degradation of aquatic habitat, soil and groundwater contamination
Heavy metals (Cr, Cd, Ni, Cu, Pb)	Health diseases and soil degradation
Noise generation	Degradation of human health and the biota in the surroundings
Light disturbance	Visual impact on the surrounding community and disturbance of local biota, mainly birds.

*Note: CO_2 – carbon dioxide; VOC – volatile organic compound; NO_x – nitrogen oxides; (N_2O) - nitrous oxide, SO_x – sulphur oxides. Data complied based on consultation of various reports by airports.

The impacts of airport operations on the environment have also gained an increasing importance in the European policy [33; 34; 35; 36; 37; 38] agenda and also in academia [39; 40; 41]. The main environmental aspects are noise and gaseous substances. There has been several individual airport studies conducted to assess environmental impacts at selected airports [42; 43; 44]. A more recent research assessed the shortcomings in current decision-making practices for aviation environmental policies by reviewing the knowledge of the noise, air quality, and climate impacts of aviation [45]. In order to have a more precise measurement of the environmental impact of commercial aviation around airports in Europe, it is convenient to measure environmental factors in a scenario of absence of commercial aviation, and compare the data represented by this scenario with those related to a scenario involving regular aircraft and airport operations in Europe. Such comparison has been undertaken by Airports Council International Europe [46] by addressing the scenario with the absence of commercial aviation operations in Europe during the period of volcano eruption in Iceland in 2010. A conclusion of this report is that meteorological conditions like wind speed or nearby larger emission sources have a more significant influence on the measured concentration of pollutants than the number of aircraft movements or calculated emissions. Another important statement from that report is that commercial aviation has a negligible impact on NO_x and PM10 concentrations.

On the other hand, when possible health effects were estimated by another research from aircraft noise annoyance, odour annoyance and hypertension around Amsterdam Airport Schiphol, results demonstrated that far more people outside the area for which environmental standards apply were affected than inside [47].

In fact, the complexity related to environmental impacts of airport operations is significant. Once properly monetized, the local impacts on the environment caused by airport operations can also be internalized in the pricing for airport services, either aggregated to airport taxes or to local government tax on domestic and international flights.

1.1.3 Environmental reporting in the European airline industry

The increasing importance given on the measurement of environmental impacts associated with airport operations became more evident with the development of the *Sustainability Reporting Guidelines & Airport Operators Sector Supplement* by Global Reporting Initiative [48], an international institution that promotes economic sustainability. An analysis on the quality of sustainability reporting by airports was conducted in 2009 and has shown that European airports had the best coverage on environmental aspects of their operations, particularly the international airports in Zurich, in Munich, in Frankfurt and in Amsterdam [21 p. 33]. Among the environmental issues addressed by airports, it has been noted that more importance was given to energy, solid waste reduction and recycling, and to water conservation measures. Climate change was less relevant on their reports, except by Incheon International airport in South Korea.

Several of these impacts are also relevant from the perspective of airlines but international guidelines for sustainability reporting for airlines is currently not available yet. It does not mean, however, that airlines have not been reporting on social and environmental aspects and impacts associated to their operations. Previous research among various airlines worldwide has observed a greater importance on environmental issues on the reports of leading airlines from Asia, Europe and Oceania [22].

Table 7 highlights the main environmental issues usually covered by sustainability reports of airlines and airports based on the same research. In the appendices a comparison of environmental indicators reported by largest European airlines is provided together with some key achievements in reductions in fuel consumption and CO_2 emissions. As it can be noted, the most common indicators reported by largest European airlines are those related to fuel consumption, age of aircraft fleet, CO_2

emissions and NO_x emissions from flight operations. Only Air France-KLM reports on SO_2 emissions. All three airline groups report on CO_2 in terms of passenger-kilometre but only Lufthansa Group reports other emissions in terms of this parameter. These airline groups also report on several indicators for ground operations. British Airways and Iberia (together they form the group IAG mentioned in the appendix) are the only ones reporting on the percentage of waste recycled. Taking in account all indicators, IAG is the European airline group that reports in a more extensive manner.

Table 7 Main Environmental themes covered by sustainability reports in the air transport sector [48].

Sector Theme	Examples of information	TBL dimension	Targeted stakeholder
Air Quality	Clean indoor air quality, monitoring concentrations and measures to reduce emissions of greenhouse gases, ozone-depleting substances and air pollutants.	Environmental	Society and Government
Energy	Description of the management measures taken to ensure conservation of as much energy as possible. Quantitative information on total fuel consumption per traffic unit. Percentage of biofuels used per total jet fuel consumed.	Environmental	Society and Government
Solid Waste Reduction and Recycling	Amounts of in-flight service waste collected by categories. Overview on the disposal methods and major recycling initiatives, among other themes.	Environmental	Society and Government
Noise Abatement	Reduction in the noise levels from aircraft take-off and landing cycles.	Environmental	Society and Government

Table 7 (cont.) Main Environmental themes covered by sustainability reports in the airport sector [48].

Sector Theme	Examples of information	TBL dimension	Targeted stakeholder
Green Initiatives, Buildings and Facilities	Actions taken with the aim of being in general, environmentally friendly (e.g., light-saving mechanisms, recycling activities within offices, "green" purchasing).	Environmental	Society and Employees
Water Conservation and Management	Estimates of volumes of water consumed per year. Description of water conservation initiatives (e.g., treatment of waste water and "storm water").	Environmental	Society and Government
Hydrocarbon spills	Detailed numerical information on hydrocarbon spills (e.g., graphs showing the causes of spills, number of spills in liters per 1,000 movements and number of spills that went into the environment).	Environmental	Society and Government
Environmental Communication	Commitment to engaging in environmental communication with various stakeholders in all applicable and relevant issues about the environment.	Environmental	All
Climate Change	Initiatives to reduce greenhouse gas emissions (estimated CO_2 emissions per passenger on annual basis).	Environmental	Society and Government
Natural Resources Management	Activities carried out to protect habitats, endangered species and the soil.	Environmental	Society and Government

Commercial aircraft operates at cruise altitudes of 8 to 13 km, where they release gases and particulates which alter the atmospheric composition and contribute to climate change [49 p. 136]. Cruise altitude is an altitude or flight level maintained during the part of the flight that occurs between ascent and descent phases and is usually the majority of a journey. This is also the most fuel-efficient phase of the flight. Technological progress has been made in reducing greenhouse gas (GHG) emissions through aircraft fuel efficiency by reducing weight, improving aerodynamics performance and engine design [9]. However, the perceived rapid growth of this sector can turn it into a significant source of greenhouse gas emissions, despite improvements in aircraft fuel efficiency.

In 2010 the air passenger transport industry has shown a good recovery from the downturn observed in the previous two years and resumed its historical trajectory of impressive growth. Global passenger traffic rose by 6.6% in 2010, topping the 5 billion passenger mark for the first time and registering increases in all continents [46 p. 1; 50 p. 1].

According to IPCC [51 p. 30], aviation currently accounts for about 2% of human-generated global carbon dioxide emissions, the most significant greenhouse gas. This 2% estimate includes emissions from all global aviation, including both commercial and military. Global commercial aviation, including cargo, accounted for over 80% of this estimate. The sector also contributes to about 3% of the potential warming effect of global emissions that can affect the earth's climate, including carbon dioxide. Additionally, the report also states that the amount of CO_2 emissions from aviation is expected to grow around 3% or 4% per year. Medium-range forecasts provided by IPCC estimates by 2050 the global aviation industry, including aircraft emissions, will emit about 3% of global carbon dioxide emissions and about 5% of the potential warming effect of all global human-generated emissions. Medium-term mitigation for CO_2 emissions from the aviation sector can potentially come from improved fuel efficiency. However, such improvements are expected to only partially offset the growth of CO_2 aviation emissions.

A complicating factor in developing a mitigation strategy for the sector is the impact of other factors than just CO_2 emissions on climate change. These factors include NO_x compounds, ozone, methane, water, contrails and particles which are emitted from aircraft exhausts at the same time as CO_2.

The 2007 report by IPCC also addressed this concern by reporting that the impact of these emissions from aviation can be about 2 to 4 times greater than those of CO_2 alone [52 p. 328]. The global warming effects of these factors in air travel have been investigated by several researchers in terms of the Radiative Forcing Index (RFI), which is the ratio of the total radiative forcing (RF) of all GHGs to RF from CO_2 emissions alone for aircraft emissions [9 p. 185]. Radiative forcing is defined as the difference between radiant energy received by the Earth and energy radiated back to space. In 1992, the RFI for aircraft was estimated at approximately 2.7 with an uncertainty of at least ±1.5 [53].

More recent estimations have updated the RFI figure to a value of 1.9, which has been considered the best estimate of RFI of aviation, excluding the probable but unproven effects of cirrus clouds [54].

Radiative forcing for aviation represents the radiative forcing at a given time due to all prior and current aviation activity (accumulated CO_2 emissions, plus present day, short-lived impacts like contrails). Therefore, the estimation of radiative forcing from aviation is subject to misleading results when a comparison is undertaken of the relative contribution from short lived and long-lived effects.

The IPCC projected in its "base" scenario that carbon emissions from aviation, even assuming fuel efficiency gains, would rise from 489.29 million tonnes in 2002 to 1,247.02 million tonnes in 2030, an increase in emissions of over 2.5 times [52 p. 43].

Despite this rapid growth in the contribution of aviation sector to climate change greenhouse gas emissions from aviation are currently excluded from any restrictions under the Kyoto Protocol. Increasing pressures, however, have been perceived on the political agenda, starting with domestic or regional emission targets for the aviation sector.

An extensive research conducted in 2009 [22] across fifty largest airlines worldwide has shown that few of them had developed a climate change policy and did not report on indicators related to initiatives to mitigate climate change.

1.1.4.1 The current state of European airlines

In the European Union a directive for the inclusion of the aviation sector into the EU ETS was published in January 2009 [55]. The EU ETS aims at including the GHG emissions of intra-community flights as well as planes departing or landing in the European Union as of 2012. This applies to all airlines, irrespective of nationality, which will then be allowed to sell pollution credits on the EU carbon market or buy credits if their emissions increase.

The European Commission believes that market-based instruments like EU ETS and emissions charges are considered more promising ways to address the climate impact of aviation. However, it has faced a strong rejection by European and non-European airlines due to expected significant increases in costs with the acquisition of carbon credits to meet their annual emission allowances. Airlines argue that only a market-based mechanism based on a global cap-and-trade system might work properly but it will be necessary to negotiate it and identify the right baseline year(s) for the calculation of allowances to be distributed. After several claims by non-European airlines and governments against the EU ETS, the mechanism came into effect in 2012 only for intra-community flights until a global scheme can be negotiated under the auspices of the International Civil Aviation Organization (ICAO). Section 1.4.2 explains the main operational features and targets of EU ETS.

In the past few years, airlines have been investing in new satellite-based Air Traffic Management (ATM) which has been proving to be more efficient by providing continuous descent arrivals and consequently, significant reductions in CO_2 emissions per flight. In Europe, these initiatives are being extended to optimized air traffic with the "Single European Sky" as discussed in section 1.1.5. For airlines, the reduction of fuel consumption and consequently, CO_2 emissions is a major target, especially in recent years with the surge in oil prices. In summary, the initiatives taken by airlines to address this important issue are concentrated in:

- Optimizing fuel consumption (by minimizing on-board mass, maximizing efficient use of the cruising speed and improving engine maintenance procedures).
- Replacing planes in existing fleets with more recent, fuel-efficient models.

Additional initiatives are being discussed with airport service management in order to ensure optimized air traffic, more airport runways (fewer approach manoeuvres) and shorter taxiways.

Apart from these initiatives, some European airlines have also provided opportunities for their passengers to offset their air emissions, mostly measured in terms of $CO_{2,}$ by contributing on voluntary basis with a certain donation to a project certified by the United Nations related to renewable energy, energy efficiency or carbon dioxide sequestration. Once certified, these projects can result in the issuance of carbon credits that can be surrendered by polluters to comply with climate change mitigation commitments. These initiatives, however, are quite arguable since passengers do not know exactly the level of precision in the calculation of their emissions and the uncertainty related to the amount of CO_2 sequestered or avoided from those projects being supported by airlines.

Table 8 presents differentiated performance levels among largest European airlines in terms of carbon emissions per passenger-kilometre (herein defined in "g CO_2/pax-km"). The abbreviation "pax" is conventionally used by airlines to refer to passengers.

The numbers provided show that after British Airways have merged with Iberia in 2011 to form the International Consolidated Airlines Group (IAG), their level of carbon emissions per passenger-kilometre has slightly reduced in a continuous manner. Other two airline groups have also achieved continuous reductions in their carbon emissions being Air France-KLM the airline group with the best results. All number are publicly reported in their reports. In the appendices, two graphs illustrate the variations in the amount of passengers carried and carbon emissions released per passenger-kilometre per year as presented in table 8. Another way to show how efficiently resources have been allocated by these largest European airlines within the context of climate change is to measure the Gross Value Added (GVA) generated per each tonne of carbon emissions released on annual basis. The GVA of each airline group is obtained from Earnings before interest, taxes, depreciation and amortization (EBITDA), added by amortization, depreciation and personal expenses.

Table 8 Development perceived in amount of passengers carried and carbon emission reductions among the largest European airlines.

	British Airways / IAG		Lufthansa		Air France-KLM	
Year	**Passenger carried**	**CO_2 emissions g / pax-km**	**Passenger carried**	**CO_2 emissions g / pax-km**	**Passenger carried**	**CO_2 emissions g / pax-km**
2008	34,613,000	107	70,459,927	109	73,819,200	96
2009	33,117,000	106	76,113,819	108	74,500,000	95
2010	31,825,000	103	88,470,605	106	70,715,000	93
2011	51,687,000	102	98,122,199	105	76,053,000	92
2012	54,600,000	101	103,051,000	N/A	77,448,000	N/A

*Note: Data compiled based on information provided by annual reports of airlines, by "Corporate Responsibility Report of British Airways 2011-2012", by "Air France-KLM CSR Report 2011-2012", and by "Lufthansa Balance Sustainability report 2012".

Figure 1 demonstrates the variation of GVA generated per each tonne of CO_2 emitted by each airline group. Data was compiled from publicly available financial results released on annual financial reports and emissions reported in their annual reports related to CSR or sustainability.

The chart shows that the highest result was obtained by Lufthansa in 2010 when they have registered a significant increase in GVA accompanied by a slight increase in carbon emissions. Except by that year, Air France-KLM has achieved the best result in this indicator since 2008. It is also noticeable a lower average result among these European airline groups obtained in 2011.

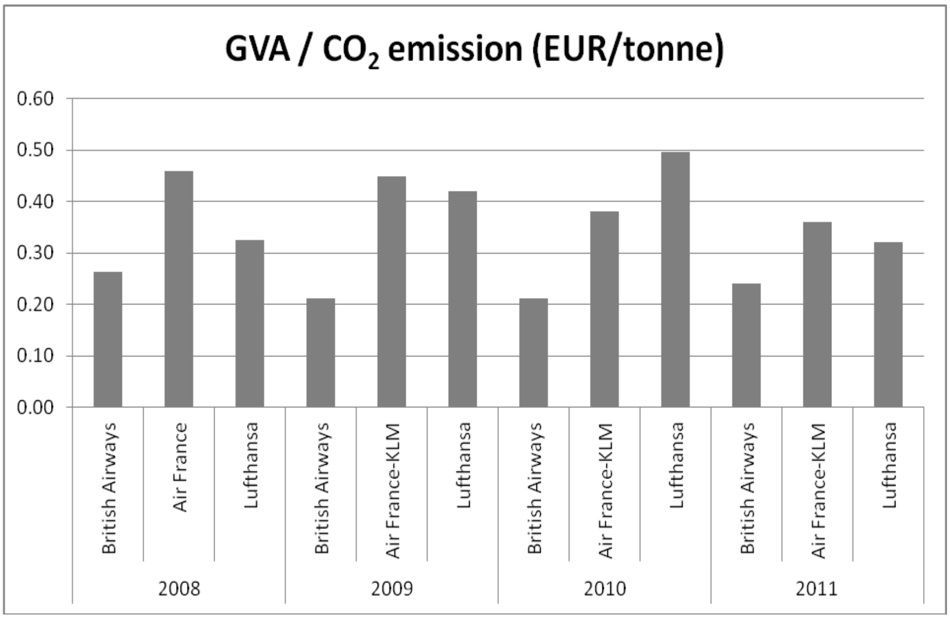


Figure 1 The performance of largest European airlines in terms of value created per tonne of carbon emissions released on annual basis.

*Note: Compiled from data available in annual financial reports and in annual corporate social responsibility/sustainability reports of airlines.

1.1.4.2 The European Union Emissions Trading System

As previously mentioned the original proposal was to include in the EU ETS all intra-community flights as well as planes departing or landing in the European Union as of 2012. Such regulation would require major carbon emission reductions of all airlines flying over European Union, irrespective of nationality. However, after several claims by non-European airlines and governments, the scheme went into force in 2012 including only intra-community flights until a global scheme can be negotiated under the auspices of the International Civil Aviation Organization (ICAO).

Just like in the implementation of EU ETS for industrial installations, airline operators also receives free allowances (herein named “EU Aviation Allowances – EUAAs”) to cover most of their carbon emissions in each year of compliance. After each year airlines must surrender a number of allowances equal to their actual emissions in that year. If their actual emissions will be lower than their allowances, they can sell their surplus allowances on the market or else "bank" them to cover future emissions. If they anticipate that their emissions will exceed their allowances, they can either take measures to reduce their emissions - for instance by investing in more efficient technologies or operational practices - or they can buy additional emission allowances on the market, whichever is cheaper. Thus, airlines may be able to buy allowances from industrial installations that have reduced their emissions (herein named “EU Allowances – EUAs”). In addition, to help meet their obligations under the EU ETS, airlines can also buy emission credits from clean energy projects carried out in third countries under the Kyoto Protocol mechanisms (herein named "Certified Emission Reductions – CERs or Emission Reduction Units – ERUs").

Figure 2 presents the total quantity of allowances allocated to the aviation sector, the baseline years, and the the benchmark for free allocation of emission allowances.

According to the regulations of EU ETS in 2012 the corresponding amount of 85% of emission allowances were given for free to airlines and 15% of the allowances were allocated by auctioning. The remaining 3% was allocated to a special reserve for later distribution to fast growing airlines and new entrants into the market. The free allowances were allocated by a benchmarking process which measures the activity of each airline in 2010 in terms of the number of passengers and freight that they carry and the total distance travelled [56].

Based on data reported by airlines from 2010 and on the explanations of the requirements prescribed by EU ETS for the European aviation sector as shown in figure 2, author presents in table 9 the estimated amount of carbon emission allowances to be allocated among each of the largest European airlines included in this research.

Main requirements of European airlines in the EU ETS

The cap
Sizes the total quantity of allowances allocated to the aviation sector.
- 97% (2012)
- 95% (2013-2020) of the baseline

The baseline
- Is the average of the annual aviation emission for the years 2004, 2005 and 2006.
- Baseline was published by the EC in March 2011 and is approx. 221 million tonnes of CO_2.

The benchmark
Is used to allocate the free of charge allowances to the operators.
Is calculated by dividing the total cap by the sum of tonne-km data provided by the operators in 2010.
The benchmark is set at
- 0.6797 allowances/1000 tonne-km (2012)
- 0.6422 allowances/1000 tonne-km (2013-2020)

Free allocation
Operators had to report their tonne-km date for 2010 to get free allocation.
Amount of allowances for a certain operator is calculated by multiplying the benchmark with the 2010 tonne-km data of the operator.
The operators will receive
- 85% of the calculated allowances in 2012 and
- 83% in 2013-2020

Offset use
Airline operators can use
- 15% of their emissions (2012)
- at least 1.5% of their verified emissions (2013-2020)

Main goal of airlines within the EU ETS:
Reduce their overall emissions while increasing their amount of passengers performed.
This study suggests to transport more passengers in more fuel-efficient aircrafts in terms of Kg of fuel per passenger-km.

Figure 2 Main requirements of European airlines in the EU ETS [57].

Table 9 Estimations of carbon emission allowances to be allocated in each year among the largest European airlines until 2020.

Indicator	Year	Air France	Lufthansa	British Airways
Passenger carried	2010	70,750,000	98,122,199	31,825,000
RPK (Revenue Passenger Kilometres)	2010	203,114,000,000	202,656,000,000	106,082,000,000
AVG kilometres performed per passenger	2010	2,870.87	2,065.34	3,333.29
RTK (Revenue Tonne Kilometres)	2010	20,311,400,000	28,245,000,000	15,588,000,000
Amount of allowances allocated (in tonnes of CO_{2e})	2012	13,805,658.58	19,198,126.50	10,595,163.60
	2013-20	13,043,981.08	18,138,939.00	10,010,613.60
Free allowances allocated (in tonnes of CO_{2e})	2012	11,734,809.79	16,318,407.53	9,005,889.06
	2013-20	10,826,504.30	15,055,319.37	8,308,809.29
CO_2 Emissions (tonnes of CO_2)	2011	28,193,000.00	28,424,568.00	17,100,000.00

*Note: Calculations based on data provided on annual reports released by airlines.

Scheelhaase, Grimme, and Schaefer [58] have investigated the impacts of the inclusion of aviation sector into the EU ETS and their analysis showed that that network carriers based outside the EU and with a moderate growth of emissions between 2006 and 2012 will most likely gain a significant competitive advantage compared to EU network carriers. This prognosis is applicable when comparing the EU network carriers competing with non-EU network carriers on markets for long-haul air services. Long-haul flights are journeys typically made by wide-body aircraft that involve long distances, typically beyond six and a half hours in length, and often are non-stop flights. The disadvantage of EU network carriers relies mainly on the fact that not only all long-haul flights arriving at and departing from airports in the EU will be included into the EU ETS, but also all short-haul flights, which are less eco-efficient than long-haul flights when calculations are performed on the basis of emissions per Revenue Tonne-kilometre (RTK) or Revenue passenger kilometres (RPK). RTK is the utilized (sold) capacity for passengers and cargo expressed in metric tonnes, multiplied by the distance flown. RPK is a measure of the volume of passengers carried by an airline. A passenger for whose transportation an air carrier receives commercial remuneration is called a revenue passenger.

All feeder services from short-haul flights needed to achieve and surpass the break-even seat load factor on the long-haul flights of EU network carriers are subject to the EU ETS. On the other hand, non-EU network carriers operate its own feeder network outside the EU and therefore this part of their operations is not included in the EU ETS.

It can be noted that, although Air France and Lufthansa had similar levels of carbon emissions in 2011, Air France will receive lower amount of emission allowances due to their lower level of tonne-km performed.

1.1.5 Fuel-efficiency opportunities in the European airline industry

The aviation sector—aircraft manufacturers and airlines—has made significant efforts to improve the fuel efficiency through more advanced jet engines, high-lift wing designs, and lighter airframe materials. However, these improvements were more significant in the 1960s and have slowed down since the 1970s due to the slower pace of technological advancement in engine and aerodynamic designs and airframe materials. Four main reasons have contributed to this fact, such as [59 p. 3792]:

- The long lead-time in product development and fleet turnover.
- The high costs associated with radical technological breakthroughs.
- The passengers' willingness to pay higher fares as a result of increased income and the convenience of air travel.
- The scientific knowledge and public awareness about the impacts of aviation emissions.

Lee *et al.* [60] suggest that 57% of the reductions in energy intensity during the period 1959–1995 were due to improvements in engine efficiency, 22% resulted from increases in aerodynamic efficiency, 17% were due to more efficient use of aircraft capacity, and 4% resulted from other changes, such as increased aircraft size. Meaningful reduction in environmental impact can be achieved through biofuels and offset mechanisms in the near future since technological breakthrough will take a long time for development and diffusion, mainly due to cost of development and passenger's actual willingness to pay more for the environment. Anyway, due the rising price of jet fuel, all of the major suppliers in the aviation sector are exploring technological and operational options to improve aircraft performance and to limit the rapid growth in aviation GHG emissions expected in a business-as-usual future. These include improved navigation systems in the near to medium term and advanced propulsion systems, lightweight materials, improved aerodynamics, new airframe designs, and alternative fuels over the medium to long term. Combining the various abatement options, there is a potential to cut annual GHG emissions from global aviation by more than 50% below business as usual (BAU) projections in 2050 [61 p. 14].

Even though operational and technical options are available for airlines, their associated abatement opportunities may be overwhelmed if the predicted growth in airline travel becomes concrete, particularly in Asia [62 p. 1]. Considering all suggested possibilities by IATA in comparison to a business-as-usual projection out of the year 2025, fleet renewal can provide the largest carbon emissions abatement [63].

The Intergovernmental Panel on Climate Change (IPCC) estimated in 1999 that there was 12% fuel inefficiency in air transport infrastructure [9]. Since then a 4% improvement in efficiency has been achieved as reported by IATA but there is still a pathway for significant improvements. Full implementation of more efficient ATM and airport infrastructure could provide an additional 4% in fuel consumption and consequently, in carbon emissions reduction by 2020. These measures include among others the implementation of the Single European Sky (SESAR) which would produce a 70% cut in route extension [64 p. 2]. Airspace improvements based on Performance-Based Navigation (PBN) and Continuous Descent Arrival (CDA) rather than the traditional stepped approach to landing can save up to 630 kg of CO_2 per landing. Initiatives in this sense have been implemented between 100 airports in Europe which together expect to contribute to an avoidance of 500,000 tonnes of CO_2 by the end of 2013 [63 p. 5].

The Single European Sky is a European Commission initiative by which the design, management and regulation of airspace is planned to be coordinated throughout the European Union to ensure an efficient air traffic management system. Airspace management is planned to move away from the previous domination by national boundaries to the use of 'functional airspace blocks' the boundaries of which will be designed to maximize the efficiency of the airspace. Within the airspace, air traffic management, while continuing to have safety as its primary objective, will also be driven by the requirements of the airspace user and the need to provide for increasing air traffic. The aim is to use ATM that is more closely based on desired flight patterns leading to greater safety, efficiency and capacity [65].

The first Single European Sky legislative package was adopted in 2004 in order to provide the framework for the creation of additional capacity and for improved efficiency and interoperability of air transport management systems in Europe [66]. A second SES package has been put forward by the European Commission in order to make the European sky safer and more sustainable by [67]:

- Introducing a performance framework for European ATM with quantified target setting;
- Creating a single safety framework to enable harmonized development of safety regulations and their effective implementation;
- Opening the door to new technologies enabling the implementation of new operational concept and increasing safety levels by a factor of ten;
- Improving management of airport capacity.

Some researchers have included the results of a several studies analyzing airline costs and emission reductions that are possible from different mitigation options into a systems model of European aviation [68; 69]. A set of nine scenarios was created (three internally consistent projections for future population, gross domestic product, oil and carbon prices, each run with three policy cases), a technology uptake and the resulting effect on fuel life cycle CO_2 emissions with and without an ETS were analyzed. While improved ATM are expected to be quickly taken as an option under all scenarios, others may be taken up more slowly by specific aircraft classes depending on the scenario (e.g., biofuels).

In the global regulatory arena, after being criticized by European Parliament, ICAO has recommended in 2009 a 2% annual improvement in fuel efficiency from civil aviation through 2012 until 2020 but only as a voluntary measure [70]. More recently, ICAO has announced that it would accelerate its efforts to develop a market-based emissions policy for the global aviation sector with the goal of having the scheme finalised by the end of 2012. Also in response to growing external pressure, the International Air Transport Association (IATA) has made public its vision for addressing climate change through improved technology, effective operations, efficient infrastructure and positive economic measures.

In 2009, IATA launched a more detailed strategy to reduce carbon emissions through the following three targets [64 p. 2]:

- A cap on aviation CO_2 emissions from 2020 (carbon neutral growth).
- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020.
- A reduction in CO_2 emissions of 50% by 2050, relative to 2005 level.

Nevertheless, difficulties found on bringing biojet production costs down significantly may complicate the achievement of carbon reduction targets proposed by IATA as well as the target of replacing 6% of global kerosene use with biojet by 2020. Another concern that has been shown relates to the competition between food and energy crops as the main purpose of using large areas of land and associated resources to be deployed, such as water, labour force, pesticides, fertilizers and infrastructure [63 p. 4].

When considering opportunities for reducing fuel consumption per passenger-kilometre, it is important to look at the passenger load factor for different categories of flights (short, medium and long-haul flights). The passenger load factor (PLF) of an airline, sometimes simply called the load factor, is a measure of how much of an airline's passenger carrying capacity is used. It is passenger-kilometres flown as a percentage of seat-kilometres available.

The growth rate in passenger traffic for European airlines was 5.3% in 2012, sharply down on the 9.5% observed in 2011. The capacity measured in terms of passenger load factor increased by 3.1% pushing the full-year average load factor to 80.5%. Growth was generated by the long-haul performance of Eurozone airlines. Air passenger traffic stagnated within the EU due to slow economic growth [71]. Considering only intra-Europe flights, European airlines registered an average passenger load factor of 75% in 2011 [72]. Therefore, for short-haul and medium-haul flights there is still opportunity to improve in eco-efficiency also by increasing passenger load factor. The slow economic growth in Europe and the high competition imposed by low-cost airlines and other means of transport have contributed to a lower passenger load factor than the global average.

In fact, commercial aviation across Europe is one of the most burdened in terms of fuel surcharges, airport and security fees, and government taxes. Apart from government fees for domestic flights, some countries also charge taxes for international flights that vary significantly depending on the country where they will be departing from and arriving (e.g. UK, France, Germany, Austria and Ireland). The government fees per air passenger in the UK are the highest in Europe and are called “air passenger duty” (APD). The values of the air passenger duties in the UK take in account mainly the flight distance and the flight class. Therefore, the air passenger duty on long distance flights become significantly more expensive than for short distance flights, even though it is well know that long-haul flights are much more eco-efficient than short-haul flights. Similar flaws are noted in the pricing criteria of taxes imposed by other European governments, although with a lower impact on air passenger traffic. From an environmental perspective these taxes take no account of the efficiency of the aircraft. An airline using an old inefficient plane is treated equally to one using the latest most efficient engines [73 p. 96]. Therefore, specific reforms aimed at a more accurate tax system on international flights based on eco-efficiency are necessary together with other alternatives that can be implemented solely by airlines or in combination with European airports.

Some of these alternatives may include the award of bonus miles or the application of discounted fuel surcharges to passengers opting for more eco-efficient flights whenever it will be possible for the airlines to use more fuel-efficient aircraft for the same flight route. Airlines that provide different aircraft types for the same flight route on a daily basis could motivate potential passengers to choose the most eco-efficient flights by providing these discounts in fuel surcharge or bonus miles. Apart from these initiatives that would be under their own responsibilities, airlines could also jointly claim to the governments that are currently applying taxes on domestic and international flights a proportional reduction in the levels of these taxes based on their annual improvements verified in terms of eco-efficiency.

Rather than further burdening the aviation industry, it would be better to alleviate these taxes, charges and fees by rewarding those airlines that demonstrate improvements in energy efficiency and emission reductions across its supply chain, while respecting the physical limits for takeoffs and landings at each airport (efficiency criteria for takeoffs and landings at major airports could be enforced) and more stringent conditions for the construction of new airports and new runways. It is time to deliver instruments that contribute to influence the demand of air passengers by enhancing their awareness related to their contribution of climate change and by motivating them to choose the most eco-efficient flights. For a more effective result in this sense, a more accurate and fair pricing system of air fares, fuel surcharges, airport fees and government taxes may become necessary.

1.2 METHODS FOR CALCULATION OF FUEL CONSUMPTION AND EMISSIONS FROM AIRCRAFT

An increasing worldwide interest in the causes and consequences of climate change has been observed since the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, the first global effort to feed scientific insights on climate change to governments. From its establishment until today IPCC has published four comprehensive assessment reports with a review on the latest knowledge on climate change science and has issued various special reports on particular topics. This intergovernmental scientific body has played an important role in the formation of the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty with the goal of estabilizing GHG concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. The efforts put forth by UNFCCC in turn led to the Kyoto Protocol [74], an international agreement to cut GHG emissions, with specific reduction targets by country, signed in December 1997 and entered into force in 2005.

For different reasons various private and public organizations as well as non-governmental organizations and individuals have decided to measure and monitor the size of their contributions to climate change in terms of GHG emissions [75], which has been widely defined by carbon footprint. Nothwithstanding it was rooted by ecological footprint, a previous term coined by Wackernagel [76], there has been a lack of a common and clear academic definition for carbon footprint. In fact, the concept has been initially defined mainly by private organizations and businesses [77; 78]; and later adopted by academia. Consequently, the term became popular and has been largely used and promoted by the communication department of organizations and by the media by means of different estimation approaches of GHG emissions. In fact, many business have been using carbon footprint as a marketing tool rather than as a tool to measure their contribution to climate change [75 p. 2].

The different definitions of carbon footprint perceived by organizations and individuals have led to various methods of calculation and response formulations, ranging from basic online calculators of CO_2 emissions to sophisticated full LCA [79] performed with the support of computational tools as described in chapter 1.3 [80].

Basically, carbon footprint can be defined as the amount of greenhouse gases released per year by an item manufactured, consumed and disposed of or by an activity performed by an organization or individual, measured typically in units of carbon dioxide equivalent per year [81; 82; 83]. The Global Footpring Network, an organization that compiles "National Footprint Accounts" on annual basis [84] sees the carbon footprint as a part of the Ecological Footprint.

Every methodology defined so far for calculating GHG emissions (also defined simply by "carbon emissions") is based on certain assumptions and involves some degree of approximation and subjective decisions about boundaries of responsibility for emissions and the actors they should be assigned to. In order to be useful for identifying possible ways to mitigate impacts of a product or activity on climate change, a calculator methodology has to be simple to use, but based on high quality input data and sound modelling, while sophisticated enough to make every change in the system analyzed noticeable in terms of calculated carbon footprint [85].

In this chapter, author reviews the methodology of most commonly used GHG emissions calculators. It can be noticed that discrepancies remain between calculators concerning the quality of the data sources, the assumptions made, the allocation of emissions and the use of multipliers. Nevertheless, the same methodology is adopted in each step of the practical part of this research for all airlines analyzed. This tend to provide more consistency in the results obtained and deliver more plausible insights in terms of eco-efficiency opportunities facing climate change. Commonly, emissions are calculated indirectly based on a known quantity such as fuel burned, or units of electricity consumed. In the case of analysis of aircraft contribution to climate change, fuel consumption during flight operations is the most important parameter to consider since fuel combustion is a stoichiometric chemical reaction and CO_2 emissions can be directly related to that (e.g. 3.157 Kg CO_2/kg of jet kerosene). Emissions resulting from the use of electricity are more complex to calculate as they depend on the mix of generating plant in the host country. Although fuel consumption per flight is not regularly monitored, it can be estimated based on certain assumptions and parameters.

1.2.1 The three methodological tiers of IPCC for estimating emissions from flights

The chapter 3 of 2006 IPCC Guidelines for National Greenhouse Gas Inventories proposes three methodological tiers for estimating GHG emissions from all civil commercial use of airplanes, particularly emissions of CO_2, CH_4 and N_2O. In general, 90% of aircraft emissions occur at higher altitudes and only about 10% of aircraft emissions, except hydrocarbons and CO, are produced during airport ground level operations and during the LTO. For hydrocarbons and CO, the situation is slightly different being 30% released during the LTO and 70% released at higher altitudes [23].

All tiers distinguish between domestic and international flights, although Tier 2 and 3 provide more accurate methodologies to make these distinctions. Tier 1 is solely based on jet fuel consumption, while Tier 2 is based on fuel use and on the number of LTO cycles. Tier 3, on the other hand, takes into account the movement data of individual flights and offers two variants:

- Tier 3A measures fuel use based in the origin and destination by aircraft type
- Tier 3B measures fuel consumption in a more sophisticated manner by considering full flight movements and engine data of each aircraft analyzed.

The choice of methodology depends on the type of fuel used, the availability of data and on the relative importance of aircraft emissions.

Tier 1 provides a rough estimation of aggregate emissions for each GHG considered without discriminating the fuel consumption between LTO cycle and cruise stage. The emission factors (EF) used are the same no matter the flight mode or phase. This simple method as highlighted by equation 1.1 can be applied only for domestic flights operated by small aircraft with aviation gasoline. For these cases, operational use data is typically not available.

$$\text{Emissions} = \text{fuel consumption} * \text{Emission factor} \qquad (1.1)$$

Tier 2 method is only applicable for jet fuel use in jet aircraft engines. Operations of aircraft are divided into LTO (under 914 m) and cruise (above 914 m) phases. In this case, the number of LTO operations per aircraft type is a relevant data for calculations of emissions both in domestic and in international flights.The following steps are taken for calculation emissions according to Tier 2 method:

$$\text{Total emissions} = \text{LTO Emissions} + \text{Cruise Emissions} \qquad (1.2)$$

where:

$$\text{LTO Emissions} = \text{Number of LTOs} * \text{Emission Factor LTO} \qquad (1.3)$$

LTO Fuel Consumption = Number of LTOs * Fuel Cons. per LTO (1.4)

Cruise Emissions = (Total Fuel Cons. - LTO Fuel Cons.) * EF at Cruise (1.5)

In Tier 2 method, the fuel consumed in the cruise phase is estimated as the difference between total fuel use and the fuel used in the LTO phase of the flight. The estimated fuel use for cruise is multiplied by aggregate emission factors (average or per aircraft type) in order to estimate CO_2 and NO_x cruise emissions. On the other hand, emissions and fuel used in the LTO phase are estimated from statistics related to the number of LTOs (aggregate or per aircraft type) and default emission factors or fuel use factors per LTO cycle (average or per aircraft type).

Tier 3A method is based on flight distances and on aircraft type. Average fuel consumption and emissions data for the LTO phase and various cruise phase lengths are considered for an array of representative aircraft categories. It can be realized through this method that aircraft use a higher amount of fuel per distance for the LTO cycle compared to the cruise phase. Therefore, fuel burn is comparably higher on relatively short distances than on longer routes.

The EMEP/CORINAIR Emission inventory guidebook [86] which is annually updated by the European Environment Agency provides tables with emissions per flight distance.

Tier 3B method is used to estimate fuel consumption and emissions throughout the full trajectory of each flight segment by means of specific aircraft and engine-related aerodynamic performance information. Sophisticated computer models can be used in this method for estimating output for fuel burn and emissions in terms of aircraft, engine, airport, region, and global totals, as well as by latitude, longitude, altitude and time [87]. Therefore, this method aims to calculate aircraft emissions from input data that is influenced by air-traffic changes, aircraft equipment changes, or any changes in the conditions of scenario proposed. Tier 3B models are used, e.g. in the System for Assessing Aviation's Global Emissions (SAGE), by the United States Federal Aviation Administration [88]and [89]; as in AERO2k [90] by the European Commission.

Figure 3 illustrates a decision tree proposed by IPCC that helps in the selection of the appropriate method. Table 10 summarizes the data requirements for the different tiers proposed by IPCC.

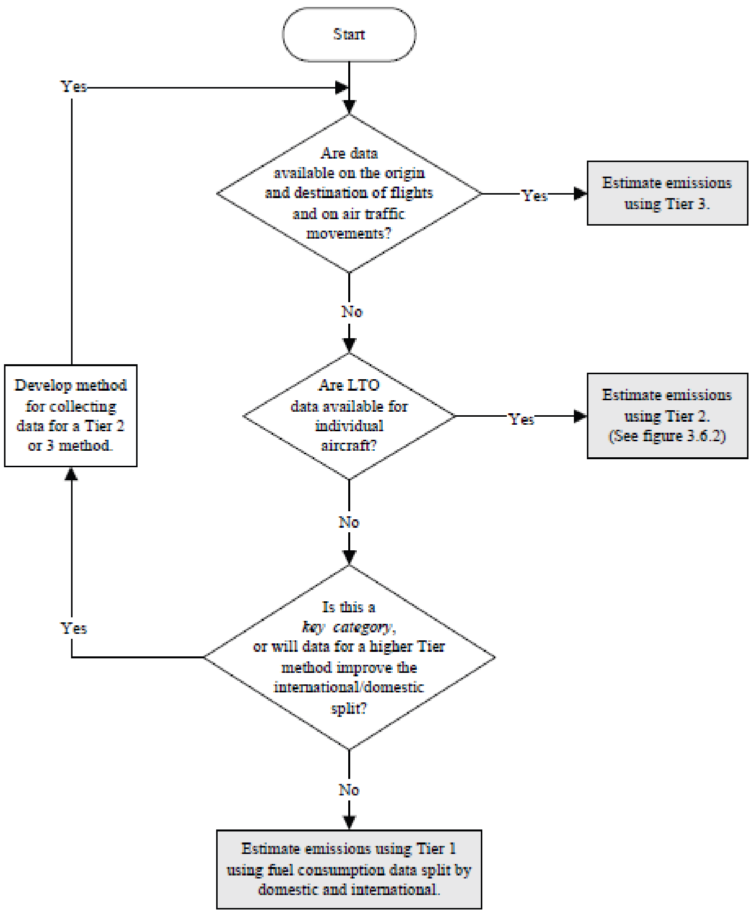


Figure 3 Decision tree for estimating aircraft GHG emissions .

Table 10 Data requirements for each methodological tier proposed by IPCC [7].

Data, both domestic and international	Tier 1	Tier 2	Tier 3A	Tier 3B
Aviation gasoline consumption	x			
Jet fuel consumption	x	x		
Total LTO				
LTO by aircraft type		x		
Origin and Destination (OD) by aircraft type			x	
Full flight movements with aircraft and engine data				x

1.2.2 The method of DEFRA

In the United Kingdom the responsible body for the CO_2 emissions reporting is the Department for Environment, Food and Rural Affairs (DEFRA). Being so it has also developed its own methodology, which was later adopted by various international organizations. Their methodology uses different CO_2 emissions factors for domestic, short-haul international and long haul international flights due to the different share of aircraft types used for each of these categories of flight, which in turn incurs in more significant differences in terms of average fuel burn data, freight load, passenger load factor (PLF), and seating configuration. Actually, emissions are allocated between economy, premium, business and first class on the basis of space allocation. There is no widely accepted definition of the terms "domestic", "short-haul" and "long-haul", though DEFRA/DECC [91] assumes the following typical one way flight distances:

- domestic = flight distance no greater than 463 km
- short-haul international = flight distance between 463 km and 1108 km
- long-haul international = flight distance greater than 1108 km

Additionally, UK Defra’s guidance considers other relevant parameters for estimating CO_2 emissions, such as:

- Freight load – less than 1.0% for domestic and short-haul flights, and 28.8% for long-haul.
- Passenger load factor - 66.3% for domestic flight, 81.2% for short-haul flight, and 78.1% for long-haul flight.

The DEFRA methodology considers carbon emissions factors as follows:

- 0.165 Kg CO_2/km for domestic flights
- 0.943 Kg CO_2/km for short-haul flights
- 0.1079 Kg CO_2/km for long-haul flights

The emission factors provided in the 2012 GHG Conversion Factors Annex 6 and Annex 7 refer to aviation's direct CO_2, CH_4 and N_2O emissions only. There is currently uncertainty over the other non-CO_2 climate change effects of aviation (including water vapour, contrails, NO_X etc) and over the potential trade-offs between warming and cooling effects of different emissions. However, a multiplier factor of 1.9 has been recommended as a central estimate, based on the best available scientific evidences [92].

1.2.3 The method of ICAO

The International Civil Aviation organization (ICAO) is an agency of United Nations responsible for setting standards and recommending principles and best practices concerning all aspects of international civil aviation including air navigation, to ensure safe and orderly growth as well as air accident investigation.

The ICAO Carbon Emission Calculator [93] employs a distance-based approach to estimate the emissions per kilometre for every economy class passenger (measured in terms of Kg/Y pax.km) using data currently available on a range of aircraft types. In order to implement this methodology, ICAO uses the best publicly available data regarding fuel consumption and continuously monitor and seek improvements and updates in the data used, in order to obtain better emissions estimation. The method requires few input information related to the flight concerned, such as aircraft type, flight distance, and the total number of economy equivalent seats. Additionally, it adopts industry averages for the other important parameters like PLF and passenger to freight factor (PFF).

The calculations of CO_2 emissions per economy equivalent passenger-kilometre can be performed as follows:

$$CO_2 \text{ per pax.km} = 3.157 * (TF * PFF)/(\text{Y-seats} * PLF * \text{flight distance}) \quad (1.6)$$

Where

3.157 *is a multiplying emission factor as recommended by the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.*

TF *is "total fuel" consumed for the flight distance performed. It represents the average amount of fuel consumed by all aircraft of equivalent type for each flight distance considered measured in nautical miles (nm).*

PFF *is "passenger-to-freight factor" which is the ratio calculated from ICAO statistical database based on the number of passengers and the tonnage of mail and freight, transported in a given route group.*

Y-seats *mean "number of y-seats" and represent the total number of economy equivalent seats available in the aircraft type considered. This value represents the maximum seat capacity the aircraft type considered can have if all seats available were configured for economy class (high density seat configuration).*

PLF *is "passenger load factor" which is the ratio calculated from ICAO statistical database based on number of passengers transported and the number of seats available in a given route group.*

Flight distance *corresponds to the great circle distance (GCD) which is the distance between origin and destination airports and is derived from latitude and longitude coordinates originally obtained from ICAO Location Indicators database.*

The fuel burn to flight distance relationship is interpolated from the CORINAIR table [94], while PLF and PFF correspond to traffic data per route group updated by ICAO and economy class (Y) seat capacity is given by aircraft manufacturer.

Although some of these factors cannot be captured on a flight-specific basis, this methodology considers them at least on average values to show the public and the aviation industry how they affect an individual passengers' emission intensity. The method recommends airlines to provide more robust data to the fuel consumed on their operated flights, to their cargo factor, to their PLF as well as to aircraft configuration.

1.2.4 The method of ClimateCare

Climate Care is an independent 'profit for purpose' organization committed to tackling climate change, poverty and development issues. They run some of the world's largest corporate carbon offsetting programmes. In addition, they originate and source compliance and voluntary carbon credits on behalf of large corporations, NGOs, and nation states. Although emissions can be allocated per passenger, based on average flight occupancy data, it is Climate Care's policy that passengers should not be charged more to offset the emissions from their flight, just because there are empty seats on the plane. Therefore, emissions are allocated by their method on a per seat basis, as if the plane is full.

Their method [25 p. 12] takes the following assumptions in order to account only the emissions for which the passenger is directly responsible:

- The commercial freight load of the plane is ignored. Commercial freight loads are estimated to be 20% of the total weight of the plane, so only 80% of emissions are attributed to the passengers.
- Emissions are allocated per seat. The number of seats on standard models of aeroplanes is readily available.

The model gives a series of curves of carbon dioxide emissions per seat as a function of distance travelled. Departure and destination airports are selected from a database, which returns the longitude and latitude of the respective locations. The length of flight is then calculated using trigonometry, and the corresponding emissions determined from the appropriate curve. In order to be consistent with other policty measures such as the Kyoto Protocol and the emissions trading schemes, this method also takes in account the radiative forcing index (RFI) of 1.9 as the multiplier factor to reflect the whole contribution of aircraft operations to climate change.

1.2.5 The method of Sabre Holdings

Another method for estimating the carbon emissions of commercial aircraft was developed by Sabre Holdings, a global technology company. This method rely on a computer reservations system (GDS) that consists in a database with a wide range of information about all flights. Information includes the date of travel, the airline that operated the flight, the departure and destination airport, the aircraft type, and the seating configuration.

More detailed and accurate estimations of CO_2 emissions can be achieved with this method due to two high quality and detailed data source: the SAGE model and the Passenger Name Record.

The SAGE model was developed by the US Federal Aviation Administration's Office of Environment and Energy. Unlike other databases, it provides modelled fuel consumption for a large number of aircraft types, which in turn minimizes the innacuracies perceived when adopting an "equivalent" aircraft type that in fact has different technical characteristics.

The SAGE model allows the analysis of various scenarios developed in a regional, national, airport or individual flight levels. Such scenarios can refer to different policy measures, technological development, aircraft fleet, and operational characteristics of aircraft currently used.

The passenger name record (PNR) consists in a database of individual flights used for booking flights for passengers. It provides additional detailed data about each individual flight, including the seating configuration. PRN also provides provides the departure point and destination, which allows the calculation of great circle distance based on known latittude and longitude coordinates. SAGE model takes in account the variations in fuel consumption resulting from deviations in great circle route.

Each aircraft type has a specific fuel burn formula as a function of distance and the result can also be given per seat by considering seating configuration of each aircraft. The emission multiplying factor used by SABRE model is the same applicable by other methods, i.e. 3.157 kg CO_2/kg Fuel.

Figure 4 presents the key features and main differences between these carbon emission calculators. This model can show e.g. that two aircraft of the same model but different seating configuration when travelling the same distance will present different carbon emissions per seat. Apart from the advantage of being more accurate, this calculation model can be embedded into a booking system and allow the passengers to know in advance the flight options and their related environmental impacts in terms of carbon emissions for the same departure and arrival airports. Thus, a campaign may be promoted by more eco-efficient airlines in order to engage the passengers into more environmentally friendly flying choices. A positive reaction by air passengers may encourage airlines to invest in capital equipment which promotes low carbon dioxide emissions per seat (e.g. newer and more efficient aircraft or at least newer engines, high density seats for short-haul flights).

SUMMARY OF DIFFERENT EMISSIONS CALCULATORS

Key features of different emissions calculators

Parameter	DEFRA	ICAO	ClimateCare[d]	Sabre Holdings
GCD correction	10%	Up to 11%	10%	Accounted for in FAA/SAGE
Plane type	Indicative short, medium, long haul calculated from range of typical aircraft	Uses aggregated data from model. Based on scheduled aircraft mapped onto 50 equivalent aircraft types	Indicative hybrid short and long haul (5 planes)	Scheduled aircraft mapped onto >200 equivalent aircraft types. Exact match 95% of time.
Fuel burn data	Corinair	Corinair	Corinair	FAA/SAGE
Form of emissions algorithm	$y=ax$, for domestic, short-haul and long-haul (0.180, 0.126 and 0.11 $kgCO_2/km$)	$y=ax+b$	$y=ax^2+bx+c$	$y=ax+b$
Freight factor	<1% domestic and short-haul 28.8% long-haul	47-88% depending on route and wide/narrow body. 34 classes	20% long-haul 0% short-haul	20% widebody 10% narrow body 1% regional jets
Per seat/passenger	Passenger	Passenger	Seat	Seat
Load Factor	65.3% domestic 81.2% short-haul 78.1% long-haul	67-100% depending on	n/a	n/a
Seating configuration	Representative from CAA data	Number of economy seats that can be fitted in cabin	Median	Specific to airline and aircraft model
Cabin class adjustment (economy:premium)	Range of ratios for different seat classes in domestic, short-haul and long-haul	1:2 based on space allocation	1:1.1 short-haul 1:1.5 long-haul	1:1.1 narrow body 1:1.5 wide body Based upon relative weight
Multiplier	No	No	Yes, 2, applied to ax^2 and bx terms only.	No, but may be applied to ax term.

Figure 4 Decision tree for estimating aircraft GHG emissions [85].

1.3 THE USE OF LIFE CYCLE ASSESSMENT IN THE AIR PASSENGER TRANSPORT SECTOR

The significant growth in commercial air traffic has resulted in more noticeable environmental impacts, and consequently, in more stringent environmental regulations for airport expansion and in the inclusion of the aviation sector in the EU ETS. Further inclusion of the aviation sector in a global scheme focused in GHG emissions reduction is also being negotiated under the auspices of ICAO. Within the perspective of European airlines these environmental factors together with ever-decreasing profits in a highly competitive market and major oscillations in oil prices observed in the last ten years have contributed to an increasing interest for seeking alternatives for reduction in resources consumption, waste generation and carbon emissions [95]. For achieving this goal in environmental management, a commonly used methodological tool is Life Cycle Assessment (LCA), which is defined in ISO 14040 standard [96] as a “systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle”. In other words, LCA can also be defined as an eco-efficiency analysis of products that estimates the customer benefit generated in relation to its associated environmental impacts within the whole life cycle of the product. It is a decision support tool that when used in the right way, can help a company to ensure that choices are environmentally sound, whether in the design, manufacture or use of a product or system [97]. On the financial side, experience have shown that some companies using LCA discovered important product improvements, new approaches to process optimization and even, in some cases, radically new ways of meeting the same need - but with a new product, or with a service. In certain circumstances, the (financial) costs of a product during its lifetime have been estimated under the term "life cycle costing" (LCC) and combined with LCA through a normalization approach, thus covering both the economic and environmental dimension of eco-efficiency for the same product system boundary [98; 11]. The normalized impact score profile that results from this approach consists in dividing the effect scores on impact categories of a product system by the overall magnitude of these categories. Examples of this normalization approach have been implemented on an enterprise level as presented by Sailing et al. [99].

Once well designed and implemented, LCA enables a consistent and transparent analysis of products based on a chosen functional unit from a system-wide point of view that can provide a valuable support in the choices of raw materials, in product innovation and in design packaging with lower impact. A functional unit is the amount, weight and quality of the specific product investigated. In fact, most LCAs are comparative in nature. Thus, the functional unit provides a logical basis for calculating the inputs and outputs in the material and energy flow which in turn will allow the comparison of the environmental performance of alternatives proposed to a product or a service [100; 101]. Choosing a functional unit is not always straightforward and can have a profound impact on the results of the study. For example, in the LCA of power generation systems a suitable functional unit would be 1 kWh of electricity. Other example may involve the choice of functional unit when comparing the best material for sacks in groceries stores between plastic and paper. Considering that plastic sack may not hold the same volume as paper sack, the best functional unit to use may be volume of groceries [102 p. 4].

The analysis and measurement of resources use, emissions, and wastes generated in the whole supply chain related to a product or service, allows the identification of opportunities for improving overall system performance, to benchmark the product or service over time and report progress. In other words, it is possible:

- To compare two different manufacturing processes for the same product in terms of resource use and emissions.
- To compare the current product with regular products available in the market in terms of resource use and emissions.
- To evaluate the relative contributions of the different stages in the lifetime of a product or service and compare with the total emissions in its whole life cycle.

The following elements are essential in a LCA, according to the international standard ISO 14040 series [103]:

- **Goal and scope definition**: defines the goal and intended use of the LCA, and scopes the assessment concerning system boundaries, function and flow, required data quality, technology and assessment parameters.
- **Life Cycle Inventory analysis (LCI)** - it is an activity for collecting data on inputs (resources and intermediate products) and outputs (emissions, wastes) for all the processes in the product system.
- **Life Cycle Impact Assessment (LCIA) -** it is the phase of the LCA where inventory data on inputs and outputs are translated into indicators about the product system's potential impacts on the environment, on human health, and on the availability of natural resources.
- **Interpretation of results:** it is the phase where the results of the LCI and LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis are performed to qualify the results and the conclusions.

Figure 5 illustrates the interrelations between the main phases of LCA as previously described. The phases are often interdependent in that the results of one phase will inform how other phases are completed.

Similarly to cost accounting which involves revenues and costs, a LCA relies on the principle of cause and effect and points to the underlying concept of efficiency, which can be perceived as a ratio between revenues and the environmental impacts related to the positive outcomes [104].

Some researchers developed a comprehensive LCA to quantify the energy inputs and emissions from cars, buses, heavy rail, light rail and air transportation in the U.S. associated with the entire life cycle (design, raw materials extraction, manufacturing, construction, operation, maintenance, end-of-life) of the vehicles, infrastructures, and fuels involved in these systems [105].

They normalized the inventory results to effects per vehicle-lifetime, vehicle miles travelled (VMT), and passenger miles travelled (PMT).

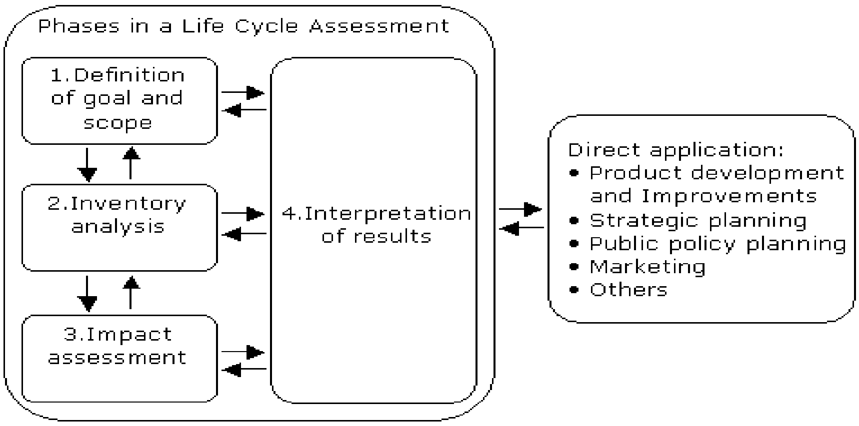


Figure 5 Interactions between the phases of LCA [96].

In the airlines sector the major products are flight services for passengers. Therefore, each scheduled flight may be considered as a separate product within a LCA framework. In turn there are several activities that contribute to the provision of these services, such as: in-flight services, which refer to services provided to passengers during the flight; ground services, such as baggage handling, passenger handling, waste disposal and engineering and maintenance; finance; marketing; and human resource management [106]. The economic, environmental and social effects of each activity can be classified as direct or indirect based on the presence of control over the activity by the airline. Inputs can be considered in terms of materials, energy and water (e.g. food and beverage, fuels, grease, oil, composite materials, electricity, water used for washing the aircraft and other vehicles). Outputs can comprise air emissions, noise, waste and discharge of water.

The adoption of LCA tool for identifying opportunities of in-flight service waste minimisation [107] has shown that on board sorting and collection programmes for paper, plastic, transparent polystyrene drinking cups, food covers, and aluminium cans can achieve a recycling rate of as much as 45–58% of the total galley and cabin waste from in-flight services. Other applications focused in the possibilities of industrial aluminium recycling from aircraft end-of-life cycle [108]. More recently, researchers have investigated the environmental benefits of recycling and reusing aircraft components after reasonable modifications and investments [109].

A more comprehensive LCA approach was conducted by taking in account the environmental impacts of the entire aircraft life cycle for Airbus A330 [10] and Airbus A320 [110]. Both analyses showed that operation phase of aircraft account for most of the environmental impacts, while the manufacturing of the aircraft is responsible for a much smaller contribution. The end-of-life scenario (aircraft disassembly, reuse, disposal or recycling) results in a small positive contribution for all environmental impacts considered.

In the context of climate change mitigation for airlines, it is essential to optimize fuel consumption, which can be done by several means as described in chapter 2.1. A LCA can be designed to compare different types of fuels and feedstock used by different aircraft types in terms of GHG emissions per MJ of fuel, GHG emissions per kg-km or GHG emissions per passenger-km [111; 112; 113]. In such analysis, the following phases in fuel life cycle can be considered: recovery and extraction, raw material movement, jet fuel production, jet fuel transportation, and jet combustion. Other applications of LCA for alternative fuels focused on their contributions to reductions in particulate matter (PM) emissions at the engine exit plane in comparison to conventiona jet fuel A-1 [114].

Some researchers have undertaken LCA aimed at reducing fuel life cycle aviation emissions in the United States [115] and in Greece [116]. Others have adopted a cradle-to-grave LCA of structural aircraft materials to identify potential emissions savings of lightweight composite aircraft components [117]. Other study has also recommended the ratio of the energy liberated during a flight to the revenue work done (ETRW) of an airplane as a key indicator to assess its environmental impact [118]. The revenue work done can be calculated as follows:

$$ETRW = MMF.LCV/Mp.g.R) \qquad (1.7)$$

where MMF = weight of the fuel used in a flight mission

LCV = fuel lower calorific value

Mp = payload mass

R = equivalent still air distance flown

g = acceleration due gravity

This indicator remains constant during the life cycle of the aircraft and is fixed by its designers. Therefore, the goal of an environmentally optimum airplane is to minimize the ETRW.

Despite the considerable interest in the application of LCA in air transport sector, the environmental management literature has dedicated slight concentration to the study of airline's choice of aircraft size and model on short-haul flights for high density routes where significant opportunities in eco-efficiency may be pursued within the context of climate change mitigation. This kind of analysis can also be conducted within the conceptual framework of LCA but focusing in the operational phase of aircraft. It has been observed that airlines tend to reduce the size of the aircraft used on short-haul routes, especially on routes between hub airports. Givoni and Rietveld [119] evaluated and quantified environmental consequences of the choice of service frequency and aircraft size by considering local air pollution, climate change and noise impacts. The results based on their assumptions showed that that increasing aircraft size and adjusting the service frequency to offer similar seating capacity will increase local pollution but decrease climate change impact and noise pollution. When local pollution and climate change impacts are monetized and aggregated the analysis showed that environmental benefits will result from increasing aircraft size.

A common aspect among the applications of LCA highlighted in this section is that they all deal with a large amount of quantitative data items that have to be combined in the correct manner. For an integrated approach for life cycle impact assessment one needs mathematical rules and algorithmic principles [120; 121]. There are modelling techniques available that enable analysis of “what-if” questions, which in turn facilitate the evaluation and optimization of different scenarios. This is for instance the case when analyzing the performance of supply chains not only from the economic point of view and service level but also in relation to prescribed environmental indicators [122]. Besides strict mathematical modelling which has been the most used approach in such analysis, other modelling techniques with more accuracy have been developed, such as queuing networks [123], Markov Chains [124] and Petri Nets [125; 126; 127]. In order to develop an integrated approach for life cycle impact assessment, a general method as recommended by Seppelt [128] consisted of three modules as described below:

a) Life cycle inventory (LCI) that can be created e.g. for a production process or for the provision of a service based on a graphical model by Petri nets.
b) The creation of a dispersion model comprising chemical reactions and the spatial spread of emissions.
c) A detailed environmental impact assessment based on the results of the previous step and operated by fuzzy expert systems, which allow an assessment of ecological impacts for several categories at one site involved in the system life cycle.

The modules described in this methodological concept are considered from top to bottom, being the LCI considered at the top and the fuzzy-expert system at the bottom with several methodological boundaries being crossed between them. While the LCI based on Petri nets represent the deterministic modelling of event-based and continuous systems, the fuzzy-expert systems consist in soft-computing methods of artificial intelligence which are recommended when the uncertainty of the knowledge and the imprecision of the information is higher.

Next sections of this chapter briefly introduces some of the most common graphical and mathematical tools and expert systems used for LCA as well as most used computational tools and software for this purpose.

1.3.1 Graphical and mathematical tools for LCA

In this section, three important graphical and mathematical tools that have been used for Life Cycle Assessment are briefly introduced as well as their applications in the aviation sector: queuing networks, Markov Chains and Petri Nets. More details are provided on Petri Nets since this is the graphical model used in part of the methodology adopted by author, particularly in the environment of software Umberto as later described.

Queuing networks

Queuing theory is the mathematical study to predict queue lengths and waiting times [129]. It deals with the performance of technical systems for processing flows of customers [130]. This theory is useful for providing models for forecasting behaviours of systems subject to random demand.

The first problems addressed by means of queuing theory concerned congestion of telephone traffic [131]. In his study, Erlang observed that a telephone system can be modelled by Poisson customer arrivals and exponentially distributed service times. In probability theory, a Poisson process is a stochastic process which counts the number of events and the time that these events occur in a given time interval. The time between each pair of consecutive events has an exponential distribution with parameter "λ" and each of these inter-arrival times is assumed to be independent of other inter-arrival times.

Queuing theory finds many applications such as:

- Traffic control in communication networks or in air traffic.
- Planning of manufacturing systems or computer programmes.
- Dimensioning of facilities in factories or shops.

To describe a queuing system, an input process and an output process must be specified as described by examples in table 11. The input process is usually called the *arrival process* and the output process is conventionally called by *service process*. Arrivals to the system are called *customers*.

Figure 6 illustrates a basic structure of single queuing systems and figure 7 shows the graphic notation usually adopted to represent a single queuing system. In such processes, it is important to remind that:

- Customers need not be people. It can also be considered as parts, vehicles, aircraft, machines, jobs, among other possibilities.
- Queue might not be a physical line. It can also consist in customers on hold, jobs waiting to be printed, planes circling airport, among other situations.

Table 11 Examples of input and output processes analyzed by means of queuing theory.

Situation	Input Process	Output Process
Bank	Customers arrive at bank	Tellers serve the customers
Pizza parlor	Request for pizza delivery are received	Pizza parlor send out truck to deliver pizzas
Airport terminal	Passenger arrives at the airport terminal for check-in	Passengers checked-in
Air traffic control	Aircraft waiting for landing authorization	Aircraft lands
	Aircraft waiting for take-off authorization	Aircraft takes-off

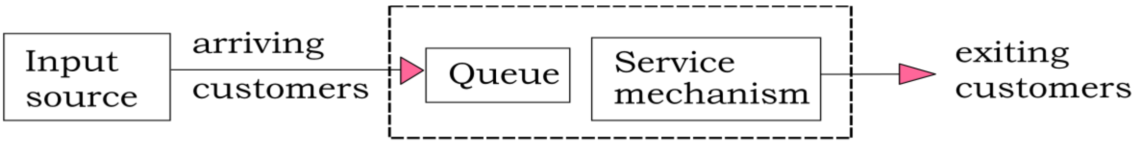


Figure 6 Basic structure of single queuing systems.

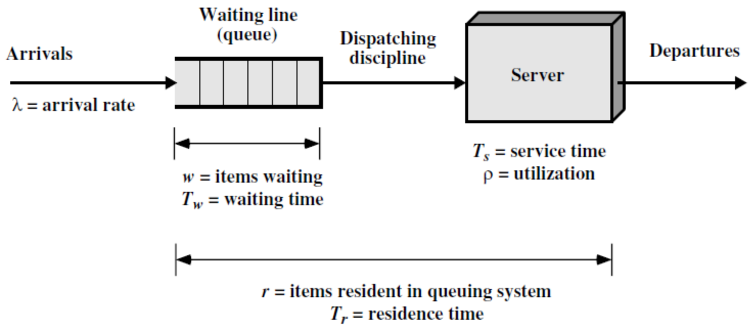


Figure 7 Queuing System Structure and Parameters for Single-Server Queue [132].

There are some simplifying assumptions considered in queuing systems. Given the following information as input:

- Arrival rate
- Service time

Provide as output information concerning the average values and variability (e.g. standard deviation) of following parameters:

- Items waiting
- Waiting time
- Items in residence
- Residence time

In many applications, an arrival has to pass through a series of queues arranged in a network structure as illustrated in figure 8.

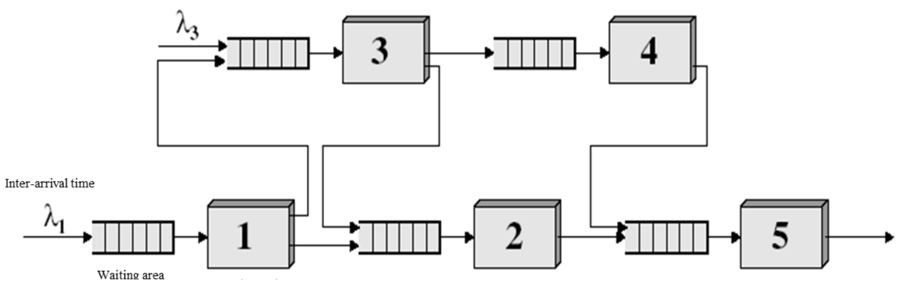


Figure 8 Basic structure of single queuing systems [132].

The standard system used to describe and classify a queuing node was originally based on three main factors proposed by D. G. Kendall [133] also named “Kendall's notation” and presented in the form A/S/C where “A” describes the distribution of inter-arrival times, “S” the service time distribution, and “C” the number of servers at the node. Later, the notation was extended and included other factors like:

- K: Queue capacity
- P: Size of the population
- Z: service discipline

Usually the distribution of inter-arrival times “A” and the distribution of service time “S” can have the following values among others:

- M: markovian (i.e. exponential)
- G: general distribution

- Dt : deterministic
- Ek: Erlang distribution

In the model it has to be considered that some arriving customers can leave if the queue is too long or service is not available to all of them. This restriction is defined by queue capacity “K”. The size of the population considered is also important and can be either finite or infinite. For a finite population, the customer arrival rate is a function of the number of customers in the system: λ (n).

Other particularities of queuing networks as illustrated in figure 9 involves the interrelation between the service nodes and the arrival rates distributed throughout the service nodes. Each node is an independent queuing system with Poisson input determined by partitioning, merging or simple tandem queue. Mean delays at each node can be added to determine mean system (network) delays.

The queue discipline “Z” describes the method used to determine the order in which customers are served.

The most common queue discipline is the FCFS discipline (first come, first served), in which customers are served in the order of their arrival. Under the LCFS discipline (last come, first served), the most recent arrivals are the first to enter service. If the next customer to enter service is randomly chosen from those customers waiting for service it is referred to as the SIRO discipline (service in random order). Other important queuing disciplines involves customer priority. A priority discipline classifies each arrival into one of several categories. Each category is then given a priority level, and within each priority level, customers enter service on a FCFS basis. Another factor that has an important effect on the behaviour of a queuing system is the method that customers use to determine which line to join.

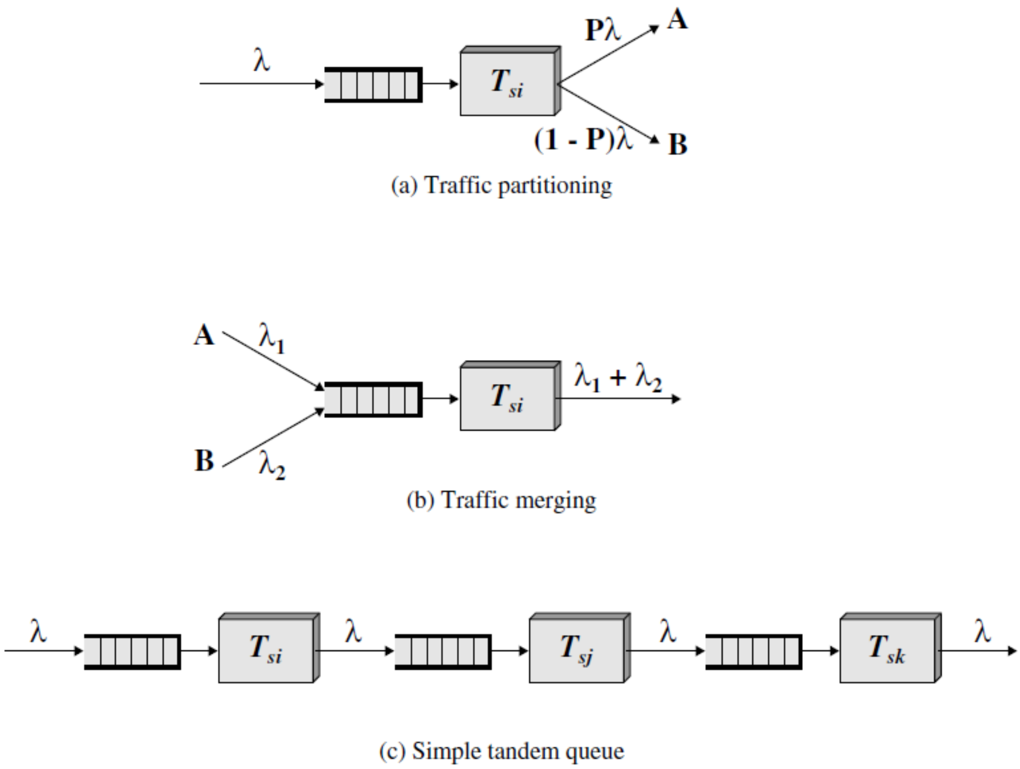


Figure 9 Elements of Queuing Networks [132].

Many theorems in queue theory can be proved by reducing queues to mathematical systems known as Markov chains, first described by Andrey Markov in his 1906 paper [134]. A Markov chain is a mathematical system that undergoes transitions from one state to another on a state space depending only on the current state and not on the sequence of events that preceded it.

Conventionally, it is assumed that no more than one arrival can occur at a given instant. If more than one arrival can occur at a given instant, it is said that bulk arrivals are allowed. Models in which arrivals are drawn from a small population are called finite source models. If a customer arrives but fails to enter the system, it is said that the customer has balked. In order to describe the output process of a queuing system, it is important to specify a probability distribution – the service time distribution – which governs a customer’s service time. For this reason, it is also important to study two arrangements of servers: servers in parallel and servers in series. Servers are in parallel if all servers provide the same type of service and a customer needs only pass through one server to complete service. On the other hand, servers are in series if a customer must pass through several servers before completing service.

In the commercial aviation sector queuing theory has served as a fundamental tool for understanding the dynamics of airline scheduling. However, traditional results take air passenger behaviour (customers) as an exogenous parameter, unaffected by the details of the model, and thus cannot capture the impact of pricing and competition within the models. These impacts on air passenger demand are not negligible from higher fuel surcharge or an additional airport charge and airline fees, such as carbon tax.

Unlike other transport modes, competition in air transport is affected by certain factors that make it subject to the Game theory, which is a branch of applied mathematics that is used in conformity with economic principles [135 p. 319]. These particular factors are related to sovereignty in the award of traffic rights and the requirement of ownership and control of an airline mostly on the hands of nationals of a country in which an airline is registered. The Game theory suggests that the success of the strategic choices of an airline depends on choices made by other airlines. This anomaly has spawned hundreds of bilateral air services agreements and enabled States to adopt a protectionist attitude in guarding the “market share” of its own national carrier, thus stultifying competition among carriers and depriving the consumer of the most efficient and cost effective air transport product that an otherwise liberalized market would have produced [135 p. 320]. Game theory can be applied in air transport economics, security and also in environment protection. Although game theoretic techniques have been applied to characterize the impact of customer behaviour/reactions, it does not take in account the queuing dynamics of networking in this sector. Therefore, studying the interactions between game theory and queuing models may result in more consistent models for airline scheduling.

In the airline scheduling it may also be possible to identify possibilities to reduce overall fuel consumption and GHG emissions from aircraft engines but it is important to understand among other parameters the temporal air passenger demand, the average duration of different flight phases (including taxi times of aircraft in very busy airports) and their respective settings for aircraft engine throttle.

There is a constant interest in improving air traffic flow efficiency in regions around the world that are regularly faced by high volume of air traffic demand. This is for instance a major challenge to tackle across the US airspace and the European airspace systems due to many uncertainties involved. Many queuing models have been studied and tested for this purpose in which inter-arrival times and service times have been mainly assumed to be exponentially distributed and stationary. Roongrat [136] showed that these assumptions may not be suitable for all scenarios since they do not account for increases and decreases in demand across airspace systems. Instead of using traditional probability distribution functions for inter-arrival times/service times of airspace systems, he proposed a method that uses a Coxian distribution to data combined with different time dependent queuing models of airspace systems like in the United States.

Queuing theory was also applied to facilitate the resolution of fundamental technical issues related to airport demand management in response to increasing delays and congestion [137]. Further research on this approach has been conducted by Andreatta and Odoni [138].

Markov chains

A Markov process is a stochastic process (random process) in which the probability distribution of the current state is conditionally independent of the path of past states, a characteristic called the Markov property. Markov chain is a discrete-time stochastic process with the Markov property. Markov chains are the basis for the analytical treatment of queues (queuing theory).

Analytically, a discrete-time stochastic process is a **Markov chain** if, for $t = 0,1,2\ldots$ and all states, the following condition is met:

$$P(\mathbf{X}_{t+1}=i_{t+1}|\mathbf{X}_t=i_t,\mathbf{X}_{t-1}=i_{t-1},\ldots,\mathbf{X}_1=i_1,\mathbf{X}_0=i_0) = P(\mathbf{X}_{t+1}=i_{t+1}|\mathbf{X}_t = i_t)$$

Essentially this says that the probability distribution of the state at time $\boldsymbol{t}$**+1** depends on the state at time $\boldsymbol{t}(\boldsymbol{i_t})$ and does not depend on the states the chain passed through on the way to $\boldsymbol{i_t}$ at time $\boldsymbol{t}$.

In the study of Markov chains, it can be assumed that for all states $\boldsymbol{i}$ and $\boldsymbol{j}$ and all $\boldsymbol{t}$, $P(\mathbf{X}_{t+1} = \mathrm{j}|\mathbf{X}_t = i)$ is independent of $\boldsymbol{t}$.

This assumption allows us to write $P(\mathbf{X}_{t+1} = \mathrm{j}|\mathbf{X}_t = i) = \boldsymbol{p_{ij}}$ where $\boldsymbol{p_{ij}}$ is the probability that given the system is in state $\boldsymbol{i}$ at time $\boldsymbol{t}$, it will be in a state $\boldsymbol{j}$ at time $\boldsymbol{t}$**+1**.

If the system moves from state $\boldsymbol{i}$ during one period to state $\boldsymbol{j}$ during the next period, it can be declared that a **transition** from $\boldsymbol{i}$ to $\boldsymbol{j}$ has occurred.

The $\boldsymbol{p_{ij}}$**'s** are often referred to as the **transition probabilities** for the Markov chain.

This equation implies that the probability law relating the next period's state to the current state does not change over time.

It is often called the **Stationary Assumption** and any Markov chain that satisfies it is called a **stationary Markov chain**. It must also be defined the parameter $\boldsymbol{q_i}$ as the probability that the chain is in state $\boldsymbol{i}$ at the time **0**; in other words, $P(\mathbf{X}_0=i) = \boldsymbol{q_i}$.

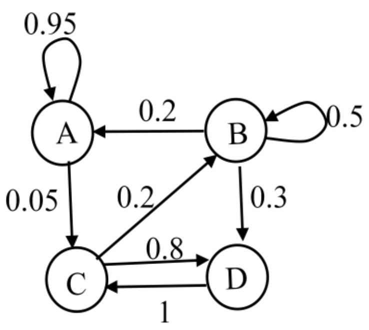
A vector representing the **initial probability distribution** for the Markov chain can be defined as $\mathbf{q}= [q_1, q_2, \ldots q_s]$.

In most applications, the transition probabilities are displayed as an s x s **transition probability matrix** P. The transition probability matrix P may be written as:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1s} \\ p_{21} & p_{22} & \cdots & p_{2s} \\ \vdots & \vdots & & \vdots \\ p_{s1} & p_{s2} & \cdots & p_{ss} \end{bmatrix}$$

It is important to remark that each entry in the P matrix must be nonnegative. Hence, all entries in the transition probability matrix are nonnegative, and the entries in each row must sum to 1. Figure 10 illustrates a graphical representation of a Markov chain with the values presented in a transition probability matrix.

Markov chains have found several applications on education, marketing, health services, finance, accounting, and production. In the aviation sector, Markov chains have been used for waiting lines of servers involving the replacement of aircraft components within the Scheduled Removal Component (SRC) card, which in turn confirms the component's life cycle, verifies that the part is ready-for-issue, and verifies how many flight-hours it still has left [139]. Some authors considered the use of decomposition approach to analyze the time-dependent congestion in airports [140; 141; 142].



	A	B	C	D
A	0.95	0	0.05	0
B	0.2	0.5	0	0.3
C	0	0.2	0	0.8
D	0	0	1	0

Figure 10 Graphical representation of a Markov chain and a transition probability matrix [143].

A model based on semi-Markov processes was proposed to estimate economic efficiency within the conceptual framework of life cycle that can be useful for various applications, including for air traffic control and aviation safety monitoring [144]. Two interrelated problems were highlighted in this application:

1. Estimation of the time, material (hardware and money), and labour resources required at individual steps of the design, manufacture, and service of system prototypes and
2. Estimation of the total cost of realization of the phases of life cycle.

A model based on discrete choice and Markov chain models proposed by Gelhausen [145] calculated the expected time span of delayed runway expansion at a congested airport. A runway expansion delay means that runway capacity is insufficient to meet the actual demand and results in modification of demand, e.g. a temporal or regional demand shift or a demand loss. The econometric model proposed assumes various factors that jointly represent the degree of opposition that population surrounding the airport shows against runway expansion due to noise emissions.

Petri Nets

Petri nets are a graphical and mathematical modelling tool that were originally proposed by Carl Adam Petri in 1962 [146] and since then have evolved into a formalism and gained different extensions to be applied in several fields, such as informatics, electronics and chemistry, among others. As a graphical tool, Petri nets can be used as a visual-communication aid similar to flow charts, block diagrams, and networks. As a mathematical tool, it is possible to set up state equations, algebraic equations, and other mathematical models governing the behaviour of systems [147].

Petri Nets consist of four basic elements as represented in figure 11: *places*, *transitions*, *tokens* and *arcs*. *Places* represent the current state of an object and the type of a data in Petri nets. *Transitions* represent the stochastic or time-based nature of changes in the model. Transitions can be immediate, deterministically time-delayed, or time-delayed based on a probability distribution defined by the user. When the state transition occurs or the data transaction is performed, it is said that the transition was "fired". The condition and time period for the firing of each transition has to be prescribed [148].

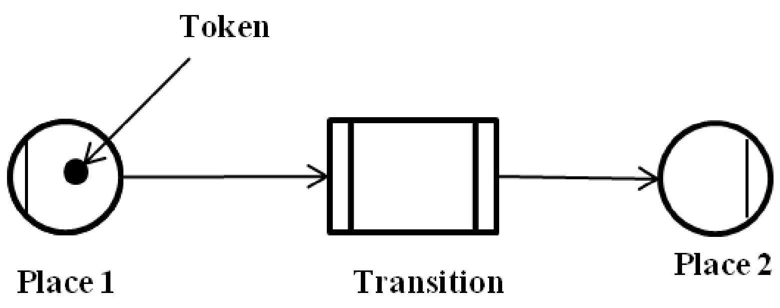


Figure 11 Graphical representation of Petri nets in a simple model [148].

A *token* expresses a data or an object in Petri nets. *Arcs* determine the path that tokens take throughout the model. Arcs can either enable or inhibit movement in the model, depending on their use. Any distribution of tokens over the places will represent a configuration of the net called a *marking*.

Basically, a Petri net is a 5-tuple, PN = (P, T, F, W, M_0) where:

P = {p_1, p_2, …, p_n} is a finite set of *places*,

T = {t_1, t_2, …, t_n} is a finite set of *transitions*,

F $\subseteq (P \times T) \bigcup (T \times P)$ is a set of arcs (flow relation),

W: F $\rightarrow$ {1, 2, 3, …} is a weight function,

M_0: P $\rightarrow$ {0, 1, 2, 3, …} is the initial marking,

P ∩ T = Ø and P U T ≠ Ø.

A Petri net structure N = (P, T, F, W) without any specific initial marking is denoted by N. A Petri net with the given initial marking is denoted by (N, M_0).

The functional and quantitative behaviour of a Petri net is defined by the specification of transitions and the weights associated with the arcs.

Conventionally, every Petri net has a *reachability* defined by R(N, M) which gives the set of all markings M reachable from initial marking M_0.

There are two important properties involving Petri nets that are important to remark: *boundedness* and *liveness*. The characteristics related to these properties that Petri nets can have are described as follows:

- **Boundedness**
  - A net N with initial marking M_0 is safe if places always hold at most 1 token.
  - A marked net is (k-)bounded if places never hold more than k tokens.
  - A marked net is conservative if the number of tokens is constant.
- **Liveness**
  - A transition is deadlocked if it can never fire.
  - A transition is live if it can never deadlock.

Some extensions of Petri nets have been introduced to various models since this graphical and mathematical tool was created:

- **Coloured Petri nets (CPN)**: those that allow tokens to have a data value attached to them. This attached data value is called token colour. Tokens are "coloured" to represent different kinds of resources.
- **Augmented Petri nets**: those in which transitions additionally depend on external conditions.
- **Timed Petri nets (TPN)**: those in which there is a duration associated with each transition.

Time is an important aspect of all discrete dynamic systems. When processes with different time characteristics are considered, transitions have to be extended by an attribute $\Delta\tau > 0$. The attribute $\Delta\tau$ can be interpreted as switching or processing time or duration of execution.

Therefore, in time-based Petri nets each transition $t \in T$ is associated with a switching period $\Delta\tau: T \rightarrow \mathbb{R}^+$. If $\Delta\tau$ is defined for a transition t, the last time of switching is also stored: $\tau: T \rightarrow \mathbb{R}$.

These extensions of the basic Petri net model were proposed to make it more suitable for the modelling of systems encountered in logistics, production, communication, flexible manufacturing and information processing.

The coloured Petri nets allow the modeller to make much more succinct and manageable descriptions and for this reason they are called 'high-level' nets. Precursors of coloured Petri nets have been presented since the late 1970s [149; 150; 151; 152].

In a TPN model, time can be quantified or not but usually it is quantified when there is an intention to express quantitative temporal properties, such as deadlines, activity durations, response times, delays, etc. In this case, it is important to consider a *place* containing one *token*, whose value represents the current time. This *place* has to be connected to every *transition* in the model. When the concept of time is introduced into the basic Petri net model, it is important to decide on two main things: (1) the location of the time delays and (2) the type of these delays. Several authors have also proposed a Petri net model with explicitly quantitative time [153; 154; 155; 156] since the early 1970s.

Petri nets have been mainly used to describe manufacturing systems, supply chains and logistics networks [157]. In the latter case, high-level timed coloured Petri nets have been proposed [158] that combine the capabilities of Petri nets with the capabilities of a high-level programming language. It is appropriate for formulating concurrent systems and analyzing their properties.

More recent applications of Petri nets in Life Cycle Inventory (LCI) have taken the advantage provided by expert systems based on soft computing to model and quantify the material and energy flow. General applications were represented by Moeller, Prox, Schmidt, & Lambrecht [159]. More specific approaches were focused in the application of Petri nets in LCI to compare different approaches in municipal waste management [160] and to compare different types of heating fuels used in the household sector in the Czech Republic [161].

In the commercial aviation sector, Petri nets has been used for simulating passenger flow of airport terminal [162] and also considered trip delays experienced by passengers due to missed connections and cancelled flights [163]. Other authors applied in air traffic system considering it as a timed discrete events system [164].

Vidosavljevic and Tosic [165] modelled the turnaround process of aircraft at an airport by using Petri Nets in order to identify opportunities to reduce the incurred time for various tasks performed during the process and avoid extra costs. As both researchers explain in their analysis "the turnaround of an aircraft comprises the sequence of ground operations required to service the aircraft between two flights, from the time the chocks (rubber blocks to prevent aircraft from moving) are put in front of the wheels after it lands, to the time the chocks are removed and the aircraft is ready to depart".

The assessment and comparison of fuel consumption and emissions released by each aircraft model for different distances flown and flight conditions as being proposed in this research can be modelled based on the conceptual framework of Petri nets (PN). An example of this model based on Petri nets is illustrated in section 1.3.

1.3.2 Artificial Intelligence tools for LCA

Artificial intelligence (AI) is a branch of computer science research focused in the study and design of intelligent agents, where an intelligent agent is a system that perceives its environment and takes actions that maximize its chances of success [166]. It involves the creation intelligent machines that work and react like humans. Some of the activities computers with AI are designed for include speech recognition, learning, planning, and problem solving. Machines can often act and react like humans only if they have abundant information relating to the world. AI must have access to objects, categories, properties and relations between all of them to implement knowledge engineering. AI tools are comprised mainly of expert systems, fuzzy logic, and neural networks. In some cases, a combination of two or more intelligent technologies is used like when neural network is combined with fuzzy system, resulting in a hybrid neuro-fuzzy system. These hybrid intelligent systems capable of reasoning and learning in an uncertain and imprecise environment form the core of soft computing. Each of these AI tools are briefly described in this section but more importance is given to neural networks and its applications in the aviation sector. Expert systems find various applications with the support of computational tools presented in the next section of this chapter.

Expert systems

Expert systems also termed interchangeably by knowledge-based systems are computer programs that are derived from a branch of computer science research artificial intelligence. It simulates the judgement and behaviour of a human or an organization that has expert knowledge and experience in a particular field [167 p. 1]. Conventionally, such a knowledge-based system contains accumulated experience and a set of rules for applying the acquired knowledge to each particular situation that is described to the program [168]. Expert systems can be upgraded with enhanced knowledge base or additional set of rules. An expert system is a problem solving and decision making system that uses a knowledge and perform logic rules obtained from the experience of a specialist in a particular area.

The knowledge base of expert systems contains both factual and heuristic knowledge. Factual knowledge is the knowledge of the domain concerned that is widely shared, typically found in textbooks or journals. Heuristic knowledge is an experiential knowledge gained through experience that involves good judgment, and plausible reasoning in a particular field of research. The knowledge is commonly represented by means of a **production rule** and an **unit** or **frame**. The production rule consists of a set of IF (condition) and a THEN (action) parameters. A unit consists of a list of properties of the entity and associated values for those properties. The problem-solving model or paradigm, organizes and controls the steps taken to solve the problem. One common but powerful paradigm involves chaining of IF-THEN production rules to form a line of reasoning.

Neural networks

Artificial neural network (ANN) is a machine learning approach that models human brain and consists of a number of artificial neurons [169]. Neuron in ANNs tend to have fewer connections than biological neurons. Each neuron in ANN receives a number of inputs. An activation function is applied to these inputs which results in activation level of neuron (output value of the neuron). Knowledge about the learning task is given in the form of examples called training examples.

An Artificial Neural Network is specified by [170]:

- Neuron model: the information processing unit of the NN.
- An architecture: a set of neurons and links connecting neurons. Each link has a weight.
- A learning algorithm: used for training the NN by modifying the weights in order to model a particular learning task correctly on the training examples.

The aim is to obtain a NN that is trained and generalizes well. It should behaves correctly on new instances of the learning task.

The neuron is the basic information processing unit of a NN. As figure 12 illustrates a neuron diagram consists of:

- A set of links, describing the neuron inputs, with weights $W_1, W_2, \ldots, W_m$.
- An adder function (linear combiner) for computing the weighted sum of the inputs: $u = \sum_{j=1}^{m} w_j x_j$
- Activation function φ for limiting the amplitude of the neuron output. Here ‘b’ denotes bias: $y = \varphi(u + b)$

The bias “**b**” has the effect of applying a transformation to the weighted sum “**u**” as: v = u + b

The bias is an external parameter of the neuron. It can be modelled by adding an extra input. The parameter "**v**" is called induced field of the neuron.

$$v = \sum_{j=0}^{m} w_j x_j$$

$$w_0 = b$$

The choice of activation function φ determines the neuron model, which can be described according to a step function, a ramp function, a sigmoid function with z, x, y parameters, or as a Gaussian function.

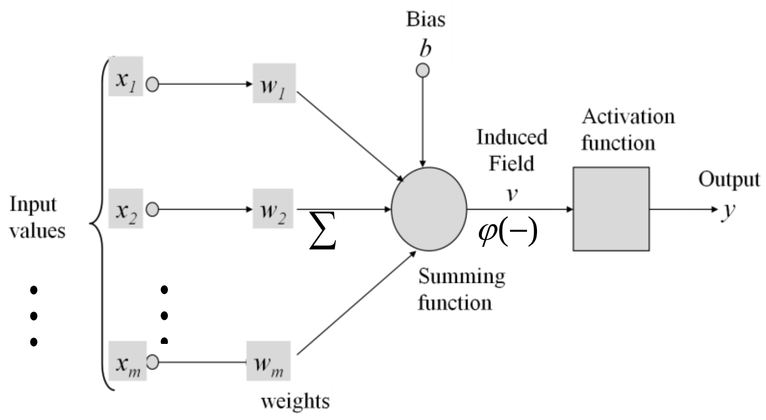


Figure 12 A representation of neuron diagram.

There are three different classes of network architectures as shown in figure 13. The architecture of a neural network is linked with the learning algorithm used to train.

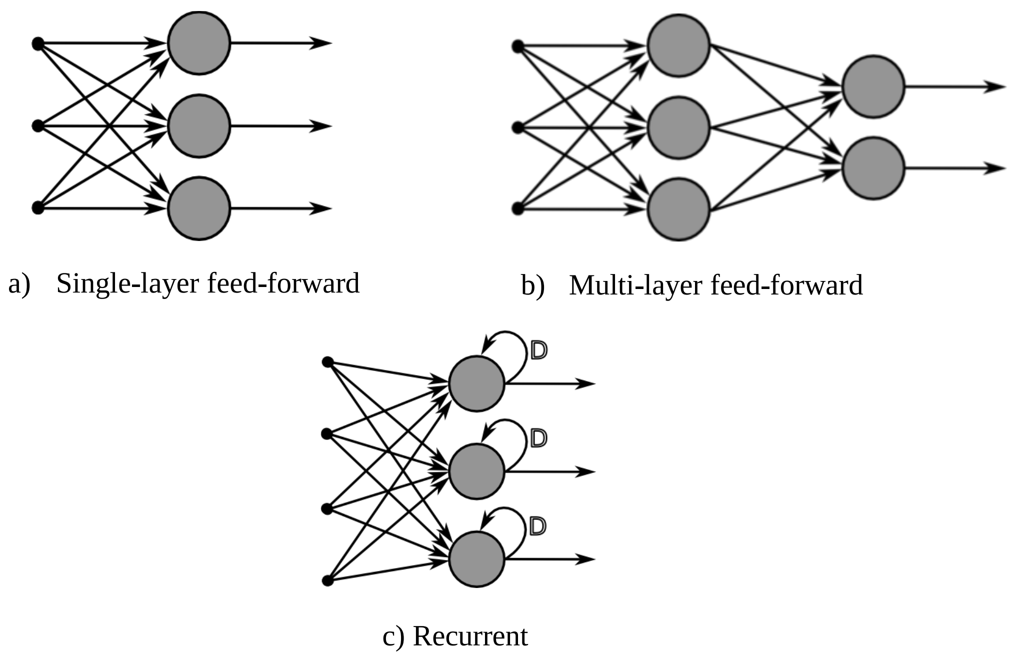


Figure 13 Classes of neural network architectures

Fuzzy logic

Fuzzy logic is a mathematical logic that attempts to solve problems by assigning values to an imprecise spectrum of data in order to arrive at the most accurate conclusion possible [171]. Fuzzy logic is designed to solve problems in the same way that humans do: by considering all available information and making the best possible decision given the input. It is an approach to computing based on "degrees of truth" rather than the usual "true or false" (1 or 0) Boolean logic on which the modern computer is based [172]. Natural language (like most other activities in life and indeed the universe) is not easily translated into the absolute terms of 0 and 1. Fuzzy logic seems closer to the way our brain work. We aggregate data and form a number of partial truths which we aggregate further into higher truths which in turn, when certain thresholds are exceeded, cause certain further results such as a motor reaction. Fuzzy logic has been extensively in washing machines, electronic devices like cameras, temperature controller, anti-lock brake system (ABS) and even in stock trading applications. In the case of modern wash machines e.g. sensors continually monitor varying conditions inside the machine and accordingly adjust operations for the best wash results.

Neuro-fuzzy systems

Together neural networks and fuzzy logic are used to create behavioural systems, commonly named by fuzzy logic neural networks (FLNNs). These systems are usually chosen when there is interest in the analysis of the structure of data whose classification is previously unknown followed by an interest in learning how to interpret models and classify data. In unsupervised learning process and classification by FLNNs it is recommended to use Kohonen's self-organizing feature maps (KSOFMs).

A good example of application of FLNN with KSOFMs has been shown in the design of classification model of air quality in chosen localities in the town of Pardubice in the Czech Republic [173]. The classification into five categories proposed by these authors was based on parameters related to harmful substances and meteorological conditions as a better approach than the currently used air stress indices (ASIs) and air quality indices (AQIs). This model takes in account that long-term exposures to lower concentrations of air pollutants can result in adverse health effects. Thus, it also provides a classification based on mean values in each locality observed on monthly and on annual basis. Subsequent modelling by same authors was provided for these localities based on IF-relations and their determination by KSOFMs and K-means algorithms for air quality classification processing [174]. These proposed models can be of valuable support in assessing and classifying air quality in the surroundings of airports across Europe that in turn will contribute for more consistent and well grounded environmental policies concerning air pollution control.

Applications of artificial intelligence in LCA

A neural network approach has been proposed to predict an approximate LCA for the conceptual design stage by grouping products according to their environmental characteristics and by mapping product attributes to impact driver index [175]. Trained learning algorithms for the known characteristics of existing products will quickly give the result of LCA for new design products.

Other researchers also applied neural networks for the prediction of eco-efficiency in the design process of new technologies based on highly reduced number of descriptive design parameters, which are very difficult to collect at the conceptual design stage [176].

Most of examples of research conducted associated LCA in the air transport sector as highlighted in the beginning of this chapter have been benefited by AI tools, mainly expert systems. Some researchers developed a functional product life-cycle simulation model for cost estimation in conceptual design of jet engine components by means of knowledge based engineering-system coupled to databases and spreadsheets [177].

In the air transport sector, neural network was already applied to model aircraft fuel consumption [178]. A recent research suggested an artificial neural network model to determine the healthy risk level induced by aircraft pollutant impacts around Soekarno Hatta International Airport-Cengkareng Indonesia [179]. Artificial neural network has also been used for investigating the feasibility of using an electric hybrid system consisting of a fuel cell and battery to power a small model aircraft with the purpose of identifying opportunities of reducing environmental impact of aviation [180]. In fact, technologies based on neural networks are currently being developed which may assist in addressing a wide range of complex problems in aeronautics.

1.3.3 Computational tools used for LCA

In the past twenty years various software tools and databases have been developed to support the environmental impact assessment of a service, product or process, particularly when adopting a life cycle assessment (LCA) approach. These tools jointly contributed to increase the general acceptance of LCA as a tool with a range of uses, such as environmental labelling, product environmental improvement, eco-design, and policy evaluation. Many of these software tools and databases are available for licensing or purchase. Because LCA requires extensive data collection for each component contained in each phase within the boundaries of the assessment, these computational support tools demonstrated a potential to expand the breadth and depth of the information available for an assessment. These computational tools facilitate the development of corporate environmental management information systems (CEMIS), which are mainly guided by the principle of efficiency. In this context, efficiency is not aimed directly at profit maximization but is rather considered as an overall concept that contributes to viability and eco-efficiency of companies, supply chains and societies that jointly consist in a precondition of future economic success [181]. These tools are usually flexible applications that contain spreadsheets and databases of material and energy flow in different process categories that can be manually modified in order to store and compute the impact values that meet the requirements of the process designer.

In 1996, 37 LCA-based software tools (and vendors) were identified across the U.S. and Europe in different forms of development and use [182]. Since that time, some of them might not have flourished while some gained more popularity and other new software tools were developed and introduced in this market.

In 1999, researchers already described the implementation of an application (ECOLOGUE) for comprehensive computational assessment of environmental impact indicators over the building life cycle, which includes different phases such as construction, operation and decommissioning [183]. In that time, however, limitations were more evident in terms of data availability and the precision of the environmental impact assessment methods.

Currently, the most popular life-cycle assessment modeling software are:

- GaBi product sustainability
- SimaPRO LCA software
- Umberto LCA software
- GREET Life-Cycle Model
- GHGenius (focused on LCA for transportation fuels)

First three software (GaBi, SimaPro and Umberto) have been used by practicioners for applications in several sectors mainly with the purpose of enhancing efficiency of value chains and developing products that meet environmental regulations and have smaller environmental footprints in terms of material, energy, resource use, GHG emissions, water consumption and waste. While GaBi and SimaPro have their calculation models based on linear equation systems, the design of model and calculations performed within Umberto environment are based on Petri Nets [184]. The calculations performed in LCA by these software use the Ecoinvent database, which in turn contains several thousands of LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, basic and precious metals, metals processing, information and communications technology, electronics as well as waste treatment [185].

GREET and GHGenius are used for estimating energy use and emissions mainly associated with conventional and alternative fuel production in transportation models. Although it was not developed with the primary purpose of conducting life cycle assessment, Excel software can also be of valuable help for advanced users and practicioners of LCA, considering that some additional spreadsheets have to be developed or added to Excel. In these tools, metrics like the Global Warming Potential (GWP) are estimated based on a conversion database of resources consumption.

Most of those studies involving the application of LCA in the aviation sector as highlighted in the first section of this chapter have used the support of these computational tools.

The Community Multi-scale Air Quality (CMAQ) Model is another powerful computational tool that has been used by U.S. Environment Protection Agency (EPA) and and local states for air quality management and has also been used for the development of a response surface model of aviation's air quality impacts in the United States [186]. By using CMAQ reseachers may understand the life cycle of air pollutants from its release into the atmosphere to its deposition on land and water, enabling the development of deposition scenarions and compilation of its impacts. This tool can be used e.g. for addressing $PM_{2.5}$, ozone concentrations and NO_x emissions from aviation in the surroundings of airports [187; 188; 189].

2 PRACTICAL PART

2.1 RESEARCH OBJECTIVES AND HYPOTHESES

Several initiatives that can be implemented by airlines in order to mitigate the climate change effects of their operations as described in the introductory part depend not only on their own decisions but also on the negotiations for a collaboration with other airlines, airports, governments. Several initiatives are illustrated in figure 14 and those that in the scope of this study are highlighted, i.e., those at the operational level of airlines.

The purpose of this research is to highlight and demonstrate some opportunities for increasing eco-efficiency of European airlines by means of a simplified life cycle analysis conceptual framework oriented to climate change mitigation in their flight operations. In order to achieve this goal, author estimates the average fuel consumption and GHG emissions per passenger-kilometre in different perspectives of analysis based on data provided by three largest European airlines in terms of total passengers carried per year [71]. These airlines are Deutsche Lufthansa AG, Air France (a subsidiary of the Air France-KLM group), and British Airways (a subsidiary of the International Airlines Group).

The following hypotheses are tested in this study for validating the eco-efficiency opportunities available for European airlines within the context of climate change mitigation:

Hypothesis 1: in the whole life cycle of a commercial aircraft the GHG emissions released during the operation phase are much more significant than the embodied emissions during the aircraft manufacturing phase, and the aircraft maintenance phase.

Hypothesis 2: for every aircraft type, there is a range of flight distance at which aircraft can perform better in terms of fuel consumption and GHG emissions per passenger-kilometre.

Hypothesis 3: for every aircraft type, there are considerable differences in terms of fuel consumption and CO_2 emitted per passenger depending on the type of jet engines used, being other parameters the same, including flight distance, passenger load factor, seating configuration, among others.

Hypothesis 4: For all aircraft analyzed, the amount of fuel consumed during LTO cycle is less significant than fuel consumed during the cruise stage.

Hypothesis 5: Short-haul flights offer more opportunities for airlines in reduction of fuel consumption and CO_2 emissions than medium and long-haul flights.

Hypothesis 6: for short-haul routes, being certain conditions met, it is preferentially recommended to use wide body aircraft (commercial aircraft with two aisles) with lower frequency to reduce fuel consumption and CO_2 emissions.

Hypothesis 7: The fuel surcharge on air passengers does not take in account their real contributions in fuel consumption when measured in passenger-kilometre.

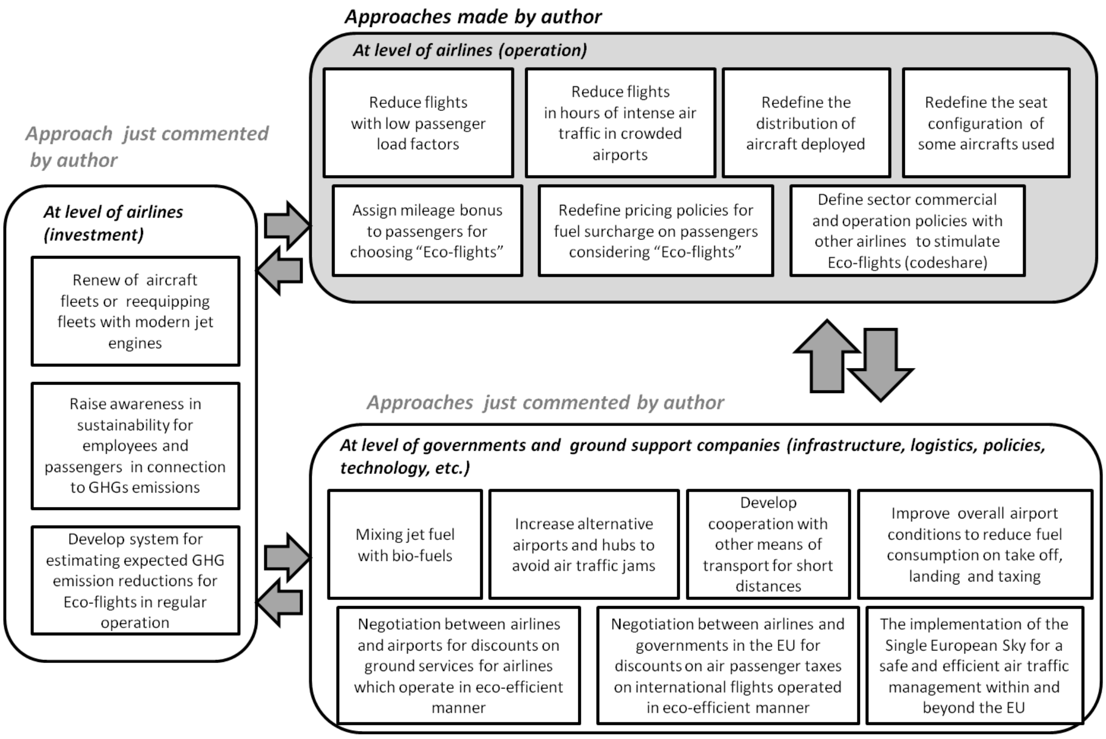


Figure 14 Possible means to reduce GHG emissions per passenger-kilometre by airlines.

The impact of aircraft operation on climate change is mainly related to CO_2, NO_x and H_2O emission. Emissions of CO_2 and H_2O are directly related to fuel consumption and therefore can be estimated accurately using conversion factors that are presented in section 2.3. NO_x emission is not directly related to fuel consumption but depends on combustion temperature which increases with engines' power setting.

Initially, an estimation is undertaken of the embodied GHG emissions per passenger-kilometre during the following life stages of an aircraft: aircraft manufacturing, maintenance and the end-of-life scenario that includes disassembly, reuse, disposal or recycling. Subsequently, an estimation of GHG emissions during the operations of aircraft through all its lifetime is undertaken. Emissions are presented in terms of kg CO_{2eq}/pax.km. Two aircraft types that are widely used by these three largest European airlines are selected: Airbus A330-200 and Boeing 777-200. Previous research in life cycle assessment of a commercial aircraft showed that most part of GHG emissions per passenger-kilometre occurs during the aircraft operation as commented in section 2.2. This is also demonstrated in this study and for this reason author only focuses in this life stage of aircraft during the further analysis, which proceeds with the calculation of fuel consumption and GHG emissions per passenger-kilometre for different aircraft types used by these three largest European airlines. Fuel consumption and emissions are also presented in terms of two main flight cycles, such as: landing and take-off cycle (LTO) and cruise stages. Further calculation is performed per chosen flight routes among main competing airlines. Then, a comparison is done to identify possible reductions in fuel consumption and GHG emissions from suggested changes in aircraft choice for hub-to-hub flights for short-haul, medium-haul and long-haul distances. An airline hub is an airport that an airline uses as a transfer point to get passengers to their intended destination.

Finally, an estimation of the climate change cost per passenger for different flight alternatives is conducted and serves as the basis for a fairer measurement of carbon tax that could be applied across all EU member states and possibly, even globally under the auspices of the International Civil Aviation Organization (ICAO). Figure 15 illustrates the research process in nine main steps as previously described.

The climate change cost per passenger for different flight alternatives can be understood as the marginal external cost of climate change for each flight, which in turn is based on the average level of emissions of CO_2, NO_x and H_2O during the specified flight distance. A carbon tax could be considered on air passengers and priced as the value of the marginal external cost for that flight based on the aircraft type, on the seat configuration, on the average passenger load factor and on the average passenger to freight factor for that flight route. The collection and use of the carbon tax can be explored basically in two ways: collected by airlines and then used to offset their GHG emissions by acquiring emission allowances or carbon credits; or collected by airlines and transferred to a central fund of the EU responsible for investment in projects that contribute to the sequestration of carbon or avoidance of GHG emissions.

The pricing of fuel surcharge and carbon tax proportionally to the average level of carbon emissions per passenger-kilometre may motivate air passengers to choose flights that will contribute to an overall reduction in GHG emissions. For this alternative, it becomes essential to understand the air passenger demand elasticity which will be a topic for further research as commented in section 3.2.

The approach proposed in this study aims to be a cost-effective alternative for the achievement of the required reductions in CO_2 emissions by European airlines within the EU ETS in comparison to other alternatives shown in figure 14 that demand higher investments and longer timeframes, such as the acquisition of newer and more fuel-efficient aircraft. Other alternatives for reductions in fuel consumption and CO_2 emissions from aviation depend on negotiations among governments, airports and the European Organisation for the Safety of Air Navigation (Eurocontrol) and may also take long time to materialize such as the Single European Sky and carbon tax on flight operations within the EU and in a global level.

After all this approach does not intend to increase the burden of taxes, fees and charge currently applied on air passengers as the EU ETS may suggest.

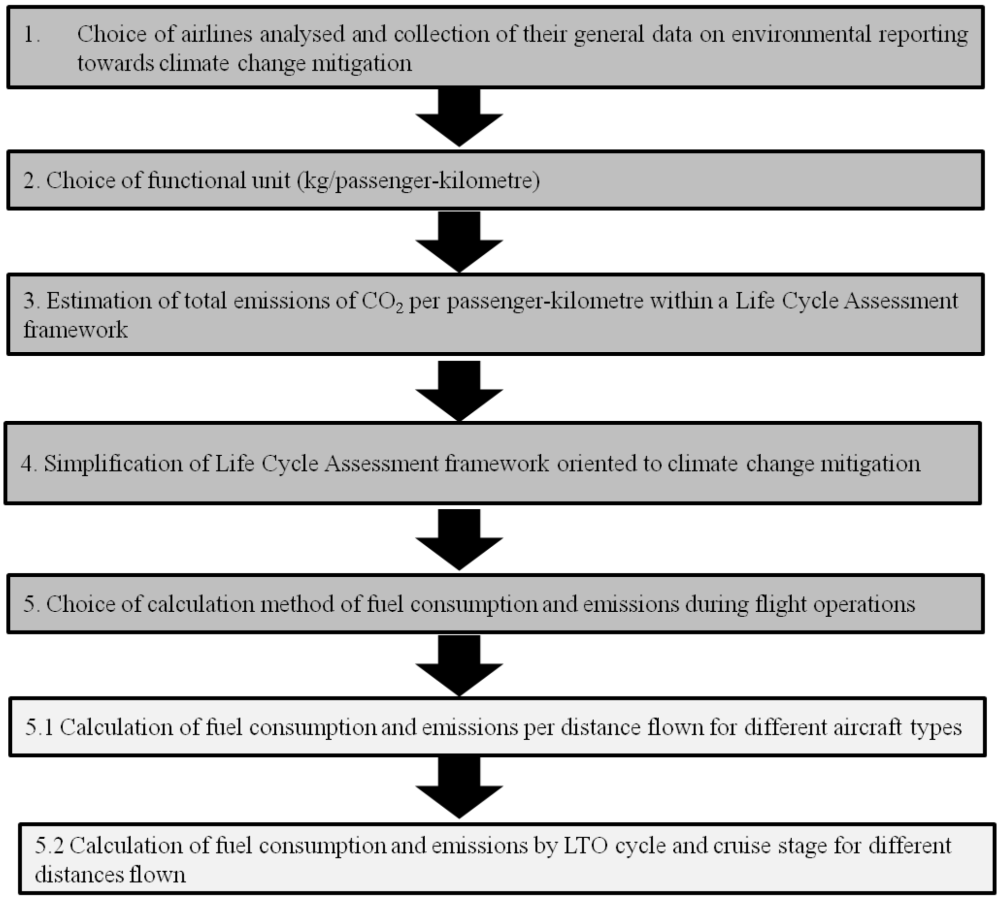


Figure 15 Main steps undertaken in the research process.

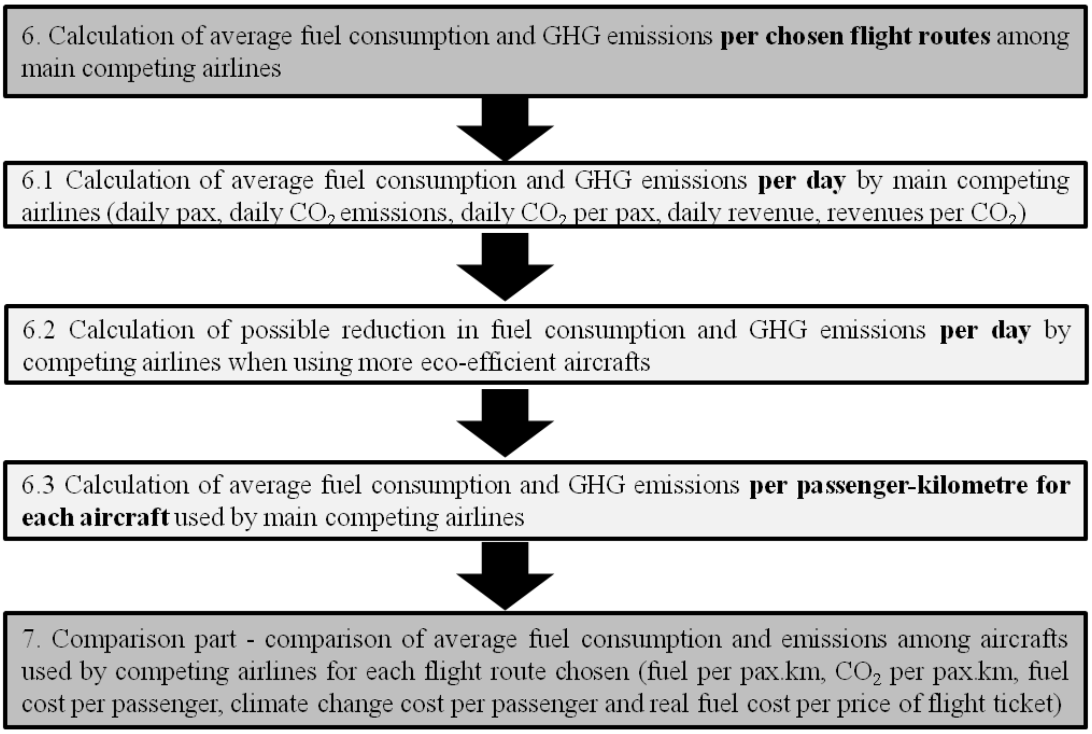


Figure 15 (cont.) Main steps undertaken in the research process.

Figure 16 remarks from those steps presented in previous diagram the main measurements and key indicators that can form the basis of the eco-efficiency analysis of flight operations by largest European airlines facing climate change mitigation. These indicators can be represented by environmental cost per available seat kilometre (ECASK) and Gross value added per carbon dioxide equivalent ($GVACO_{2e}$). However, author proposes the use of fuel consumption per passenger-kilometres, GHG emissions per passenger-kilometres and climate change cost per passenger-kilometres based on certain variable parameters that are explained in chapters 2.3 and 3.1. These measurements are presented for selected hub-to-hub flights and contributes to a fairer pricing of fuel surcharges and carbon taxes on air passengers. Other conventional indicators associated to the operational performance of airlines are also presented in the figure but are not taken in account in the eco-efficiency analysis of this research. These are e.g. Available Seat Kilometre (ASK), Revenue Passenger-kilometres (RPK), Passenger Load Factor (PLF), Passenger Revenue per Available Seat Kilometre (PRASK) and Cost per Available Seat Kilometre (CASK).

The main goals to be addressed by airlines in the context of eco-efficiency improvement towards climate change mitigation consists in:

- Increase ASK, RPK, PLF, PRASK, and $GVACO_{2e}$
- Reduce CASK and ECASK

In order to achieve these goals, among other initiatives it becomes relevant to enhance the awareness of air passengers concerning their contribution to climate change and engage them to choose more eco-efficient flights whenever is possible. A positive reaction by air passengers in this regard can be encouraged by:

- Charging fuel on air passengers proportionally to their relative consumption across different flights.
- Involving airports and government to charge taxes and fees proportionally to estimated climate change cost per seat.

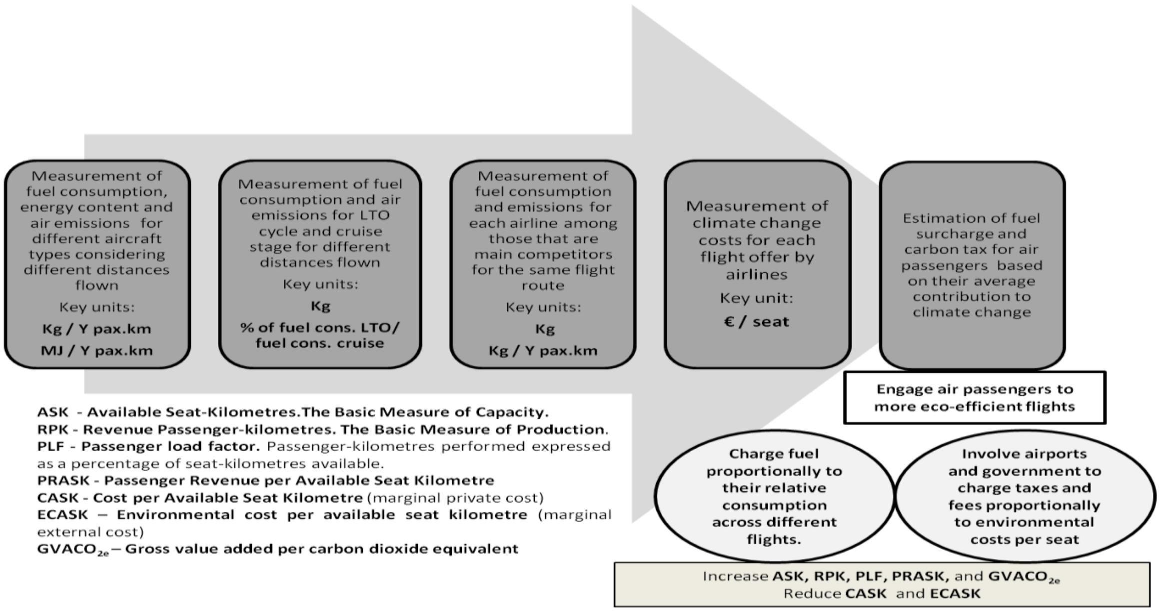


Figure 16 Main steps in the calculation of fuel consumption and GHG emissions for largest European airlines in selected hub-to-hub flight routes.

2.2 LIFE CYCLE ASSESSMENT ORIENTED TO CLIMATE CHANGE MITIGATION

There has been several publications focused on the estimation and reporting of emissions by aircraft engines in different modes of flight, which in turn can provide a valuable support for the development of benchmarking of airlines within the framework of EU ETS and can also be used by airlines to find more efficient alternatives to reduce its emissions based on fuel consumption and flight path designs [190; 191; 192; 85]. These researchers highlighted that most of environmental impacts of aircraft come from the consumption of kerosene and its airborne emissions; i.e. the fuel burn process. This is clearly the case of GHG emissions which in turn is largely represented by CO_2 released at high altitudes during the cruise stage of flights. Therefore, the most effective way to improve environmental performance of airlines facing climate change mitigation is to undertake initiatives that jointly contribute to reduction of aircraft emissions, particularly during the cruise stage.

For this reason, this dissertation presents in this chapter a full life cycle assessment focused on the emissions of carbon dioxide equivalent (CO_{2eq}) for two aircraft types regularly used by European airlines – Airbus A330-200 and Boeing 777-200. In the subsequent chapter author proposes a simplified life cycle analysis conceptual framework for climate change mitigation. The conceptual simplification consists in the estimation of GHG emissions only released during operational phase of aircraft and is based on the premise evidenced by other researchers that the operational phase of an aircraft has a much more substantial contribution to climate change than other phases of aircraft lifespan. This evidence is highlighted as the hypothesis 1 in this research and is tested for validation in this chapter based on the comparison of calculated embodied CO_{2eq} emissions per passenger-kilometre during the aircraft manufacturing phase, and the aircraft maintenance phase with the calculated CO_{2eq} emissions released during the operation phase.

2.2.1 Definition of goal and scope and functional unit

The initial LCA presented in this dissertation aims at measuring the contribution to climate change of each of the main phases of life cycle for two aircraft types extensively used by European airlines. This contribution is analyzed in terms of selected functional unit. Then, a comparison is done between both aircraft concerning their overall contribution to climate change also in terms of the functional unit.

The LCA covers the following main phases: aircraft manufacturing, aircraft maintenance, and aircraft operation. These phases form the system boundaries of this LCA.

Before clarifying the main assumptions taken for each phase, it is important to remark that previous research showed that when aircraft disassembly, reuse, recycling, incineration or disposal is considered, the overall contribution of the end-of-life scenario is beneficial to the environment, mainly due to the contribution of the aluminium recycling and in a smaller scale, to the recycling of steel [10]. Nevertheless, this positive contribution in terms of embodied emissions represents no more than 10% of the overall manufacturing phase [110]. Because data concerning precise disposal scenarios are scarce and no precise data are given regarding proportions of material recoverable, these precursor studies highlighted particular materials and assemblies and the disposal conditions that may apply [109]. For this reason, this phase of aircraft lifespan is not considered in this LCA.

In the aircraft manufacturing phase are estimated the embodied CO_{2eq} emissions to each component used. The emission factors used for calculating the embodied emissions of materials are assumed to be the same for both aircraft. Based on previous research on LCA [10; 110] and on data collected on the websites of Airbus and Boeing [193; 194], most of components used by their aircraft are produced in the same country of the assembly lines of Airbus (Toulouse, France) and Boeing (Seattle, United States). Therefore, the contribution in terms of CO_2 emissions during the transport of components to the assembly lines is not so relevant in comparison to the emissions released from energy consumption during their manufacturing.

In the aircraft maintenance phase, embodied CO_{2eq} emissions are estimated from electricity consumed and from airframe and components replaced during the aircraft lifespan. Maintenance costs are conventionally provided in terms of block hours. By definition block hour corresponds to the time from the moment the aircraft door closes at departure of a revenue flight until the moment the aircraft door opens at the arrival gate following its landing [195]. However, for simplification in the LCA maintenance phase of aircraft, author considers total block hours the same as total flight hours and thus, estimates total maintenance cost during the lifespan of aircraft based on minimum service life in total flight hours.

Another simplification considers the assumption that both aircraft as being regularly used by British Airways have all their maintenance checks at the London Heathrow International airport. Therefore, embodied emissions during this phase accrue mainly from the energy consumed during the maintenance checks in that airport.

In the operation phase, CO_{2eq} emissions released by engines during all the lifetime of aircraft are quantified. In this part of the calculation, an average distance of 3500 nm (approximately 6482 km) is considered for both aircraft types since they are largely used for long-haul flights. This distance corresponds approximately to the flight distance from London Heathrow to New York John Kennedy International airport, a flight route with high passenger demand. The passenger load factor considered in both operational analysis is 81.5%, which was the average passenger load factor of British Airways in 2011 for flights from Europe to North America [196]. Also important is to consider the passenger-to-freight factor (PFF) which is the ratio calculated from ICAO statistical database based on the number of passengers and the tonnage of mail and freight, transported in a given route group. It is necessary to deduct the flight emissions associated with the freight and mail carried on the flight from the total. For the same flight route group (Europe to North America) a PFF of 76.95% was adopted for a wide body aircraft as presented in ICAO Traffic by Flight Stage (TFS) data set [197].

All calculations were performed based on three seat configurations for each aircraft – the maximum capacity considering only economy seats available and two other seat configurations currently used by British Airways.

Concerning the service life, it is assumed that both aircraft have 60,000 flight hours since this is usually the minimum design services objective for wide body aircraft [198]. The economical (typical) cruise speed of Boeing 777 is 905 km/h [199], whilst the cruise speed of Airbus A330-200 is

871 km/h [200]. Table 12 summarizes the assumptions assumed in this analysis as previously described.

Table 12 Main assumptions for simplification in the scope of the Life Cycle Assessment of A330-200 and Boeing 777-200 facing climate change mitigation.

Environmental impact considered	Climate change
Unit of measurement	Kg CO_{2eq}
System boundaries	
Aircraft manufacturing phase	The emission factors used for calculating the embodied emissions of materials used are the same for both aircraft.
	Most of aircraft components are produced in the same country of the assembly line.
Aircraft maintenance	Block hours are considered the same as flight hours during the lifespan of an aircraft.
	All maintenance services are provided by the same airport (London Heathrow).
Aircraft operation	An average flight distance of 3500 nm (approx. 6482 km) is considered for both aircraft.
	An average PLF of 81.5% is considered
	An average PFF of 76.95% is considered

The choice of the functional unit is essential when performing an LCA since it influences the outcome of the study. The functional unit usually adopted for the passenger transportation sector is: passenger.km [201; 113]. Therefore, CO_{2eq} emissions are analysed referring to the transportation of one passenger, through a travelled distance of 1 km.

2.2.2 Inventory analysis

In a second step, a Life Cycle Inventory (LCI) is compiled with a flow diagram showing the system boundaries chosen within the horizon of boundaries that can be defined in a more extensive study. Data collection and processing are explained and results obtained are assessed and analyzed. The main inputs considered in the system under analysis are:

- Energy
- Fuel
- Raw materials
- Passengers
- Mail and freight

On the other hand, the main outputs considered are:

- CO_{2eq} emissions
- Passengers
- Mail and freight

The results of this analysis provide a valuable support in the decision-making concerning the processes where more opportunities are available for mitigating climate change.

The framework of the inventory analysis as well as the assessment of both data and results are defined in EPA´s document "Life Cycle Assessment: Inventory Guidelines and Principles" [202] and "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis" [203].

2.2.2.1 Flow diagram

Based on previously described system boundaries, a very simplified flow diagram of aircraft life cycle is shown on figure 17. Although the end-of-life cycle phase is not included in this study, it is also illustrated in this flow diagram.

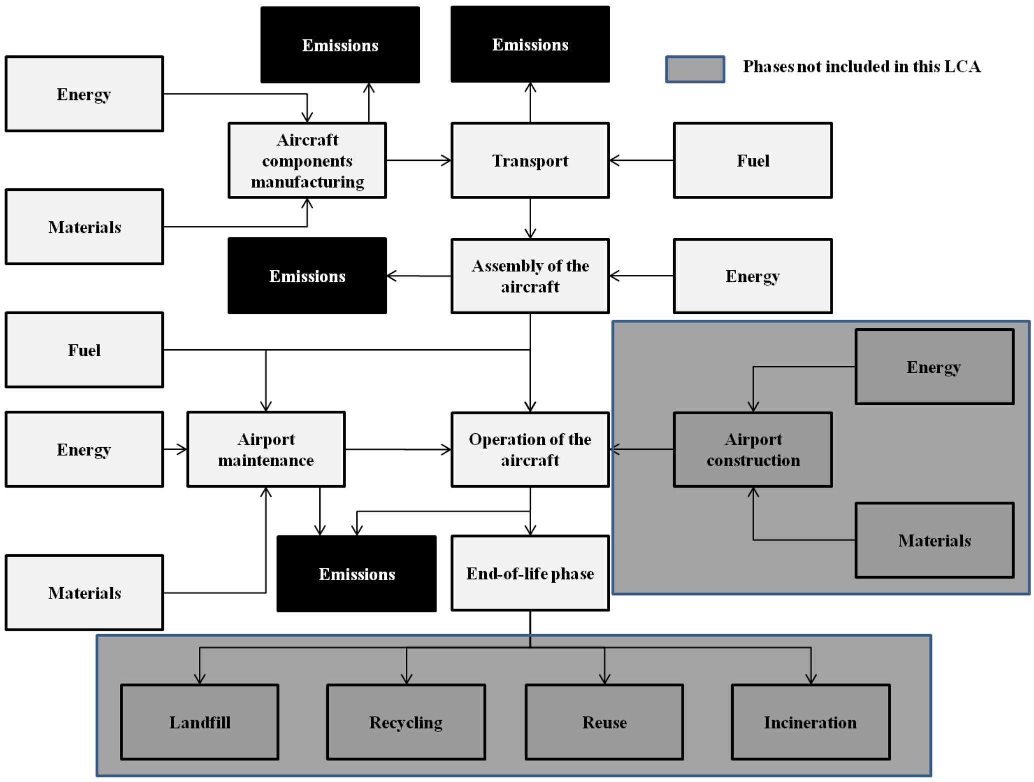


Figure 17 Flow diagram of the full Life Cycle Conceptual Framework for a commercial Aircraft.

The indirect contribution of airport construction to climate change is not included in this analysis due to a great uncertainty regarding the expected life span of the airport, the flights frequency and travelled distance per flight taking place at the airport. Actually, previous research demonstrated that the most relevant categories of environmental impacts of airport construction are agricultural land occupation, metal depletion, freshwater eutrophication and human toxicity [10 pp. 69-71]. Eutrophication can be defined as [204] “the process by which a body of water acquires a high concentration of nutrients, especially phosphates and nitrates.” This process can promote excessive growth of algae and result in the depletion of dissolved oxygen in water bodies.

2.2.2.2 Data collection and processing

In order to perform a more consistent comparison, two aircraft used by the same airline were selected (British Airways) as well as the same hub airport (London Heathrow International airport). The assumption of aircraft used by the same airline allowed the adoption of the same passenger load factor and passenger-to-freight factor. On the other hand the assumption of the same hub airport resulted in the adoption of the same percentage of cost associated with aircraft maintenance and the same price of electricity per KWh, which in turn is a relevant data in the estimation of expenses associated to electricity consumed during maintenance of aircraft. Table 13 presents in detail the relevant parameters for the calculation of manufacturing phase of LCA.

The same materials were identified in the production of both aircraft types and the weight contribution in percentage of each material was found in the literature as specified under the table. These percentages of materials used take in account the operating empty weight of each aircraft type. Operating empty weight 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 [205]. Embodied energy (MJ/Kg) and emission factors (Kg CO_{2eq}/Kg) per virgin material used, as well as emission factors during flight operation were the same for both cases, assuming that materials used in the manufacturing of aircraft have the same origin. This was one of the hypotheses for simplification described in the previous section.

Considering that aircraft analyzed (Airbus A330-200 and Boeing 777-200) are manufactured by two different companies, the process of gathering data involved consultation of an extensive source that included technical catalogues issued by each manufacturer.

Table 13 Relevant parameters for the calculation of manufacturing phase of LCA.

Material	**A330-200** [(1)] **(%)**	**B777-200** [(2)] **(%)**	**Embodied energy virgin material (MJ/kg)** [(3,4)]	**Emission factor (kg CO_{2e}/Kg)** [(5,6)]
Aluminium	58.3	70	218	12.79
Steel	19.2	11	32	2.89
Titanium	7.7	7	553	31.55
Nickel	2.8	0.9	164	13.14
CFRP	9.1	10	286	6.04
GFRP	1	1	100	8.59
Miscellaneous	1.9	0.1	72	4.18
Total	100	100		

*Note: 1 [10]; 2 [206]; 3,6 [207]; 4 [208]; 5 [209].

The average fuel consumption rate per distance flown was based on the EMEP/CORINAIR Emission Inventory Guidebook [94 pp. 22-30]. The relevant data corresponding to each aircraft type analyzed are presented in table 14.

Service life is presented in flight hours for the purpose of calculating the emissions per passenger-kilometre during the whole lifespan of aircraft. However, sometimes it can also be demonstrated in terms of flight cycle, which considers the number of take-off and landing manoeuvres. Flight cycles are primarily important for tracking time on the landing gear to avoid fatigue tracks. For example, an average mission length of 3,000nm (approximately 5556km) may generate annual utilizations of 430 flight cycles (FC) or about 3,000 flight hours (FH); a 4,000nm route length 540FC/3,500FH; and 5,000nm 650FC/4,000F [210 p. 44]. Aircraft that fly regularly on short-hauls goes through pressurization cycles every day, which in turn accelerates the fatigue of fuselage and wings. On the other hand, aircraft that are used regularly on longer flights experience fewer pressurization cycles, and can last more than 20 years. The suggested minimum design service objective for Boeing 777 is 40,000 flights or 60,000 hours or 20 years. In this study, author used the same amount of service life in flight hours for Airbus A330-200 because both aircraft are used for similar average flight distances.

The capacity of each aircraft varies according to three possible configurations. Besides the maximum capacity configuration in which all seats are in economy class, Airbus A330-200 presents two other seat configurations, being one with two classes (economy and economy premium) and another with three classes (economy, economy premium and business). Boeing 777-200 even offers a four class configuration (first, business, economy premium and economy).

Table 14 Relevant parameters related to each aircraft type analyzed for the calculation of maintenance phase and operation phase of LCA

Item	A330-200	B777-200	Unit	Seat configuration
Service life	60,000 (1)	60,000 (2)	Flight hours	
Cruise speed	871 (3)	905 (4)	Km/h	
Capacity	208 (5)	224 (5)	pax	3-class / 4-class
	293 (5)	275 (5)	pax	2-class / 3-class
	380 (5)	440 (5)	pax	Max.
Operating Empty weight	119,600 (3)	134,800 (4)	Kg	
Price	164.85 (6)	197.42 (7)	Mio EUR	
Average maintenance cost per block hour	1000 (1)	1440 (8)	EUR / block hour	

*Note: 1 [210]; 2 [198]; 3 [211]; 4 [212]; 5 [213]; 6 [214]; 7 [215]; 8 [4]. The term “pax” is conventionally used by airlines to refer to “passengers”.

According to the report “Dynamic Cost Index” issued under the EUROCONTROL Programme CARE INO III, 65% of aircraft maintenance cost across airports in Europe is due to airframe and components replacement, whilst 35% is related to energy consumed from power plants [216 p. 6].

The price of electricity adopted in the UK was 0.10 EUR per kWh in 2008 [217]. In the same year, the total energy consumed by London Heathrow airport was 1,073 GWh and the corresponding total GHG emission was 2.386 million tonnes of CO_{2eq} according to the Sustainability Performance report released on annual basis by the airport [218 p. 4].

The next section presents the calculations performed for each phase of LCA.

2.2.3 Impact Assessment

An introductory step in the life cycle impact assessment (LCI) consisted in the calculation of total amount of passenger-kilometre during the lifespan of each aircraft type, which was obtained as shown in equation 1.8:

$$\text{Pax-km}_{(LF)} = SL * C * CS \quad (1.8)$$

where

"SL" is the service life of aircraft

"C" is the capacity of aircraft (varies according to seat configuration)

"CS" is the typical cruise speed of aircraft.

Table 15 shows these values for each aircraft considering different seat configurations based on values presented on table 14. These values are important for the final calculation of $CO2_{eq}$ per passenger-km in each phase of LCA.

Tab.15 Calculated values for passenger-km during the lifespan of each aircraft.

Item	A330-200	B777-200	Unit	Seat configuration
Passenger-km during lifespan	10,870,080,000	12,163,200,000	pax.km	3-class / 4-class
	15,312,180,000	14,932,500,000	pax.km	2-class / 3-class
	19,858,800,000	23,892,000,000	pax.km	Max.

2.2.3.1 Aircraft manufacturing

In the manufacturing phase of LCA the weight of materials used in each aircraft type was calculated based on the operating empty weight shown in table 14 and on the percentage of materials used as shown in table 13. The material distribution in weight is presented in table 16 for Airbus A330-200 and in table 17 for Boeing 777-200 as well as their respective embodied energy and embodied emissions. Values presented of weight are calculated from values from table 13 and table 14. The values calculated for embodied energy and embodied emissions for virgin materials are based on the factors presented in table 11 and on the weight of each material. These values are aggregated and divided per total amount of passenger-kilometres flown during the lifespan of each aircraft type and each seat configuration chosen.

It can be observed from the values provided in table 16 and table 17 that total CO_{2eq} emissions per passenger-kilometre during the manufacturing of Boeing 777-200 is higher when comparing maximum design capacity due to the fact that there is a higher percentage of aluminium used in the components of this aircraft type, which in turn is the most energy-intensive material among those used in aircraft manufacturing.

Tab. 16 Embodied energy and embodied emissions during aircraft manufacturing phase for Airbus A330-200.

Materials in A330-200	**Weight (in Kg)**	**Embodied Energy in aircraft manufacturing (MJ)**	**Embodied emissions kg CO_{2eq}**
Aluminium	61,903	1.35E+07	7.92E+05
Steel	20,388	6.52E+05	5.89E+04
Titanium	8,161	4.51E+06	2.57E+05
Nickel	2,948	4.83E+05	3.87E+04
CFRP	9,743	2.79E+06	5.89E+04
GFRP	1,059	1.06E+05	9.10E+03
Miscellaneous	2,015	1.45E+05	8.42E+03
Total	106,217	2.22E+07	**1.22E+06**
Total emissions CO_{2eq} per pax.km	1.13E-04	kg CO_{2eq} / pax.km	3-class
	7.99E-05	kg $CO2_{eq}$ / pax.km	2-class
	6.16E-05	kg $CO2_{eq}$ / pax.km	max.

Tab. 17 Embodied energy and embodied emissions during aircraft manufacturing phase for Boeing 777-200.

Materials in Boeing 777-200	Weight (in Kg)	Embodied Energy in aircraft manufacturing (MJ)	Embodied emissions kg CO_{2eq}
Aluminium	94,360	2.06E+07	1.21E+06
Steel	14,828	4.74E+05	4.29E+04
Titanium	9,436	5.22E+06	2.98E+05
Nickel	1,213	1.99E+05	1.59E+04
CFRP	13,480	3.86E+06	8.14E+04
GFRP	1,348	1.35E+05	1.16E+04
Miscellaneous	135	9.71E+03	5.63E+02
Total	134,800	3.05E+07	**1.66E+06**
Total emissions CO_{2eq} per pax.km	1.36E-04	kg CO_{2eq} / pax.km	4-class
	1.11E-04	kg $CO2_{eq}$ / pax.km	3-class
	6.94E-05	kg $CO2_{eq}$ / pax.km	max.

2.2.3.2 Aircraft maintenance

As described in the previous section, table 18 presents the average distribution in percentage for aircraft maintenance cost across airports in Europe due to airframe and components replacement. This information enabled the first calculations during the maintenance phase of LCA. Firstly, average total maintenance cost during the lifespan of aircraft was calculated by multiplying average maintenance cost per block hour with service life of aircraft.

Table 18 Average costs associated to maintenance of aircraft during its lifespan.

Cost item	Percentage [1]	A330-200	B777-200	Units
Airframe/components	65%	39.0	56.2	Mio EUR
Power plant	35%	21.0	30.2	Mio EUR
Total	100%	60	86.4	Mio EUR

*Note: 1 [216]. The total value is calculated by multiplying "service life" by "average maintenance cost per block hour" for each aircraft as given in table 14.

Table 19 shows the average consumption of electricity associated to aircraft maintenance during its lifespan assuming that all maintenance services are offered by London Heathrow airport.

Table 19 Electricity consumption and CO_{2eq} emissions per passenger-kilometre associated to maintenance of aircraft during its lifespan.

Item	A330-200	B777-200	Unit	
Price of electricity per kWh[1]	0.10	0.10	EUR	
Consumption of electricity during aircraft lifespan	212	306	GWh	
Total energy consumed in one year by London Heathrow airport [2]	1073	1073	GWh	
Total CO_{2eq} emissions in one year by London Heathrow airport [2]	2,386,000	2,386,000	t CO_{2eq}	
CO_{2eq} emissions from power plant	5.E+08	7.E+08	kg CO_{2eq}	
Embodied CO_{2eq} emissions of replaced airframe/components	7.95E+05	1.08E+06	kg CO_{2eq}	
Total emissions CO_{2eq} during maintenance	5.E+08	7.E+08	kg CO_{2eq}	
Total emissions CO_{2eq} per pax.km	4.35E-02	5.60E-02	kg CO_{2eq} / pax.km	3-class / 4-class
	3.09E-02	4.56E-02	kg CO_{2eq} / pax.km	2-class / 3-class
	2.38E-02	2.85E-02	kg CO_{2eq} / pax.km	Max.

*****Note: 1 ***[217]***; 2 ***[218]***. Embodied CO_2eq emissions of replaced airframe and components were calculated assuming that they represented an additional 65% of all embodied emissions estimated during the aircraft manufacturing phase.

2.2.3.3 Aircraft operation

The carbon dioxide equivalent (CO_{2eq}) emissions during the aircraft operation phase were estimated based on ICAO methodology as described in section 1.2.3. Initially, fuel consumption per pax.km is estimated according to equation 2.1.

Fuel consumption per Y pax.km = (TF * PFF)/(Y-seats * PLF * flight distance) (2.1)

Where

*"**TF**" is "total fuel" consumed for the flight distance performed. As described in section 1.2.3 it represents the average amount of fuel consumed by all aircraft of equivalent type for each flight distance considered measured in nautical miles (nm).*

*"**PFF**" is "pax-to-freight factor" which is the ratio calculated from ICAO statistical database based on the number of passengers and the tonnage of mail and freight, transported in a given route group.*

*"**Y-seats**" mean "number of y-seats" and represent the total number of economy equivalent seats available in the aircraft type considered. This value represents the maximum seat capacity the aircraft type considered can have if all seats available were configured for economy class (high density seat configuration).*

*"**PLF**" is "pax load factor" which is the ratio calculated from ICAO statistical database based on number of passengers transported and the number of seats available in a given route group.*

***Flight distance** corresponds to the great circle distance as explained in section 1.2.3.*

The fuel burn to flight distance relationship is interpolated from the CORINAIR table [94], while PLF and PFF correspond to traffic data per route group updated by ICAO and economy class (Y) seat capacity is given by aircraft manufacturer.

Calculation assumes the average CO_{2eq} emissions per passenger-kilometre for each aircraft type for an average flight distance of 3500 nm (approximately 6482 km) as shown in table 20. For both aircraft types, the distance of 3500 nm is within the range at which they fly in a more fuel-efficient manner, i.e. they use less fuel per passenger-kilometre, considering other parameters the same. Therefore, it may be expected that CO_{2eq} emissions per passenger-kilometre will be the lowest in this flight distance.

Table 20 CO_{2eq} emissions per passenger-kilometre associated to aircraft operation during its lifespan considering an average flight distance and different seat configurations.

Distance	A330-200	B777-200	Unit	Seat configuration
3500 nm (6482 km)	0.204	0.215	kg CO_{2eq} / pax.km	3-class / 4-class
	0.145	0.175	kg CO_{2eq} / pax.km	2-class / 3-class
	0.112	0.110	kg CO_{2eq} / pax.km	Max.

Other parameters assumed include a passenger load factor (PLF) of 81.50%, and a passenger-to-freight factor (PFF) of 76.95% for three different seat configurations. Moreover, according to CORINAIR database an aircraft A330-200 has an average fuel consumption of 44312kg and a B777-200 consumes in average 50295kg of fuel.

It is important to remind that ICAO methodology only focuses in the emissions of carbon dioxide. Other GHGs are not considered. In order to estimate the emissions of other GHGs together with carbon dioxide, author firstly estimated the fuel consumption per passenger-kilometre and then converted into MJ per passenger-kilometre (energy content) taking in account that 1kg of aviation kerosene has 46.36 MJ [219]. Subsequently, energy content was converted to CO_{2eq} by assuming emission factor of 0.0745 kg CO_{2eq}/ MJ [220] and multiplying by 1.9 to take into account the effect of radiative forcing index (RFI) as described in section 1.1.3.

In summary the conversion of fuel consumption per pax.km to $CO2_{eq}$ per pax.km can be done according to following procedures as described in equations 2.2 and 2.3:

Energy content per Y pax.km = 46.36 * fuel per Y pax.km (2.2)

CO_{2eq} per pax.km = 0.0745 * 1.9 * energy content per Y pax.km (2.3)

Table 21 shows how embodied emissions during the aircraft manufacturing and maintenance (Accounts, 2008) phases gradually increase in relation to emissions released during aircraft operation throughout its lifespan. This increase in percentage is perceived until the aircraft reach the distance of 3500nm. For average longer distances, fuel efficiency in terms of passenger-kilometre is gradually worsened for both aircraft types and consequently, the emission levels of CO_{2eq} tend to increase again considering the same functional unit. It can be noted that when maximum seat configuration is taken, B777-200 can reach better results for CO_{2eq} per passenger-kilometre.

Table 21 Percentage represented by embodied CO_{2eq} emissions during manufacturing and maintenance of aircraft in relation to CO_{2eq} emissions released during aircraft operation throughout its lifespan.

Aircraft	1000	1500	2000	2500	3000	3500	4000
A330-200	19.14%	20.48%	21.08%	21.30%	21.31%	21.34%	21.19%
B777-200	22.88%	24.88%	25.62%	25.98%	26.03%	26.05%	25.86%

2.2.4 Interpretation of results

Figure 18 and figure 19 illustrate overall results for embodied CO_{2eq} emissions in each LCA phase analyzed for A330-200 and B777-200, respectively.

It can be noted that the most significant contribution in terms of CO_{2eq} emissions per passenger-kilometre comes from aircraft operation phase. Thus, it validates hypothesis 1 stated in section 2.1 of this research. In this phase, considering the functional unit and methodology adopted, influential parameters are: aircraft seat configuration, passenger load factor (PLF), and passenger-to-freight factor (PFF). Therefore, the contribution of each passenger to CO_{2eq} emissions per kilometre can be reduced mainly by offering high density seat configuration, by increasing PLF and decreasing PFF. Moreover, if both aircraft are used in its maximum seat capacity configuration (only economy seats) the CO_{2eq} emissions per passenger-kilometre will be slightly lower for A330-200 than for B777-200. However, when considering the same seat configuration for each aircraft (3-class) B777-200 generates less CO_{2eq} emissions per passenger-kilometre than A330-200 mainly due to the fact that B777-200 in this seat configuration has a higher passenger capacity (275 passengers while A330-200 can carry only 208 passengers).

As previously mentioned, the end-of-life scenario (aircraft disassembly, reuse, disposal or recycling) was not included in this analysis, although it is important to highlight that once measured, the results in terms of CO_{2eq} emissions per passenger-kilometre will be negative but in a much lower order (- x.xxE-13) which translate a small positive contribution for all environmental impacts considered.

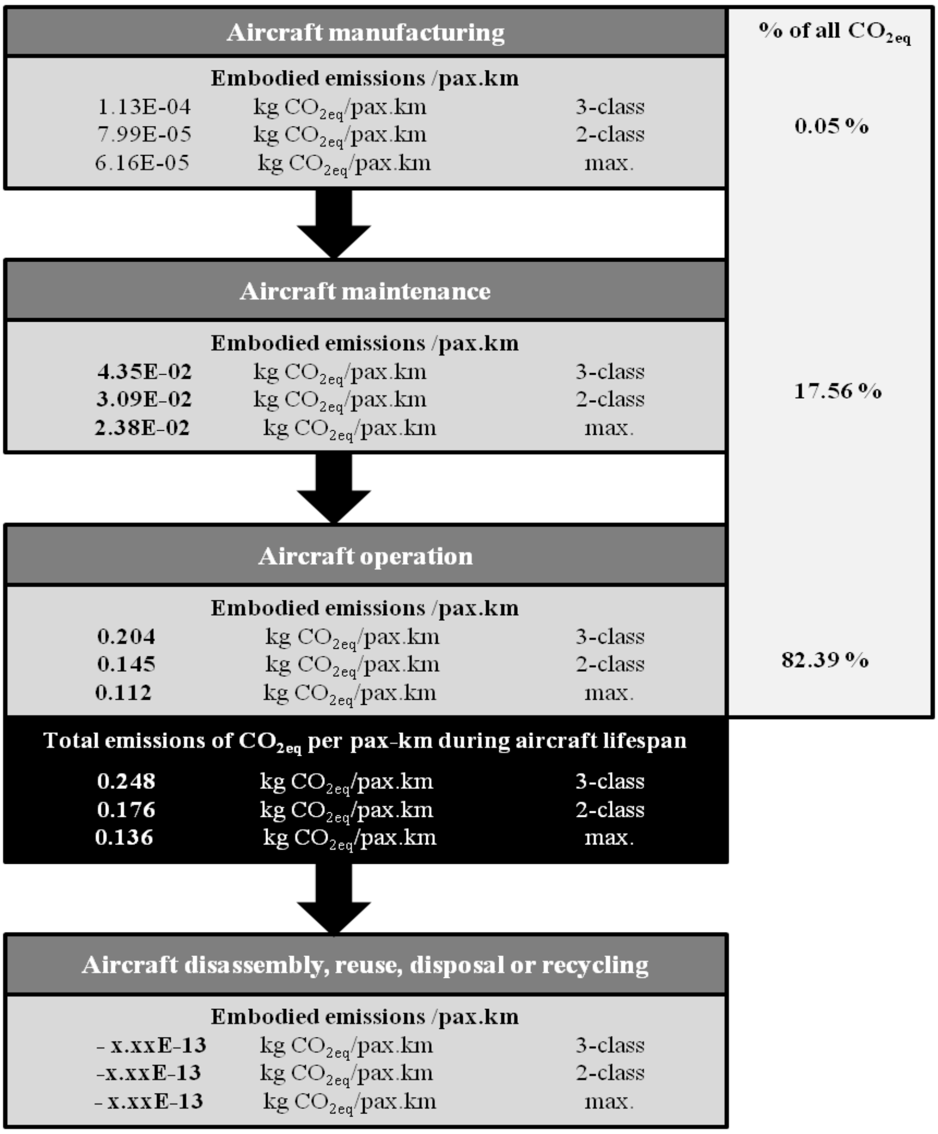


Figure 18. Embodied and released CO_{2eq} emissions during each LCA phase analysed for A330-200.

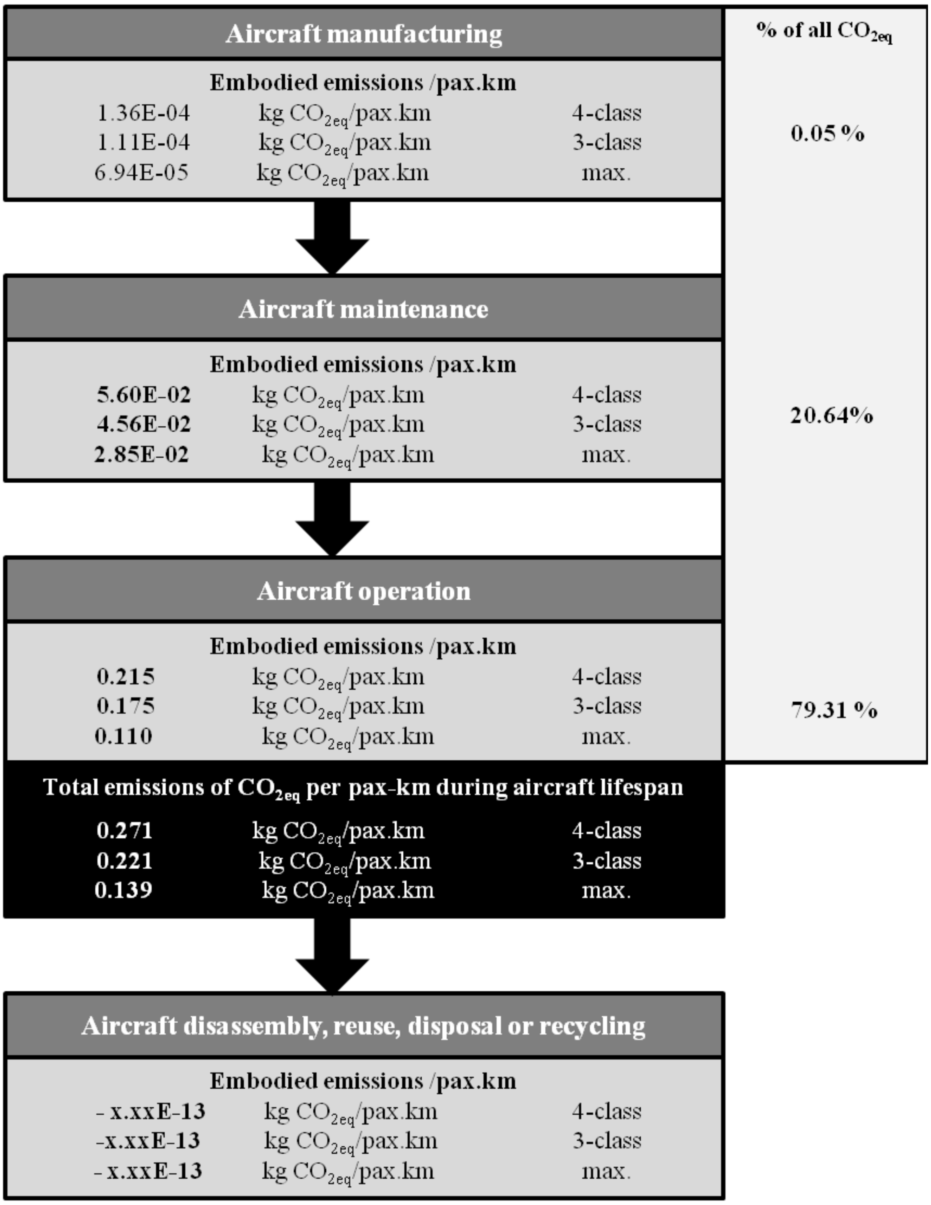


Figure 19. Embodied and released CO_{2eq} emissions during each LCA phase analysed for aircraft B777-200.

2.3 SIMPLIFIED LCA FOR COMMERCIAL AIRCRAFT WITHIN THE CONTEXT OF CLIMATE CHANGE

Considering that most of environmental impacts of aircraft come from the aircraft fuel consumption and its airborne emissions, particularly when addressing the effects of commercial aviation to climate change, a LCA can be simplified as briefly described in the section 2.2 and be focused in the aircraft operation phase. This phase consists basically of two flight cycles: landing-takeoff (LTO) cycle and cruise stage.

The LTO cycle as defined in ICAO [221] includes all activities near the airport that take place below the altitude of 1000 m (3000 feet). It includes taxi out, take-off, climb out, descent, approach landing and taxi-in manoeuvres. Taxi out is the movement of the aircraft on the ground during departure from a terminal to the runway. Taxi in is the movement of the aircraft on the ground during arrival from the runway to a terminal. Conventionally, emissions and fuel used in the LTO phase are estimated from statistics on the number of LTOs in aggregate or per aircraft type. Therefore, default emission factors or fuel use factors per LTO are given in average values or per aircraft type [222; 223; 224].

Cruise stage is defined as all activities that take place at altitudes above 1000 m (3000 feet). No upper limit of altitude is given. It includes climb from the end of climb-out in the LTO cycle to cruise altitude, cruise, and descent from cruise altitudes to the start of LTO operations of landing [86]. The cruise phase in which the aircraft covers a certain distance at a constant altitude can vary depending on the total stage length distance, which in turn corresponds to the distance that a plane stays in the air from a take-off operation to a landing operation. The flight altitude of this phase varies typically on short-haul flights in the range from about 5 to 7 kilometres, and medium and long-haul flights vary between 10.5 to 13 kilometres [192]. The largest percentages of trip time and trip fuel are consumed typically in this phase of flight. The same is evidenced for CO_2 emissions because these emissions are directly related to fuel consumption.

Two main calculations are performed in the simplified LCA with the purpose of testing the hypotheses 2, 3, 4, 5, 6 and 7 as defined in section 2.1. These hypotheses are transcribed in this chapter in the appropriate sections in which they are tested for validation. In all cases calculations are performed for flight operations of aircraft which are commonly used by three largest European airlines in their respective hub airports for flights with a high daily passenger demand. The largest European airlines in terms of total passengers carried per year as highlighted in the section 1.1.4.1 are: Lufthansa, Air France and British Airways.

An airline hub is an airport that an airline uses as a transfer point to get passengers to their intended destination. It is part of a hub and spoke model, where travellers moving between airports not served by direct flights change planes en route to their destinations. The hub airports of airlines chosen in the analysis of this research are: Frankfurt International airport (Lufthansa), Paris Charles de Gaulle international airport (Air France) and London Heathrow international airport (British Airways).

First calculations presented in section 2.3.1 are focused in the fuel consumption and GHG emissions for different distances flown by aircraft listed in table 22. Average values for fuel burnt per distance flown as those provided by EMEP/CORINAIR Emission Inventory Guidebook [94] for each aircraft type are considered together with other important input parameters such as passenger load factor (PLF), pax-to-freight factor (PFF) and seating configuration. Results of these calculations are presented in section 3.1.1.

Table 22. Aircraft chosen for analysis and comparison in the simplified LCA.

Aircraft manufacturer	Aircraft models
Airbus SAS	A318-100, A319-100, A320-200, A321-200, A330-200
The Boeing company	B767-300, B747-400, B737-400, B777-200

In section 2.3.2 calculations of fuel burnt and more detailed emissions are performed for different phases of flight operation. Firstly, in 2.3.2.1 average fuel consumption and average GHG emissions are given for LTO cycle (in Kg/LTO) and obtained directly from EMEP/CORINAIR emission inventory guidebook [86; 94; 225]. Subsequently, average fuel burnt and GHG emissions are calculated for different flight distances performed during cruise phase by each aircraft type chosen. For this calculation, author adopted the combined IPCC tier 3A methodological approach and ICAO methodology as explained in the section 2.3.2.

Author also calculates the share of fuel burnt during the LTO cycle in relation to fuel consumed during cruise stage for different distances flown by different aircraft types. In this case, however, author uses again average values for fuel burnt per distance flown as those provided by EMEP/CORINAIR Emission Inventory Guidebook [94]. Results of these calculations are presented in section 3.1.2.

In section 2.3.2.2 author calculates fuel consumption and carbon emissions by means of Petri nets with the support of Umberto software version 5.5. This software consists in one of those powerful expert systems highlighted in section 1.3. In this calculation procedure different amount of fuel consumption and carbon emissions are estimated for the same aircraft type using different engines in the same flight route. Technical parameters of most common engines used for each aircraft type could be obtained with specific fuel burn rate per second and emissions factors per Kg of fuel burnt depending on the thrust setting applied. Considering that different engine thrust setting is applied depending on the flight phase and that each phase has an average duration in minutes it was possible to calculate more specific fuel consumption and carbon emissions per each phase of LTO cycle and also for the cruise stage. Therefore, the flight time is taken as an important input parameter instead of flight distance. Other parameters as considered in first calculation procedure are maintained. A comparison is also undertaken among different aircraft types of the same manufacturer that are used by airlines considered. Results of these calculations are presented in section 3.1.3.

Further calculations of average fuel consumption and GHG emissions per passenger-kilometre as presented in section 2.3.3 are performed for specific aircraft types used by competing airlines in chosen flight routes departing from hub airports considered. These flight routes as defined in section 1.1 are categorized by: short-haul (less than 800 km), medium-haul (between 800 and 3,000 km) and long-haul (more than 3,000 km). Results of these simulations are calculated and presented in the section 8.3 in terms of aggregate amount of fuel consumed and CO_2 emitted per passenger-kilometre for all possible combinations of outbound and inbound flights offered by each competing airline considered. The real fuel cost per passenger and the associated impacts on climate change from each flight combination are monetized and also presented based on estimated individual emissions of CO_2, H_2O and NO_x.

2.3.1 Fuel consumption and GHG emissions for different distances flown

Initially, a calculation of fuel consumption and GHG emissions per passenger-kilometre for different distances flown (conventionally named by "great circle distance" as explained in section 1.2.3) is performed. In this calculation, author uses the methodology of ICAO Carbon Emissions Calculator version 5 (2012). This methodology estimates only CO_2 emissions per economy equivalent passenger (Y pax). As shown in equation 2.4, CO_2 emissions can be estimated per passenger-kilometre based on same parameters as those presented in equation 2.4 but with a multiplying emission factor of 3.157 as recommended by the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.

$$CO_2 \text{ per Y pax.km} = 3.157 * (TF * PFF)/(Y\text{-seats} * PLF * \text{flight distance}) \qquad (2.4)$$

Since these calculations are performed with the purpose of verifying the possibilities of improvements in short-haul flights for European airlines in terms of reduction in fuel consumption and CO_2 emissions per passenger-kilometre, the pax-to-freight factor (PFF) considered was 99.00% and passenger load factor (PLF) assumed was 73.96% as provided by ICAO database on average values registered in 2012 for flights within Europe.

Other emissions are calculated with the support of emission factors per ton of fuel consumed as recommended by the report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* [226], which in turn is based on the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Only the emission factors for cruise stage of international flights are considered in these calculations and are presented in table 23. As mentioned in section 1.2, NO_x emission is not directly related to fuel consumption but depends on combustion temperature which increases with engines' power setting. The same applies for other emissions such as carbon monoxide (CO) and hydrocarbons (HC), although they are not taken in account for accurate analysis in this study when only the impacts of flight operations on climate change are considered. Therefore, in order to increase the accuracy of measurements, it is recommended to adopt a separate emission factor for NO_x for each phase of LTO cycle and for cruise stage depending on the type of engines used and their respective fuel flow (measured in Kg of fuel per second) and emissions indices (measured in grams of emissions per kilograms of fuel burnt).

Table 23. Emission factors for cruise stage of average aircraft used in international flights [7].

International	SO_2	CO	CO_2	NO_x	NMVOCs	CH_4	N_2O	H_2O
Cruise (kg/ton of fuel)	1	5	3150	17	2.7	0	0.1	1237

All emissions per distance flown were calculated for each aircraft type considered in terms of passenger-kilometre. However, author emphasizes the results of fuel consumption and CO_2eq emissions per economy equivalent passenger-kilometre (Y pax.km). The same procedure as described in section 1.2.3 was adopted to estimate CO_{2eq} emissions based on fuel consumption per distance flown.

The hypothesis 2 as described in section 2.1 is verified based on the results of these calculations presented in the section 3.1. These results can help in the choice of the most appropriate flight length for each aircraft type in terms of fuel consumption and carbon emissions per km flown per Y pax.

Hypothesis 2 states that “for every aircraft model, there is a range of flight distance at which aircraft can perform better in terms of fuel consumption and GHG emissions per passenger-kilometre.”

2.3.2 Fuel consumption and GHG emissions in different phases of flight

In this section, fuel consumption and emissions released in different phases of flight are estimated by means of two different approaches: firstly, the ICAO methodology is used within the conceptual approach of IPCC tier 3A as described in section 2.3.2.1. Secondly, a more accurate method is described by means of Petri nets within the Umberto software environment. Whereas the former method seems to be more simplified, it allows a quick overview of how the ratio of fuel burnt and carbon emissions released during the LTO cycle varies in relation to those observed during the cruise stage. Latter method is more accurate because it takes in account engine data of each aircraft considered, thus resembling somewhat with the IPCC tier 3B method. It allows the visualization of differences in each particular phase of flight depending on additional parameters, such as engines used, and time elapsed during each phase.

2.3.2.1 The use of IPCC tier 3A methodological approach combined with ICAO method

In this section the values estimated are distributed only between LTO cycle and cruise stage for facilitating a comparison between aircraft types.

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories provides the emission factors for various aircraft types in each of these flight operation phases. The annex of these guidelines also provides average amount of fuel consumption and emissions during each part of the LTO cycle according to different aircraft types. Table 24 presents the fuel consumption and emission factors during the LTO cycle in Kg/LTO for different aircraft types analyzed in this study. In fact, these are average values of fuel consumption and emissions during LTO cycles for each aircraft type no matter the distance flown as suggested by IPCC.

Table 24 LTO emission factors for aircraft types used in this research

Aircraft	LTO Emissions factors (Kg/LTO)(1)							LTO fuel consumption (Kg/LTO)
	CO_2(2)	CH_4	N_2O(3)	NO_x	CO	NMVOC(4)	SO_2(5)	
A319	2310	0.06	0.1	8.73	6.35	0.54	0.73	730
A320	2440	0.06	0.1	9.01	6.19	0.51	0.77	770
A321	3020	0.14	0.1	16.72	7.55	1.27	0.96	960
A330-200	7050	0.13	0.2	35.57	16.20	1.15	2.23	2230
B737-400	2480	0.08	0.1	7.19	13.03	0.75	0.78	780
B747-400	10240	0.22	0.3	42.88	26.72	2.02	3.24	3240
B767-300	5610	0.12	0.2	28.19	14.47	1.07	1.77	1780
B777-200	8100	0.07	0.3	52.81	12.76	0.59	2.56	2560

*Note:

(1) Information regarding the uncertainties associated with this data can be found in [93; 86];

(2) CO_2 for each aircraft based on 3.16 kg CO_2 produced for each kg fuel used, then rounded to the nearest 10 kg;

(3) Estimates based on Tier I default values as in *2006 IPCC Guidelines* [7].

(4) Assuming 10% of total VOC emissions in LTO cycles are methane emissions as in the *2006 IPCC Guidelines* [7];

(5) The sulphur content of the fuel is assumed to be 0.05% as in the *2006 IPCC Guidelines* [7].

The results are presented in section 3.1.2.1 and allow the verification of hypothesis 4 as defined in section 2.1 which states that "for all aircraft analyzed, the amount of fuel consumed during LTO cycle is less significant than fuel consumed during the cruise stage."

Figure 20 outlines the procedures and input parameters used in these calculations performed in the simplified LCA focused in the effects of commercial aircraft to climate change from operational phase. The emissions estimated during the cruise stage consist in the subtraction of average values obtained during the LTO cycle from the values calculated for the whole flight in the initial calculation supported by fuel consumption rate provided by EMEP/CORINAIR Emission Inventory Guidebook (European Environment Agency (EEA), 2006). The calculations were performed based on the tier 3A method as suggested by 2006 IPCC Guidelines for National Greenhouse Gas Inventories. For climate change considerations only the emissions of CO_2, H_2O, and NO_x were analysed as well as the aggregate CO_{2eq} emissions. Although methane (CH_4) is a greenhouse gas, it is released only during the LTO cycle and in negligible levels in comparison to other GHGs. Furthermore, apart from comparing fuel consumption rates during LTO cycle and cruise stage for each aircraft type chosen, in section 3.1.1 author presents only the average CO_2 emissions during the cruise stage per distance flown for each aircraft type. Different aircraft types have different maximum flight ranges but for simplification values are presented for the same flight distance in common.

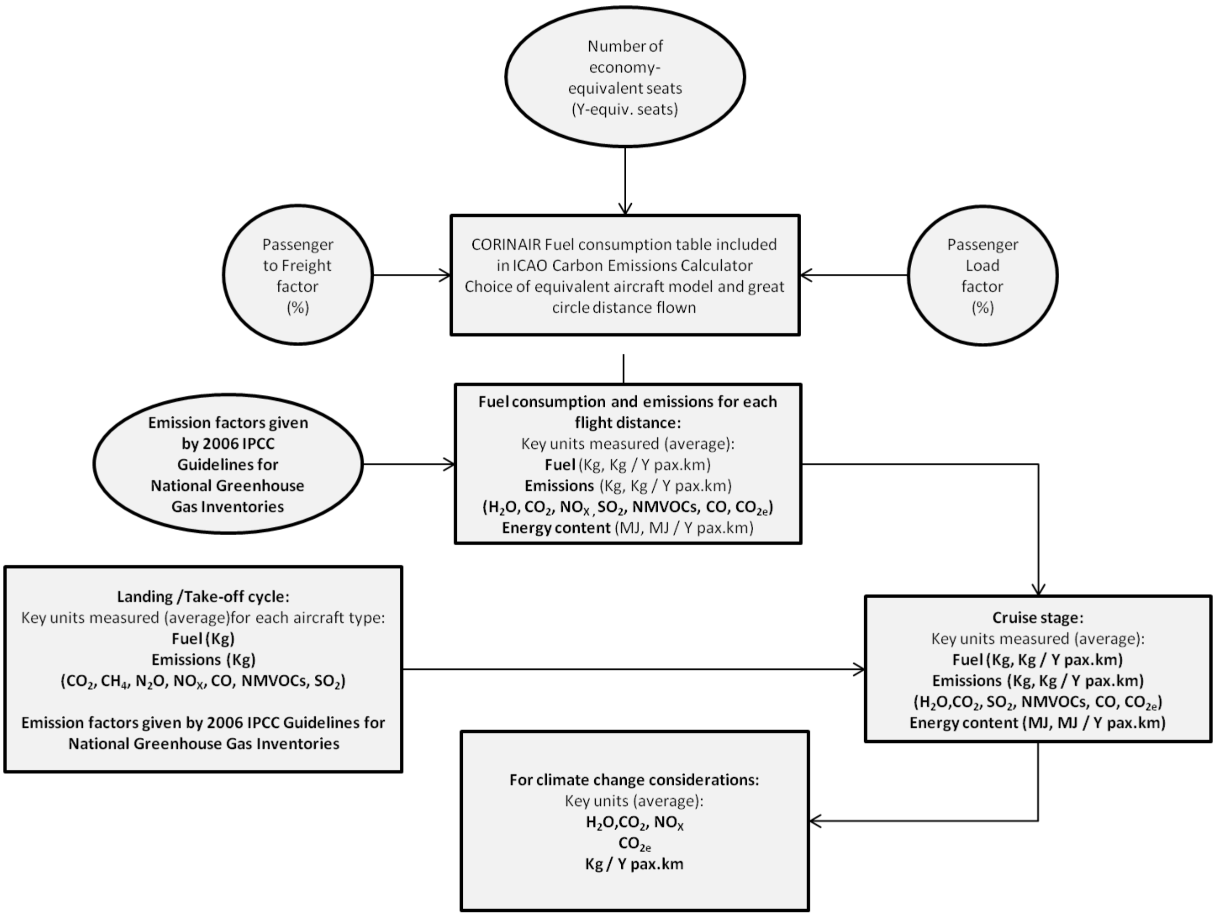


Figure 20. Outlined procedure for calculation of GHG emissions for different distances flown for a specific aircraft type.

This simplification supports the intention of the research in identifying the best alternatives for flying short-haul distances within Europe in terms of fuel consumption and CO_2 emissions per passenger-km. In fact, most of airlines which are reporting their GHG emissions during flight operations are doing solely in terms of CO_2 emissions, which is the main GHG addressed by EU ETS for the civil aviation sector.

As explained in section 1.1.2 aviation NO_x emissions at cruise altitudes result in an enhancement of ozone (O_3) in the upper troposphere and lower stratosphere (UTLS) and the destruction of a small amount of ambient methane (CH_4). The enhancement of O_3 results in climate warming, whereas the reduction in CH_4 has a cooling effect. However, despite the complex contrariness of the climatic effects of NO_x (ozone production and methane reduction) the net result is that the ozone dominates the methane effect, thus warming the Earth [66].

Despite more stringent NO_x standards for LTO cycle, there has been little progress in the reduction of NO_x emissions per seat kilometre offered. On the other hand, it has been stated that a cruise NO_x charge could reduce aviation NO_x emissions by up to 2.8% in 2020 [227].

Table 25 presents NO_x emission factors during cruise stage for different aircraft types analyzed in this part of the research. However, it is important to remind that as later shown in section 2.3.2 NO_x emission factors vary according to each aircraft engine model and also to thrust setting applied on engines. Therefore, this table presents only a rough approximation of average NO_x emission factors per aircraft type.

Table 25 NO_x emission factors for cruise levels of aircraft types used in this research [7].

Aircraft	NO_x Emission Factor (g/kg)
A319	11.6
A320	12.9
A321	16.1
A330-200	13.8
B737-400	11.0
B747-400	12.4
B767-300	14.3

2.3.2.2 *The use of Petri nets within Umberto software environment*

In this section, a more accurate method is presented based on the conceptual framework of Petri nets (PN) and is designed and processed within the Umberto software environment as described in chapter 3. This method takes in account all input parameters that are considered in the method described in 1.3.3 except flight distance and still adopts other key input parameters related to jet engines and time elapsed during each flight phase. In fact, flight time is the main input parameter used instead of flight distance and this is done due to the fact that aircraft engines are differentiated in terms of fuel consumption rate per second (Kg/sec) and emission indices (g/Kg of fuel) depending on the engine power setting (in % F_{oo}). F_{oo} is the rated output of an engine, or 100% thrust, which is usually given in kilonewtons (kN). This method resembles the IPCC tier 3B method. Besides allowing a more accurate measure of fuel burnt and emissions released in each phase of flight, the method also facilitates a comparison among engines that can be used by same aircraft types and the identification of possible reductions in GHG emissions by using the most fuel efficient engines. Such comparison can also be extended to other aircraft types and their respective engine models, thus enlarging the range of possibilities for emission reductions in the same flight route. Table 26 shows the average elapsed time in operating mode in minutes according to the thrust setting.

Table 26. Average thrust setting and elapsed time measurements in LTO cycle [228].

Operating mode	Thrust setting	Time in operating mode, minutes
Take-off	100 % F_{oo}	0.7
Climb	85 % F_{oo}	2.2
Approach	30 % F_{oo}	4.0
Taxi/ground idle	7 % F_{oo}	26.0

Author chose one of the most dense short-haul flight routes in Europe (London Heathrow – Paris Charles de Gaulle) in terms of air passengers carried and one of the largest European airlines that operate in this route (British Airways). The main aircraft types used by this airline in this flight route are: A320 and A321. Each of these aircraft types conventionally can use two different types of engines as specified in table 27. Other relevant parameters are included in the table. Calculations are also performed for a proposed alternative of flight with A330 and high density seat configuration. The A330 is a much larger aircraft than the former ones and is included in this analysis to compare its fuel efficiency per passenger for short-haul flight routes. In all cases, passenger load factor (PLF) considered is 74.6%, which corresponds to the average value reported by British Airways in 2012 for flights within Europe [229]. The seating capacity of each aircraft type chosen was taken from SeatGuru website, which in turn provides precise seat maps directly from airlines databases [230]. There is a negligible difference in terms of space between business class seats and economy class seats in the aircraft A320 and A321, which allows the calculation of fuel burnt and emissions as an average per passenger (only for economy-equivalent seat class). Conventionally, A330 is used by airlines for medium-haul and long-haul flights and for this reason it offers more space between the business class seats which can be twice as high as the available space between seats in economy class. However, also in this case calculations are presented in terms of economy-equivalent seat class because for this short-haul flight route a high density seat configuration for A330 is proposed and not a conventional one. Calculations done in the last part of research (method described in section 2.3.3 and results presented in section 3.1.3) also include simulations for medium-haul and long-haul flights. For this reason, the differences in space available for passengers between the seats are considered and thus fuel burnt and emissions are calculated and presented specifically for each seat class.

Table 27 Characteristics of aircraft and short-haul flights chosen for analysis [228].

Aircraft type	Engines used	Manufacturer	Seating capacity	PLF
A320-200	2x CFM56-5-A1	CFM International	152	74.6 %
	2x V2500-A1	International Aero Engines	152	74.6 %
A321-200	2x CFM56-5B4	CFM International	184	74.6 %
	2x V2530-A5	International Aero Engines	184	74.6 %
A330-200	2x GE CF6-80E1	GE Aeroengines	293	74.6 %
	2x PW4168A	Pratt & Whitney	293	74.6 %
	2x Trent 772B-60	Rolls Royce	293	74.6 %

Typically, a flight from London Heathrow international airport to Paris Charles de Gaulle international airport takes approximately 1 hour and 15 minutes. Total estimated flight time was converted into seconds, thus representing 4500 seconds. The elapsed time during the cruise stage was estimated by subtracting from the total flight time the average time elapsed in each phase of LTO cycle as reported in table 26. For every aircraft engine analyzed, the following data as presented in table 28 for CF6-80E1A4 was gathered. The fuel rate based on thrust settings was obtained directly from the ICAO

Engine Exhaust Emissions Data Bank [228]. Same data was retrieved from similar technical documentation of other aircraft subsonic engines.

Table 28 Fuel rate based on thrust settings for aircraft engine type CF6-80E1A4 and elapsed time for each phase of a short-haul flight from London Heathrow international airport to Paris Charles de Gaulle international airport [228].

Phase	Thrust	Fuel rate (kg/s)	Time (sec.)
taxi out	7%	0.227	960
take off	100%	2.904	42
climb	85%	2.337	132
cruise	30%	0.744	2526
descent	30%	0.744	240
taxi in	7%	0.227	600

A material flow network was designed within Umberto software environment based on Petri nets conceptual framework as shown in Figure 21. As previously explained in section 1.3.3, input places are the elements, where material is received from the system surrounding and thus, mark the system boundary. In this model, input places are represented by fuel, cargo (freight and mail) and passengers. Fuel is measured in litres (l), while cargo and passengers are measured in kilograms (Kg). Graphically, an input place is presented as a circle with vertical line on the left. Output places are the elements, where material is released to the system surrounding and also mark the system boundary. They are represented here by emissions that include: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), particles and non-methane volatile organic compounds (NMVOC). An output place is shown graphically as a circle with a vertical line on the right. Besides a specific fuel rate for each phase of flight due to a different thrust setting, each engine type also has a specific emission factor for NO_x and CO in each phase of flight. Therefore, these emissions have to be calculated more carefully taking in account these particularities. Other emissions have the same factors for all thrust settings and are just proportional to the amount of fuel consumed, which in turn can be easily estimated based on fuel rate and elapsed time in each phase of flight. The jet fuel combustion process in each phase of flight that converts fuel into emissions represents a transition that is graphically shown in Umberto by a square symbol but here is presented with an aircraft image. Places and transitions are connected by directed arcs that indicate the direction of the material flow in the network. The material goods fuel, passengers and cargo are the tokens of input places, while the material “bads” that represent the emissions are the tokens of output places. Before performing each simulation in the model, the initial marking of Petri net had only the tokens in the input place P1 (jet fuel measured in litres of kerosene) and P2 (payload measured in Kg), which contain the amount of fuel necessary to perform the first phase of flight (taxi out) and the passenger and cargo boarded in the aircraft, respectively.

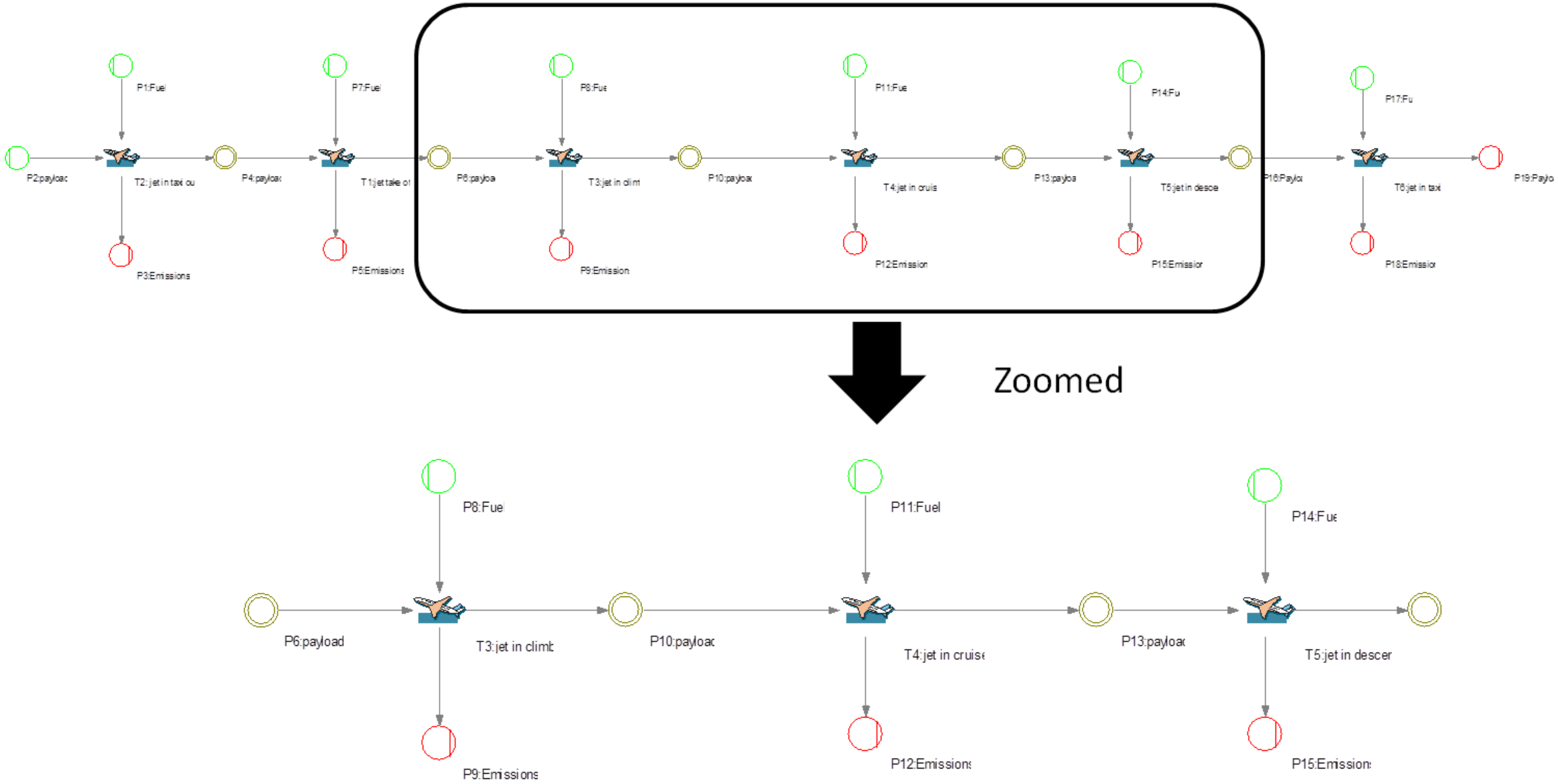


Figure 21. Material flow network designed within Umberto software environment by means of Petri Nets graphic nomenclature.

Since the time elapsed during each flight phase is considered in this analysis instead of flight distance as an input parameter, an additional input *place* can be added to each transition containing one *token*, whose value represents the elapsed time. However, in figure 21 these additional *places* represented by elapsed time are not shown because Umberto software conventionally describes only material and energy flow in the input *places* and output *places*. The elapsed time in each flight phase and the associated fuel consumption and emissions related to engine thrust setting are taken in account in the adapted algorithm used by Umberto software for this analysis. Therefore, this Petri net can be defined as coloured and time-based (or stochastic).

While fuel is consumed after each transition is fired, the amount of passengers and cargo remain constant. As the aircraft performs the first phase of flight after a certain elapsed time, a new marking of Petri net is obtained with tokens being removed from P1 and converted by transition T1 into emissions, thus generating tokens in P3. Tokens representing the payload are transferred at constant values from P2 to P4. The places that contain the payload in the middle of the system connect two sequential transitions (connected by input arcs on the left and output arcs on the right) and are graphically shown as two circles. In the subsequent phases of flight, new markings of Petri net are achieved with tokens representing payload moving at constant values throughout the sequential places (P4, P6, P10, P13, P16, P19) and new tokens added to the system through input places represented by fuel necessary to perform each phase of flight (P7, P8, P11, P14, P17), which in turn are gradually converted into emissions by sequential transitions and added to the sequential output places (P3, P5, P9, P12, P15, P18).

As previously described in the beginning of this chapter, different engine thrust setting is applied depending on the flight phase. In the case of this analysis, for simplification author has set deterministically time-delayed transitions with average duration in minutes for each flight phase and their respective conventional thrust setting as recommended by ICAO Engine Exhaust Emissions Data Bank and shown in table 26. Considering that the relative duration of engine thrust setting can be different due to flight conditions, an uncertainty is involved but can be reduced in a further research if time-delayed transitions based on a probability distribution is proposed. This adjustment can compensate the uncertainty used in this model as a correction factor of elapsed time used in the calculation of fuel consumption and emissions associated to each transition.

It is important to highlight that the uncertainty involved in this model is still less significant than those perceived in the models presented in previous sections of this chapter because more specific fuel consumption and carbon emissions per each phase of LTO cycle are estimated here and also for the cruise stage. Results obtained from this analysis conducted within Umberto software environment are presented in section 3.1.2.2. These results serve to test and confirm the hypothesis 3 as stated in section 2.1 and herein reminded as follows:

> ***Hypothesis 3****: for every aircraft type, there are considerable differences in terms of fuel consumption and CO_2 emitted per passenger depending on the type of jet engines used, being other parameters the same, including flight distance, passenger load factor, seating configuration, among others.*

2.3.3 Average fuel consumption and GHG emissions per chosen flight routes performed by largest European airlines

Further estimations are conducted for the flight operations of different aircraft types used by three largest European airlines in selected hub-to-hub flight routes of short-haul, medium-haul and long-haul distances. In this part of the research the ICAO method as described in section 1.2.3 was again used within the conceptual approach of IPCC tier 3A with a great circle distance (GCD) correction factor as later explained in this section. The results from these calculations performed are presented in section 3.1.3 for verifying the validation of hypothesis 5, 6 and 7 as stated in section 2.1 and herewith remarked again.

Hypothesis 5 asserts that "short-haul flights offer more opportunities for airlines in reduction of fuel consumption and CO_2 emissions than medium and long-haul flights."

Hypothesis 6 claims that "for short-haul routes, being certain conditions met, it is preferentially recommended to use wide body aircraft (commercial aircraft with two aisles) with lower frequency to reduce fuel consumption and CO_2 emissions."

Hypothesis 5 as proposed by author is based on previous studies conducted by other researchers which showed that most significant opportunities in carbon emission reductions are available on short-haul flights for high density routes [119; 5; 58]. In short-haul routes with high demand the possibilities of savings in fuel consumption and consequently, in the reduction of carbon emissions are greater since airlines tend to reduce the size of the aircraft used for each flight to keep load factors high.

Hypothesis 7 declares that "the fuel surcharge on air passengers does not take in account their real contributions in fuel consumption when measured in passenger-kilometre."

Table 29 presents the flight routes chosen by author and the competing airlines that are compared in each of them in terms of fuel consumption and CO_2 per passenger-km.

Since this study deals with flights offered by Lufthansa (LH), Air France (AF) and British Airways (BA), the hub airports selected are: Frankfurt International airport (FRA), Paris Charles de Gaulle International airport (CDG) and London Heathrow International airport (LHR). Other large airports such as Moscow Domodedovo (DME), Moscow Sheremetyevo (SVO) and New York John Kennedy International airport (JFK) are added for analysis and comparison of medium-haul flights and long-haul flights performed by these largest European airlines considered.

Table 29 Flight routes chosen by author and competing airlines considered.

Flight	Category	Route (route group)	Distance (GCD[1])	Airlines
1	Short-haul	LHR – CDG (within Europe)	347.92 km	BA, AF
2	Short-haul	LHR – FRA (within Europe)	655.61 km	BA, LH
3	Short-haul	CDG – FRA (within Europe)	448.18 km	AF, LH
4	Medium-haul	LHR – DME (within Europe)	2552 km	BA
5	Medium-haul	FRA – DME (within Europe)	2055.72 km	LH
6	Medium-haul	CDG – SVO (within Europe)	2461.31 km	AF
7	Long-haul	LHR – JFK (Europe-North America)	6391.25 km	BA
8	Long-haul	FRA – JFK (Europe-North America)	6204 km	LH
9	Long-haul	CDG – JFK (Europe-North America)	6732.02 km	AF

*Note: (1) Great Circle Distance (GCD) as calculated from "Great Circle Mapper" by Karl L. Swartz [231]. Great circle distance (GCD) is the distance between origin and destination airports. It is derived from latitude and longitude coordinates originally obtained from ICAO Location Indicators database.

It is important to consider a correction factor to the great circle distance (GCD) in order to include the emissions of distance flown in excess of the GCD, stacking, traffic and weather-driven corrections. In fact the actual distance flown compared with GCD that is given in the scheduled flights timetable may vary up to 11% in Europe [224].The ICAO method suggest the following GCD correction factor as shown in table 30.

Table 30 GCD correction factor due to stacking, traffic and weather-driven corrections [93].

GCD	Correction to GCD
Less than 550 Km	+ 50 Km
Between 550 Km and 5500 Km	+ 100 Km
Above 5500 Km	+ 125 Km

The result of this analysis aims to identify opportunities to carry the same amount or even a greater amount of air passenger per day, while consuming less fuel and releasing less CO_2 emissions. This can be achieved basically by using less aircraft and maintaining a high PLF or operating newer and more fuel efficient aircraft. Whenever such opportunity becomes a reality, it may be expected that airlines will not only increase passenger load factor (PLF) but also the revenues per carbon dioxide emissions (CO_2), while reducing environmental cost per available seat kilometre. When such analysis is undertaken by various airlines, it becomes possible to benchmark their flight services over time and report progress, which is one of the main outcomes of LCA.

In the initial steps of these calculations, author made a booking simulation in the website of airlines considered and consulted the aircraft types used by each airline for each flight route and their respective daily frequencies. Subsequently, the available seat capacity and seat configuration of each aircraft used by airlines in each flight route was obtained from the website of SeatGuru [232]. Based on these data it was possible to estimate the maximum amount of passengers carried per day by each airline for each flight route and for each seat class offered. The coefficients adopted for each seat class were calculated based on the area occupied by each seat in the aircraft by multiplying the reported measurements of pitch and width of each seat. A coefficient equal to 1 was assigned to economy class seats and the areas occupied by seats in other classes were presented in relation to the area of a single seat in economy class, thus providing different coefficients. Finally, average PLF reported by each airline for each route group was considered in order to estimate the average daily amount of air passengers transported by airlines in each aircraft and seat class offered. The average fuel consumption to flight distance considered for each aircraft type was interpolated from the CORINAIR fuel consumption table presented at the EMEP/CORINAIR Emission Inventory Guidebook (European Environment Agency (EEA), 2006).

Table 31 presents an example of data collected for this purpose with the aircraft types used by British Airways and their respective daily frequencies for the flight route from LHR to CDG, as well as their respective seat capacity and seat configuration. The average daily amount of passengers in each aircraft and seat class was estimated based on the average PLF of 74.6% reported by British Airways for flights operated within Europe.

Table 31 Aircraft types, seat configuration and frequency of flight offered by British Airways for flight route LHR-CDG [233; 230].

Aircraft types	Seats	Seat class	Comparison	Daily availab.	Duration	Daily pax	Daily Max
A319-100	48	Business	1.1	3	1h15	107	144
	78	Economy	1.0			175	234
A320-200	15	Business	1.1	3	1h15	34	45
	137	Economy	1.0			307	411
A321-200	15	Business	1.1	1	1h15	11	15
	169	Economy	1.0			126	169

Table 32 specifies the aircraft types and the average fuel consumption per distance flown as provided by CORINAIR database. It can be noted that CORINAIR database provides the same fuel burn rate for A319, A320 and A321, although A321 is a larger and heavier aircraft than the former ones, which in turn results in more fuel consumption for the same distance flown [234]. This is also evidenced in the results provided in the section 3.1.3. This simplification is due to the fact that since CORINAIR database was not updated since 1994 it lacks fuel data for the more recent aircraft types and their derivatives.

The UK Department for Environment, Food and Rural Affairs (DEFRA) also adopts the same aircraft mapping table [235].

Distance flown is converted from nautical miles to kilometres by multiplying by 1.852. Considering the great circle distance between LHR and CDG being of 347.92 km (187 nm), a correction factor of 50 km (27 nm) was added to account for the distance flown. Thus, flight distance was estimated at 397.92 km (214.86 nm). Figure 22 represents the fuel burn rate per distance flown in kilometres for A320, A319 and A321 according to EMEP/CORINAIR Emission Inventory Guidebook [94].

For the estimation of fuel consumption in the flight distance of 214.86 nm a coefficient of 6.82 was used by interpolation between the known values at distances 125 nm and 250 nm and multiplied by the difference between estimated flight distance (LHR-CDG) and the first inferior flight distance known from CORINAIR database (125 nm). This value was then added by the fuel consumption at distance of 125 nm.

Table 32. Average fuel consumption rate per distance flown in nautical miles for each aircraft type used by British Airways [94].

		Distance flown measured in nautical miles							
Aircraft	**Item**	**125**	**250**	**500**	**750**	**1000**	**1500**	**2000**	**2500**
A320	**Fuel consumption (kg)**	1644	2497	3661	4705	6027	8332	10866	13441
A320	**Fuel cons. Coef.**	6.82	4.65	4.18	5.29	4.61	5.07	5.15	5.38
A321	**Fuel consumption (kg)**	1644	2497	3661	4705	6027	8332	10866	13441
A321	**Fuel cons. Coef.**	6.82	4.65	4.18	5.29	4.61	5.07	5.15	5.38
A319	**Fuel consumption (kg)**	1644	2497	3661	4705	6027	8332	10866	13441
A319	**Fuel cons. Coef.**	6.82	4.65	4.18	5.29	4.61	5.07	5.15	5.38

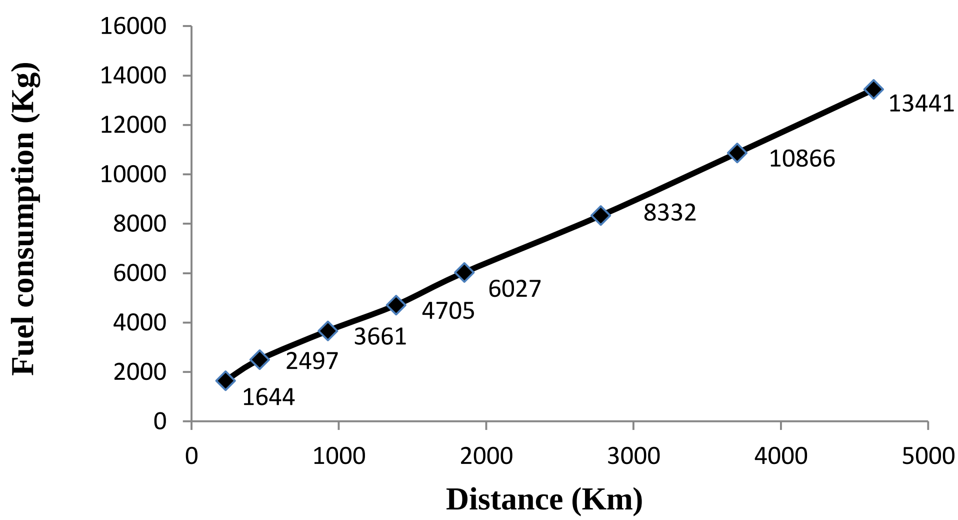


Figure 22. Average fuel consumption rate per distance flown for Airbus A320.

Equation 2.5 clarifies the calculation:

$$\text{Fuel consumption} = 6.82 * (214.86 - 125) + 1644.39 \quad (2.5)$$

Total fuel consumption for a flight operated by e.g. A320 in the flight route LHR-CDG was then estimated at 2257.52 kg.

Taking in account that British Airways offers seven daily flights as seen in Table 31 with roughly the same fuel consumption rate, the daily fuel consumption was estimated at 15803 Kg. The daily CO_2 emissions can then be calculated by multiplying this value by an emission factor of 3.157 as shown in Table 32. Considering the average daily amount of passengers transported by British Airways in this flight route and the average daily amount of CO_2 emissions, it was possible to estimate the daily average CO_2 emissions per passenger. Moreover, by knowing the PLF of each airline considered for each flight route as shown in table 29, their average prices of flight tickets charged per seat class in this flight route and the seat configuration of each aircraft used, it was possible to estimate the average daily revenues for each competing airline and the ratio *revenues* (measured in €) *per* kg of *CO_2 emissions*. These values are presented in section 3.1.3. Then, by assuming the average daily demand of passengers per seat class, author has analyzed if there was any possibility to change the amount of each aircraft type offered per day in order to reduce the daily fuel consumption and consequently, the daily GHG emissions resulting from their flight operations in this route. The same analysis was applied to the most competing airlines in the same flight route and also to other flight routes chosen as shown in Table 29.

The last part of calculations presented in this simplified LCA conceptual framework was the most exhaustive one since it comprised the calculation of average fuel consumption and GHG emissions per passenger-kilometre for each seat class in each aircraft type used by main competing airlines in each flight route chosen. The coefficients for each seat class considered per aircraft type offered was estimated as previously explained in this section. In appendices author shows how these coefficients can be three times as high as the coefficient for economy class seat in a table that compares the seat configuration for flights operated with B747-400 and B777-200 by British Airways between LHR and JFK. Author has also combined the values calculated for each aircraft offered by each airline between two airports and provided a simulation of an aggregate amount of fuel consumed and CO_2 emitted per passenger-kilometre for all possible combinations of flights. In the section 3.1.3 are presented the calculated results from six possible combinations of flights offered by British Airways and three possible combinations of flights offered by Air France between LHR and CDG. In this case, author highlights that there is no difference between economy class and business class in terms of fuel burnt per passenger and emissions per passenger. Calculations were also performed for other short-haul flight routes as listed in table 29 but are not presented in the dissertation since they would extend significantly its content. Furthermore, the same comparison in terms of fuel consumption and emissions is done among combined outbound and inbound flights offered by British Airways, Air France and Lufthansa between their respective hub airports and DME, SVO and JFK. In these cases, for every combination of flights the values provided distinguish according to the seat class. In section 3.1.3 are presented the calculated values for the flights to/from JFK. Calculations were also performed for the flights to/from DME and SVO but are not presented in the dissertation.

Each variant specifies as “fl.1” the outbound flight i.e. the departing flight and as “fl.2” the inbound flight i.e. the arriving flight. It was assumed the same distance for inbound and outbound flights between the same airports for simplification, including the same correction factor of great circle distance.

Author also calculated other important parameters associated to each variant of flights for comparison such as:

- Climate change (CG) cost per passenger – based on estimated emissions of CO_2, H_2O and NO_x per passenger for each variant of outbound and inbound flights.
- Fuel cost per passenger – based on estimated fuel consumption per passenger for each variant of outbound and inbound flights.
- Real fuel cost per price – a ratio that shows the real share of the fuel cost associated to each passenger to the average price paid for each seat class available in each variant.

The calculation of fuel cost per passenger considered a fuel price of 2.41 EUR per gallon as provided by Energy Information Administration [236], a conversion factor of 1 US gallon equal to 3.785 litres and a conversion factor of 1 litre equal to 0.8 kg of jet fuel [237].

The actual fuel surcharge that can be applied on each air passenger is estimated based on their marginal contribution on fuel consumption for the flight in question. In the proposed model, the additional fuel associated with additional passenger and its additional weight constitutes the only sizable marginal private cost. The additional labour costs for the marginal passenger and freight ton are negligible. Ground personnel for both passengers and freight are largely fixed costs in the short run [238].

In order to calculate the impact on climate change the fuel consumed was converted to emissions based on emission factors presented in table 24 and table 25 and then to the cost of climate change by taking the estimates recommended by Dings et al. [239] and Givoni and Rietveld [119] as follows:

- 30 EUR/tonne of CO_2,
- 4 EUR/kg of NO_x, and
- 8.3 EUR/tonne of H_2O.

These estimates only refer to climate change impact and are based on the 1992 air traffic situation, as analysed by the Intergovernmental Panel on Climate Change [9]. For this purpose it has been considered the cost of CO_2 emission and the relative radiative forcing and quantity of NO_x and H_2O emission in relation to CO_2 emission. The ratio between real fuel cost and average price of flight tickets considered that each passenger flies in the same seat class in both ways.

3 RESULTS AND DISCUSSION

3.1 ANALYSIS AND INTERPRETATION OF CALCULATED FUEL CONSUMPTION AND GHG EMISSIONS IN FLIGHT OPERATIONS FOR LARGEST EUROPEAN AIRLINES

In this chapter are presented the results of calculations performed during different parts of this research as explained in Part 2. For facilitating the consulting of results associated with the respective methods of calculation and assumptions proposed in each part of research, the same number sequence is shown in this chapter. In this chapter only the most relevant results are shown. Additional results are presented in the appendices section.

3.1.1 Results of calculation for different distances flown

Table 33 presents the values for fuel burnt per passenger-kilometre calculated as explained in section 2.3.1 based on average values provided by EMEP/CORINAIR Emission Inventory Guidebook [94] for each aircraft type together with other important input parameters such as passenger load factor (PLF), pax-to-freight factor (PFF) and seating configuration. The values shown on the first line correspond to different ranges of distance flown that has been converted from nautical miles (nm) as shown in EMEP/CORINAIR table into kilometres.

Table 33 Calculated values on fuel consumption (kg) per Y pax.km.

Distance (Km)	**231**	**463**	**926**	**1389**	**1852**	**2778**	**3704**	**4630**	**5556**
A319	0,0609	0,0463	0,0339	0,0291	0,0279	0,0257	0,0252	0,0249	NA
A320	0,0528	0,0401	0,0294	0,0252	0,0242	0,0223	0,0218	0,0216	NA
A321	0,0432	0,0328	0,0241	0,0206	0,0198	0,0182	0,0178	0,0177	NA
A330-200	0,0623	0,0446	0,0328	0,0288	0,0269	0,0251	0,0244	0,0241	0,0241
B767	0,0501	0,0356	0,0268	0,0239	0,0224	0,0212	0,0207	0,0205	0,0206
B747	0,0575	0,0413 19,10	0,0312 29,00	0,0280 38,93	0,0264	48,85 0,0249	69,30 0,0243	0,0240 90,209	0,0243 112,0
B777-200	0,0633	0,0462	0,0333	0,0290	0,0269	0,0247	0,0240	0,0237	0,0236

The calculated values are based on the proposed functional unit and they show that the aircraft with better fuel burnt rate per passenger-kilometre are A321 followed by B767. On the other hand, A319 presents the highest values. This is mainly due to engines and seat configuration conventionally used in these aircraft. While A321 has the same fuel storage as A320, it has a large wingspan and can carry more passengers. The conventional seat configuration of A319, A320 and A321 is shown in table 31. Table 34 presents the same differences in terms of carbon dioxide-equivalent emissions per economy-equivalent passenger-kilometre (CO_{2eq}/Y pax.km). This is evidenced by the fact that CO_{2eq} are mostly proportional to the amount of fuel burnt during the flight operation.

Table 34 Calculated values on CO_2eq / Y pax.km.

Type of aircraft	231	463	926	1389	1852	2778	3704	4630	5556
A319	0,401	0,305	0,223	0,191	0,184	0,169	0,166	0,164	NA
A320	0,348	0,264	0,194	0,166	0,159	0,147	0,144	0,142	NA
A321	0,285	0,216	0,158	0,136	0,130	0,120	0,118	0,116	NA
A330-200	0,410	0,294	0,216	0,190	0,177	0,165	0,160	0,159	0,159
B767	0,330	0,234	0,176	0,157	0,147	0,140	0,137	0,135	0,136
B747	0,379	0,272	0,206	0,185	0,174	0,164	0,160	0,159	0,160
B777-200	0,417	0,304	0,219	0,191	0,177	0,163	0,158	0,156	0,156

In section 2.3 author compared the GHG emissions of two aircraft types (A330-200 and Boeing 777-200) during the operational phase in terms of proposed functional unit (passenger-kilometre). Figure 23 illustrates average values calculated for Airbus A330-200 in terms of carbon dioxide equivalent emissions per kilometre flown of every economy-equivalent passenger (Kg $CO2_{eq}$/Y pax.km). It can be noted that GHG emissions in relation to this functional unit tend to reduce with distance flown and achieve an approximate constant value (0.159 Kg $CO2_{eq}$/Y pax.km) when the aircraft flies over 4630 km long. Therefore, it is recommended that this aircraft type fly over 4630 km per flight in order to maximize its efficiency in terms of fuel consumption and GHG emissions per kilometres flown per passenger. Figure 24 shows the average values of GHG emissions in terms of the same functional unit for Boeing 777-200. The same trend in the increase of performance efficiency is perceived for this aircraft, although it can achieve a slightly lower level of GHG emissions in relation to the functional unit (0.156 Kg $CO2_{eq}$/Y pax.km). Hypothesis 2 as stated in section 2.1 and remarked again in section 2.3.1 is therefore valid for distances flown over approximately 4630 km in all aircraft types analyzed. For aircraft designed and equipped for flying long distances like A330-200, B767, B747 and B777-200 it can also be observed that for distances flown over approximately 7400 km the fuel burnt rate and GHG emissions slightly increase again in terms of the chosen functional unit. This can be due to the fact that these aircraft are usually doing the descent maneouvres after flying over 7400 km which is a less fuel efficient phase of flight operation than the cruise phase.

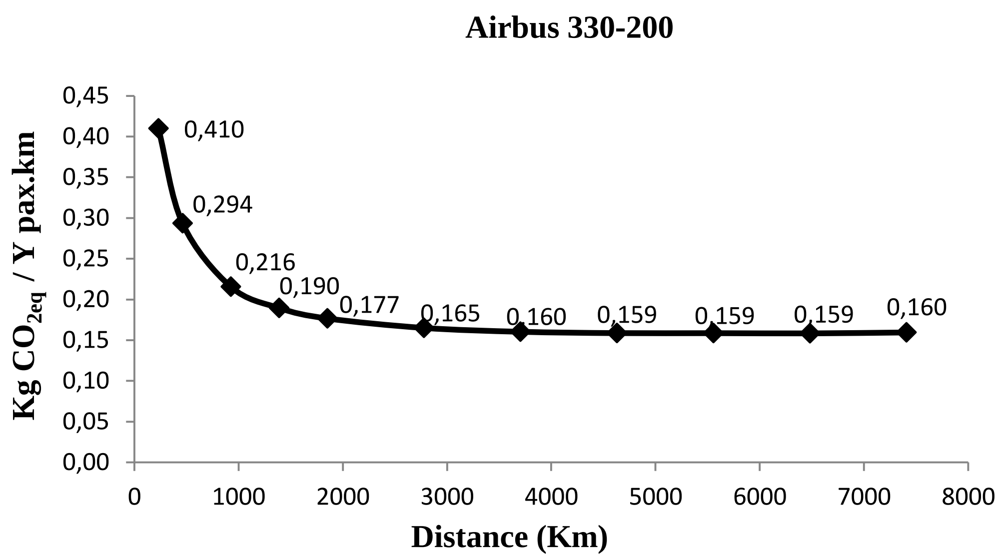


Figure 23. Emissions of carbon dioxide equivalent per Y passenger-kilometre for Airbus 330-200 (Kg CO_2eq/ Y pax.km).

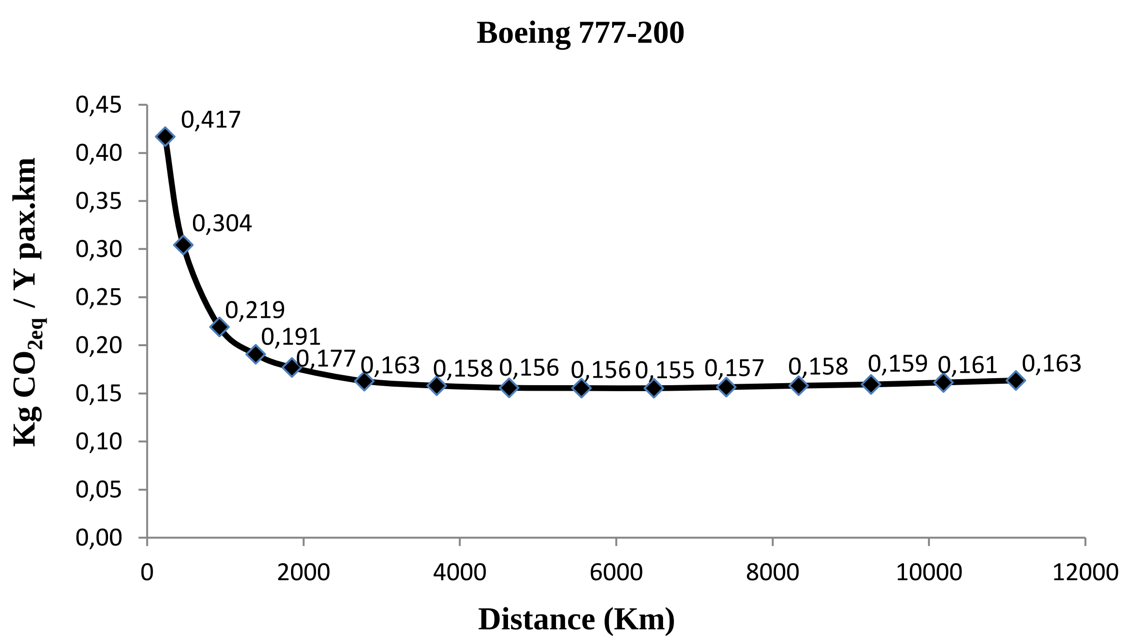


Figure 24 Emissions of carbon dioxide equivalent per Y passenger-kilometre for Boeing 777-200 (Kg CO_2eq/ Y pax.km).

3.1.2 Results of calculation in different phases of flight operation

This section presents the results of calculations performed for estimations of fuel consumption and emissions released in different phases of flight by means of two different approaches as explained in section 2.3.2. Firstly, the ICAO method was used within the conceptual approach of IPCC tier 3A as described in section 2.3.2.1. This method allowed a quick overview of the share of fuel consumed and carbon emissions released during the LTO cycle in relation to total fuel consumption and total carbon emissions during a flight. Subsequently, a more accurate method was adopted with the support of Petri nets and the expert system embedded in the Umberto software environment.

3.1.2.1 Results of calculation by means of IPCC tier 3A methodological approach combined with ICAO method

In this section the values estimated for fuel consumption and emissions during the LTO cycle as a whole and during cruise stage are presented. Figure 20 in section 2.3.2.1 outlines the procedures and input parameters used in these calculations. Table 24 in section 2.3.2.1 presents the average amount of fuel burnt and emissions released during the LTO cycle for each aircraft type considered as suggested by the IPCC Guidelines for National Greenhouse Gas Inventories. These are average values independent of total distance flown in a flight by each aircraft. Therefore, the particularities of each individual flight that may influence the overal fuel consumption and emissions during the LTO cycle are not considered here.

Table 35 presents the average values of fuel consumed and CO_2 emissions per different ranges of distances flown during the cruise phase for each aircraft type considered. Author has also calculated emissions of H_2O, NO_x, SO_2, NMVOC, CO, and even the aggregate CO_{2eq} emissions that count together the contribution of CO_2, H_2O and NO_x. However, in this table only the emissions of CO_2 during cruise phase are presented since this is the most significant and best understood element of aviation´s total contribution to climate change and is the main gas addressed by European airlines within the EU ETS. As previously reminded in section 2.3.2.1 aircraft considered have different maximum flight ranges but considering that the purpose in this section is to present the main differences in fuel consumption and CO_2 emissions for flight distances that can be performed by all aircraft types analyzed, only flight distances up to 4630 km are highlighted in table 35. The aircraft with higher fuel consumption and CO_2 emissions per distance flown is B747, followed by B777-200 and A330-200. These aircraft are larger and can carry more passengers and fuel than other aircraft types.

Figure 25 and figure 26 show the share in percentage of fuel consumed during the LTO cycle in relation to total fuel consumed during the flight for different distances flown. These graphs represent the situation for Airbus A330-200 and Boeing B777-200, respectively. Both figures serve to test hypothesis 4 as described in section 2.1 which states that "for all aircraft analyzed, the amount of fuel consumed during LTO cycle is less significant than fuel consumed during the cruise stage." In fact, other aircraft were also analyzed in this aspect and similar conditions were perceived. Hypothesis 4 is valid but only for flight distances over 232 km. For flight distances shorter than 232 km the contribution of LTO cycle in fuel consumption is still around 50% or even higher than 50% of all fuel consumed for A330-200 and B777-200. As described in section 1.2, short-haul flights can be categorized as those with less than 800 km flight distance. Therefore, for most of international flights across Europe hypothesis 4 is valid.

Table 35 Total fuel consumption and total CO_2 emissions during cruise phase for different distances flown by each aircraft type considered.

Type of aircraft	Indicator (kg)	231	463	926	1389	1852	2778	3704	4630
A319	**Fuel**	914	1767	2931	3975	5297	7602	10136	12711
	Total CO_2	2881	5574	9247	12543	16718	23994	31994	40124
A320	**Fuel**	875	1727	2891	3935	5257	7562	10096	12671
	Total CO_2	2751	5444	9117	12414	16588	23864	31864	39994
A321	**Fuel**	684	1537	2701	3745	5067	7372	9906	12481
	Total CO_2	2171	4864	8537	11834	16008	23284	31284	39414
A330-200	**Fuel**	1864	3632	6385	9130	11892	17560	23404	29485
	Total CO_2	5874	11458	20149	28813	37532	55428	73877	93074
B767	**Fuel**	1250	2525	4705	6885	9065	13629	18307	23024
	Total CO_2	3957	7982	14864	21746	28628	43035	57803	72697
B747	**Fuel**	3325	6180	11068	15956	20845	30931	41179	52015
	Total CO_2	10485	19498	34930	50363	65795	97636	129991	164201
B777-200	**Fuel**	2260	4475	7570	10666	13804	20016	26666	33467
	Total CO_2	7115	14110	23882	33656	43561	63174	84165	105636

*Note: Calculated based on parameters explained in section 2.3.2.1.

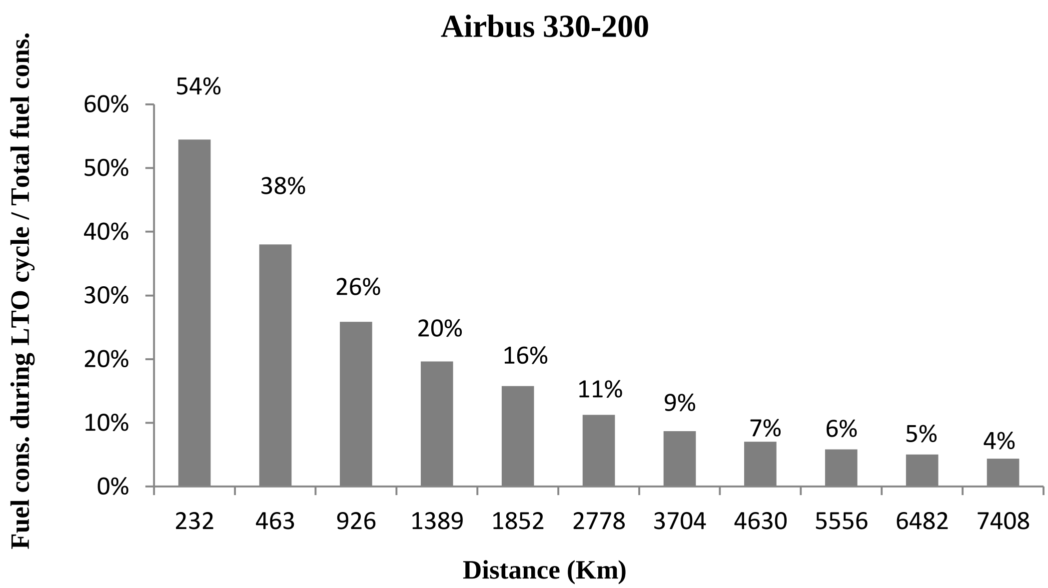


Figure 25. Percentage share of fuel consumed during LTO cycle in relation to total fuel consumed per distances flown for Airbus 330-200.

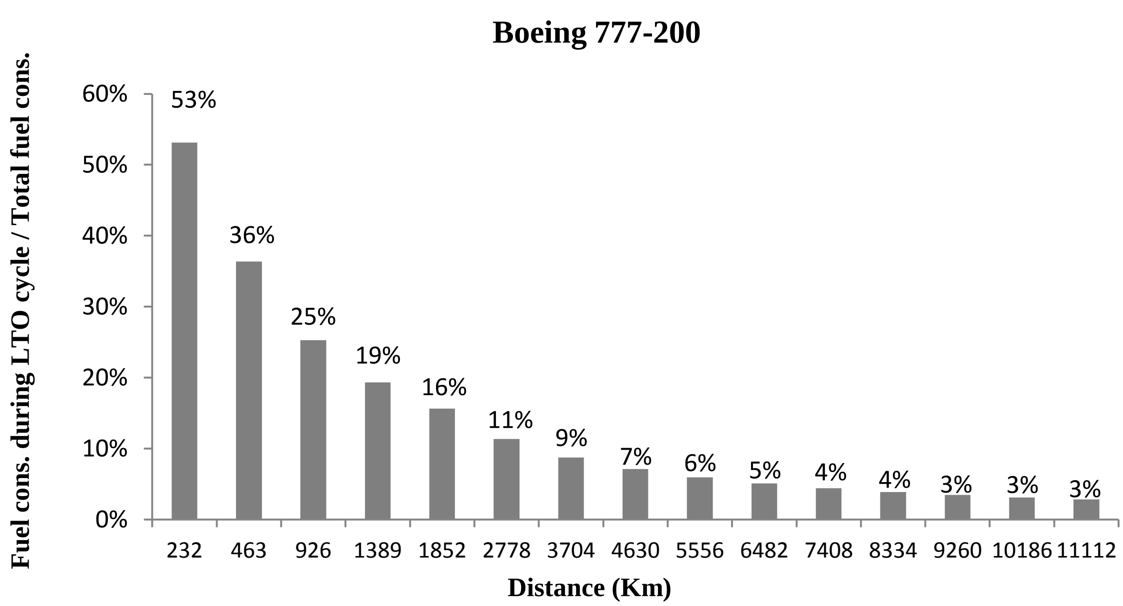


Figure 26. Percentage share of fuel consumed during LTO cycle in relation to total fuel consumed per distances flown for Boeing 777-200.

3.1.2.2 Results of calculation by means of Petri nets and Umberto software environment

More accurate values in terms of fuel consumption and emissions during each phase of flight are provided in this section based on the calculations explained in section 2.3.2 by using Petri nets graphical notation within the Umberto software environment. As previously mentioned, this method considers specific parameters related to jet engines used and the time elapsed during each flight phase. For this reason, the average thrust setting and elapsed time measurements in LTO cycle as specified in table 26 become relevant input parameters in this calculation. In addition, it was also considered the average thrust setting during the cruise phase that corresponds to 30% and a variable duration of this phase according to the flight route chosen. The specific fuel rate (kg/s) for each engine according to the thrust setting was considered for each flight phase based on the ICAO Engine Exhaust Emissions Data Bank [228]. This method resembles the IPCC tier 3B method as explained in chapter 2. It allows a comparison among engines that can be used by same aircraft types in terms of fuel consumption and emissions and facilitates the identification of possible reductions in CO_2 emissions by using the most fuel efficient engines. The model measured fuel consumption and the following emissions for each case considered: CO_2, NO_X, NMVOC, CO, SO_2 and particles. Simulations in the model (see table 27) were performed for different jet engines used by three aircraft types used by British Airways in one of the most dense short-haul flight routes in Europe: London Heathrow International airport (LHR) – Paris Charles de Gaulle International airport (CDG). In figure 21 a material flow network as designed within Umberto software environment was shown representing a coloured and time-based (or stochastic) Petri net. Input places are represented by fuel, cargo (freight and mail) and passengers. Fuel is measured in litres (l), while cargo and passengers are measured in kilograms (Kg). Output places are represented by emissions that include: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), particles and non-methane volatile organic compounds (NMVOC). The transitions consist in the jet fuel combustion process in each phase of flight that converts fuel into emissions.

The material flow can be visualized using the so-called Sankey diagrams as shown in Figure 27. Sankey diagrams are flow charts, in which the width of the arrows is shown proportionally to the flow quantity. They can be useful for identifying the prevailing contributions to an overall flow. It can be noted that fuel consumption and emissions are much more significant during the cruise stage than in other phases of flight.

Table 36 presents the calculated values of fuel burnt and emissions released during each phase of a short-haul flight from LHR to CDG operated by British Airways using an Airbus

A330-200 with two engines CF6-80E1A4 by CFM International. These calculated values took in account the thrust settings, the fuel rate for this type of engine and elapsed time for each phase of flight as previously specified in table 28. Other values regarding fuel consumption and emissions were also calculated for the same flight route but different aircraft type and different engines.

Table 36 Calculated values for fuel burnt and emissions released by A330-200 using two engines CF6-80E1A4 in the flight from London Heathrow international airport to Paris Charles de Gaulle international airport based on engine specifications of table 28.

Flight route				LHR - CDG				
Aircraft A330-200				Two Engines CF6-80E1A4				
phase	Fuel	NO_x	NMVOC	CO_2	CO	SO_2	Particles	Unit
taxi out	435.84	2.01	1.18	1375.95	16.60	0.44	0.02	Kg
take off	243.94	10.53	0.66	770.11	0.08	0.24	0.01	Kg
climb	616.97	18.69	1.67	1947.77	0.19	0.62	0.02	Kg
cruise	3758.69	38.08	10.15	11866.18	5.00	3.76	0.15	Kg
descent	357.12	3.62	0.96	1127.43	0.47	0.36	0.01	Kg
taxi in	272.40	1.26	0.74	859.97	10.38	0.27	0.01	Kg
TOTAL	**5684.95**	**74.19**	**15.35**	**17947.39**	**32.72**	**5.68**	**0.23**	**Kg**

It is interesting to note that during LTO cycle the fuel burnt is 1926.26 Kg (counting all phases except the cruise phase) which represent only about 33.9% of total fuel consumed during the flight. This is an approximate percentage as observed in figure 25 for a flight distance between these two airports (347.92 km) when using Airbus 330-200.

Table 37 shows the total values of fuel consumption and CO_2 emissions for different engines used by each aircraft type analyzed. It also provides these values as divided per passenger carried within two assumptions: a higher level of fuel burnt and CO_2 emissions by considering the passenger load factor (PLF) of 74.6% and a lower level (Fuel/pax_{min} and CO_2/pax_{min}) by considering a full aircraft with PLF equal to 100%. It can be observed that aircraft A321 with two jet engines of type 1 (2x CFM56-5B4) as described in table 27 results in less fuel consumption per passenger and less CO_2 emissions per passenger among all variants when a PLF of 100% is assumed. A ratio is provided for CO_2/pax_{min} by each variant in relation to the CO_2/pax_{min} calculated for A321 E1.

Table 37 Fuel consumption and CO_2 emissions during outbound and inbound flights daily offered by British Airways between LHR and CDG.

	A320 E1	**A320 E2**	**A321 E1**	**A321 E2**	**A330 E1**	**A330 E2**	**A330 E3**	**Unit**
Total fuel	2,742.19	3147.52	3045.85	3563.92	6957.05	7491.2513	7985.95	litre
Total CO_2	7,074.16	8119.79	7857.52	9193.99	17947.39	19325.50	20601.70	Kg
Fuel/pax	24.27	27.85	22.23	26.01	31.77	34.21	36.47	litre/pax
Fuel/pax_{min}	18.04	20.71	16.55	19.37	23.74	25.57	27.26	litre/pax
CO_2/pax	62.60	71.86	57.35	67.11	81.95	88.24	94.07	Kg/pax
CO_2/pax_{min}	46.54	53.42	42.70	49.97	61.25	65.96	70.31	Kg/pax
Ratio	1.09	1.25	**1.00**	1.17	1.43	1.54	1.65	

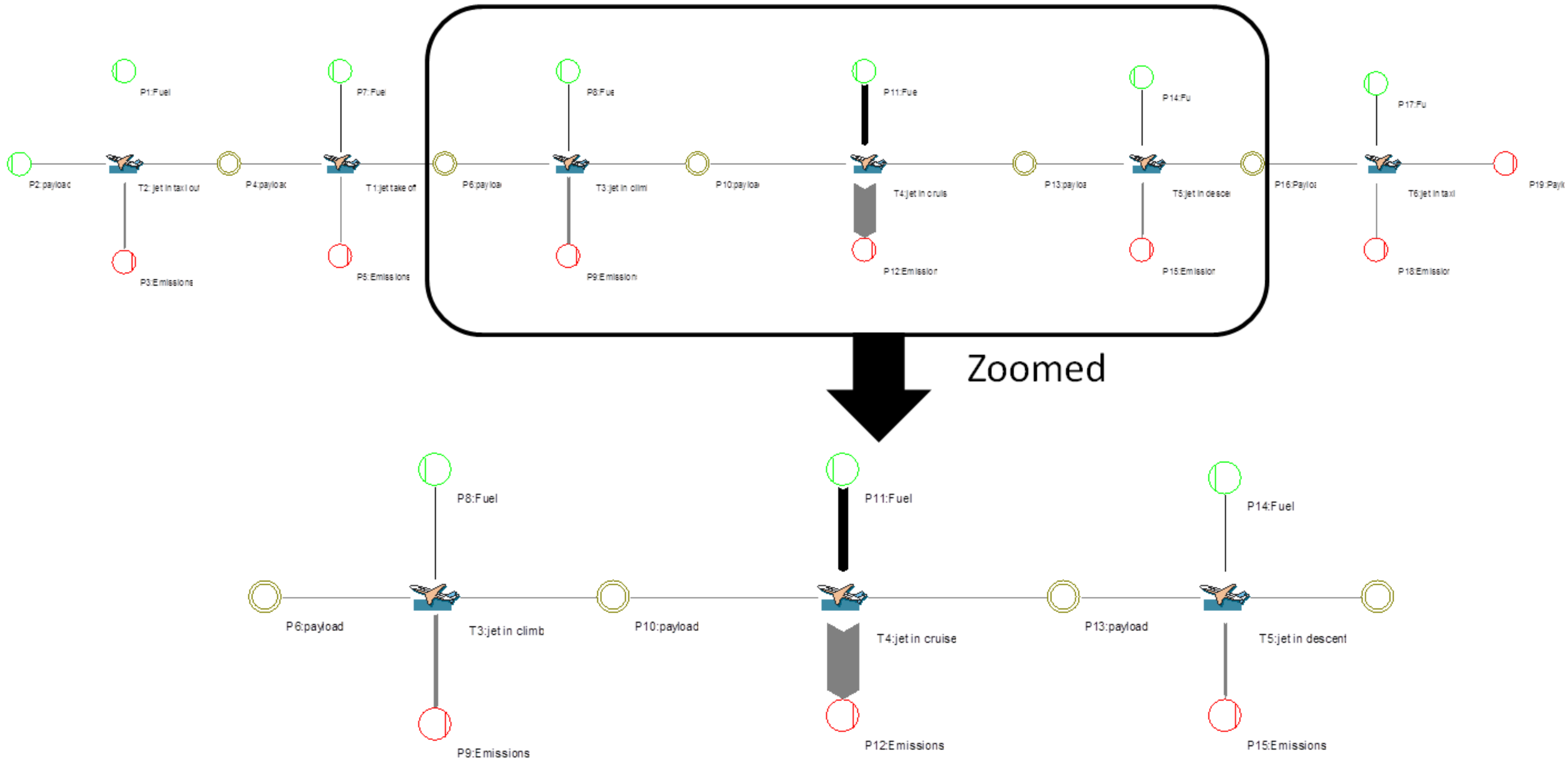


Figure 27. Sankey diagrams represented in the material flow network designed within Umberto software.

Figure 28 and figure 29 respectively present the differences in terms of fuel consumption per passenger and CO_2 emissions per passenger in each phase of flight performed by A321 with two jet engines of type 1 (2x CFM56-5B4).

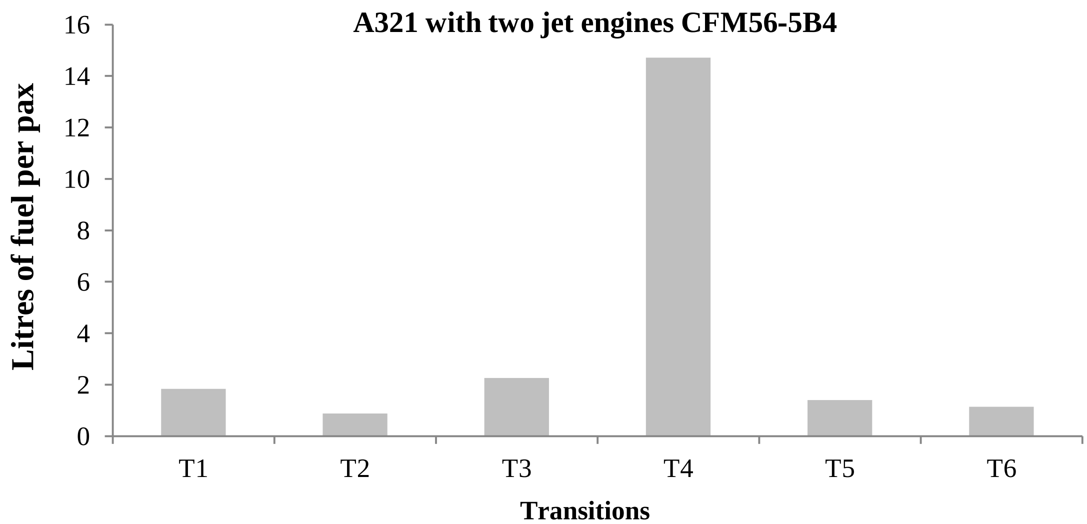


Figure 28. Fuel burnt per passenger by A321 in different flight phases with two jet engines CFM56-5B4.

*Note: T1 - taxi out; T2 - take off; T3 – climb; T4 – cruise; T5 – descent; T6 - taxi in.

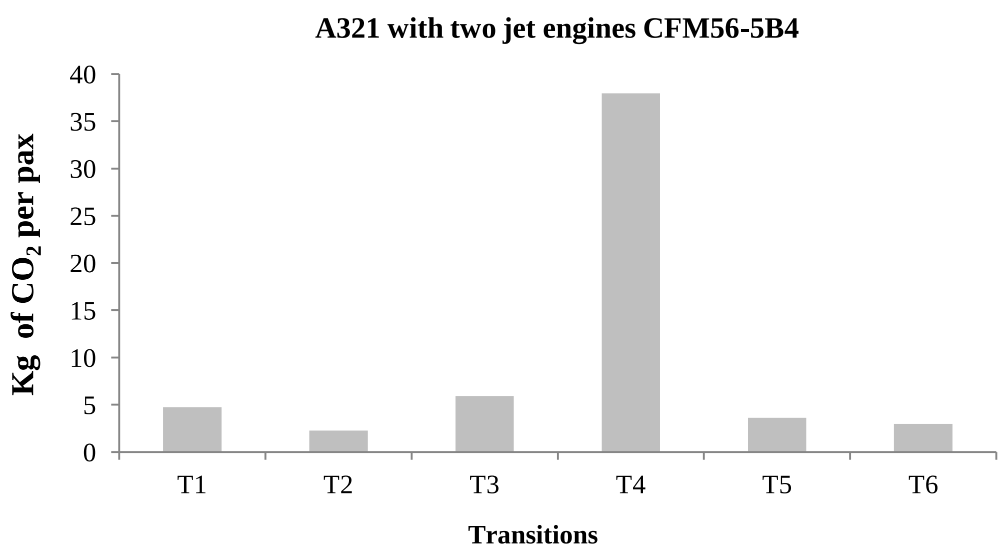


Figure 29. Carbon dioxide emissions released per passenger by A321 in different flight phases with two jet engines CFM56-5B4.

*Note: T1 - taxi out; T2 - take off; T3 – climb; T4 – cruise; T5 – descent; T6 - taxi in.

The values presented in table 37 also show that fuel/pax and CO_2/pax for each aircraft type may vary from 14% to 17% during the flight depending on the engines used, being other parameters constant. This validates the hypothesis 3 as stated in chapter 2 which declares that "for every aircraft type, there are considerable differences in terms of fuel consumption and CO_2 emitted per passenger depending on the type of jet engines used, being other parameters the same, including flight distance, passenger load factor, seating configuration, among others."

Moreover, when considering all possible aircraft and engines used by British Airways the difference can be in the range of 65% between the worst variant (A330 E3) and the best variant (A321 E1). Figure 30 illustrates the differences in total CO_2 emissions per passenger among each aircraft and its respective jet engines used for this flight.

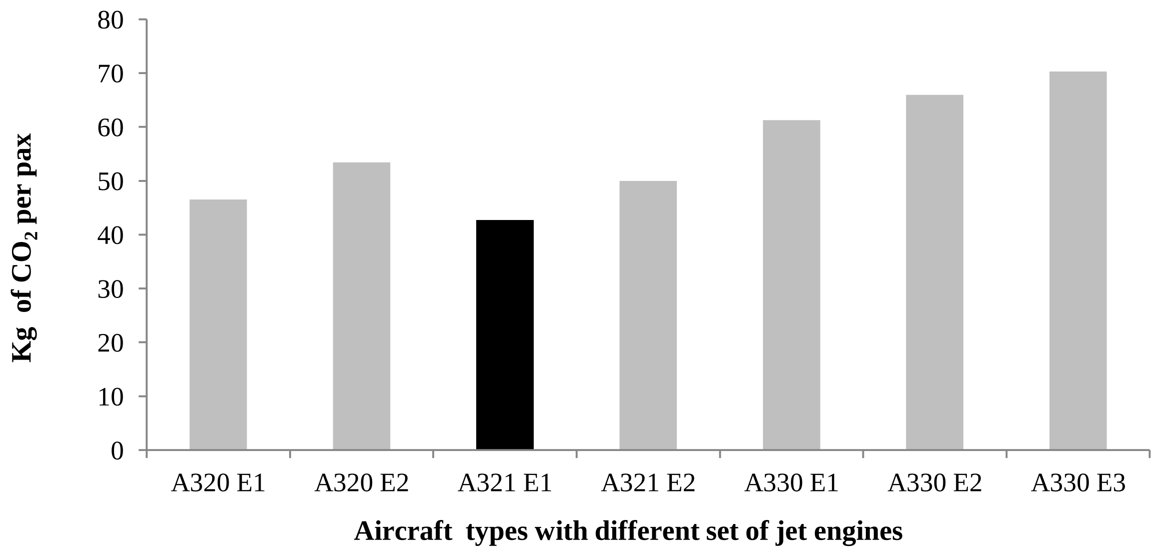


Figure 30. Comparison of total carbon dioxide emissions released per passenger among different types of aircraft with different set of jet engines.

*Note: A320 E1 – two jet engines CFM56-5-A1; A320 E2 – two jet engines V2500-A1

A321 E1 – two jet engines CFM56-5B4; A321 E2 – two jet engines V2530-A5

A330 E1 – two jet engines GE CF6-80E1; A330 E2 – two jet engines PW4168A

A330 E3 – two jet engines Trent 772B-60

3.1.3 Results of calculation of average fuel consumption and GHG emissions per chosen flight routes performed by largest European airlines

The last part of calculations performed in this research were focused in the flight operation of different aircraft used by three largest European airlines in selected hub-to-hub flights for short-haul, medium-haul and long-haul distances. In this part of the research the ICAO method as described in chapter 1 was again used within the conceptual approach of IPCC tier 3A but with the great circle distance correction factors as shown in table 30.

Table 29 in section 2.3.3 presented the flight routes chosen by author and the competing airlines that are compared in each of them in terms of average daily fuel consumption, average daily CO_2 emissions, average daily amount of passengers, average daily revenues, fuel consumption per passenger-km, CO_2 per passenger-km, fuel cost per passenger and climate change cost per passenger. Although calculations were performed for all most competing airlines in the flight routes proposed, in this section are presented only the most relevant results that are sufficient to validate hypothesis 5, 6 and 7 as described in section 2.1.

The airports considered among flight routes chosen in this analysis were: Frankfurt International airport (FRA), Paris Charles de Gaulle International airport (CDG), London Heathrow International airport (LHR), Moscow Domodedovo (DME), Moscow Sheremetyevo (SVO), and New York John Kennedy International airport (JFK). Data related to aircraft types used in the daily flights offered by competing airlines in the chosen flight routes was obtained directly from the sources as described in section 2.3.3. The average annual PLF of each flight route was also acquired by consulting the annual reports and online information available about each airline investigated.

Initially, author calculated the average amount of fuel consumption and CO_2 emissions per day by each competing airline for each flight route considered. Calculation was based on the aircraft types used and on the fuel burnt rate per distance flown as presented in the CORINAIR table [94]. In this part of analysis, the average PLF of airlines in the corresponding flight routes and aircraft types used were considered only for the estimation of average daily amount of passengers carried by each airline from one airport to another. After estimating the average daily amount of passengers author analyzed if there might be another combination of aircraft deployed by each airline in order to meet the passenger demand while reducing the overall fuel consumption and consequently, also reduce the CO_2 emissions. The recommendations by author respected the availability of aircraft by airline for each flight route and mainly considered the possibility of using less aircraft per day of certain types, such as e.g. A319 which is less efficient in terms of fuel burnt per passenger-kilometre. Whenever such possibility was identified, author named the recommended deployment of aircraft as “best scenario” and compared the overall daily fuel consumption and CO_2 emissions with those estimated under the current deployment of aircraft (“current scenario”).

Table 38 presents the results of this initial analysis related to the comparison of average daily fuel consumption and CO_2 emissions among the current and the best scenario. Flights are categorized by short-haul, medium-haul and long-haul as previously explained. Results serve to test hypothesis 5 which asserts that “short-haul flights offer more opportunities for airlines in reduction of fuel consumption and CO_2 emissions than medium and long-haul flights.”

It can be noted among flight routes considered that short-haul flights do offer more significant potential for reduction in daily fuel consumption and CO_2 emissions. For airlines considered the potential reduction in the chosen short-haul flight routes varied from 14% up to 29% but in general showed an average potential reduction of 24%. In the chosen medium-haul flight routes the potential reduction varied from 0% to 29% and thus presented an average potential reduction of 16%. On the other hand, long-haul flight routes offer a much lower potential for reduction in fuel consumption and CO_2 emissions varying from 0% up to 13% with an average reduction of 4%. This is due to the fact that these flights are operated by wide body aircraft and with a high average PLF. Thus, there are usually few opportunities to reduce fuel consumption and CO_2 emissions by redefining the deployment of aircraft for these flight routes.

Nevertheless, the assertion of hypothesis 5 may be valid only for short-haul flight routes with high daily passenger demand that is currently being met with seven aircraft or more. In short-haul routes with high demand the possibilities of savings in fuel consumption and consequently, in the reduction of carbon emissions are greater since airlines tend to reduce the size of the aircraft used for each flight to keep load factors high. It can be observed that considering the current average PLF for these short-haul flight routes airlines could transport all air passengers by using less aircraft per day but they may not decide to take such measure due to the threat of loss in market share resulting from the loss of airport slots to competition. Landing slots' or Airport slots are rights allocated to an entity by an airport, government or independent agency granting the slot owner the right to schedule a landing or departure during a specific time period. However, in the point of view of eco-efficiency and profitability these airlines are in general offering more flights per day in the short-haul flight routes considered than they were supposed to.

Subsequently, a comparison was made for short-haul flight routes chosen among the current deployment of aircraft and an alternative deployment of aircraft considering the use of wide body aircraft together with narrow body aircraft (commercial aircraft with single aisle). This was done to test the hypothesis 6 which claims that "for short-haul routes, being certain conditions met, it is preferentially recommended to use wide body aircraft with lower frequency to reduce fuel consumption and CO_2 emissions."

Table 33 in section 3.1.1 presented the calculated fuel consumption of various aircraft types per kilometre for each economy-equivalent passenger. By means of this indicator this table shows that among aircraft types considered the only narrow body aircraft that has lower fuel-efficiency than wide body aircraft is A319. Other narrow body aircraft listed in that table have a lower fuel consumption per passenger-kilometre than all wide body aircraft considered. Therefore, hypothesis 6 can only be validated for short-haul flight routes with high daily passenger demand that are currently being met only with aircraft A319. That is not the case for most of short-haul flight routes analyzed in this research except the flight route CDG-FRA that is currently performed by Air France with seven daily flights operated by A319. For this reason, author estimated only in this flight route the potential daily reduction in fuel consumption and CO_2 emissions with the use of a wide body aircraft.

Table 38 Comparison in daily fuel consumption and CO_2 emissions for each flight route between the current scenario and the best scenario.

			Fuel Consumption (Kg)		**CO_2 emissions (Kg)**		
Airline	**Flight route**	**Category**	**Current scenario**	**Best scenario**	**Current scenario**	**Best scenario**	**% Reduction**
British Airways	LHR-CDG	Short-haul	14513	10366	45818	32727	29%
	LHR-FRA	Short-haul	23099	17887	72925	56470	23%
	LHR-DME	Medium-haul	60300	42885	190366	135389	29%
	LHR-JFK	Long-haul	510377	446344	1611261	1409108	13%
Lufthansa	FRA-CDG	Short-haul	29329	21984	92590	69405	25%
	FRA-LHR	Short-haul	35828	26831	113108	84706	25%
	FRA-DME	Medium-haul	26137	26137	82515	82515	0%
	FRA-JFK	Long-haul	447031	447031	1411277	1411277	0%
Air France	CDG-LHR	Short-haul	15457	11041	48798	34855	29%
	CDG-FRA	Short-haul	17099	14656	53981	46270	14%
	CDG-SVO	Medium-haul	37719	30175	119078	95263	20%
	CDG-JFK	Long-haul	301635	301635	952263	952263	0%

Alternative 1 as shown in table 39 offers a potential daily reduction of 31% in these indicators when deploying two aircraft A319 and one aircraft B777. An additional alternative considering the deployment of three aircraft A321 and only one aircraft A319 would result in even more significant reductions in daily fuel consumption and CO_2 emissions in the range of 43%. The aircraft A321 can carry more passengers than A319 but is also a narrow body aircraft. Both alternatives however, may face strong resistance by flight planners of airlines considered due to the issues involving market share and airport slots. Moreover, a wide body aircraft require longer check-in and boarding times as well as longer time for baggage handling which may cause discomfort among air passengers who can choose other alternatives of short-haul flights in smaller aircraft that would incur in saved time.

Table 39 Potential reductions in fuel consumption and CO_2 emissions with deployment of wide body aircraft.

Key indicators	Current scenario 7xA319	Alternative 1 2x A319 1x B777	Alternative 2 3x A321 1x A319
Fuel consumption (kg)	17099	11779	9771
CO_2 emissions (kg)	53981	37186	30846
Percentage reduction		31%	43%

The PLF together with the seat configuration of each aircraft used and the average prices of flight tickets charged per seat class in each flight route were relevant parameters for calculating the average daily revenues generated from the ticket sales by each competing airline and the ratio *daily revenues per CO_2 emissions* (measured in €/kg). Table 40 presents the results calculated for these indicators for each flight route and airline considered. It can be noted on figure 31 and figure 32 that the most relevant differences in terms of daily CO_2 emissions per passenger and revenues per CO_2 emissions are observed in the comparison among daily flights offered by British Airways, Lufthansa and Air France between their respective hub airports and Moscow Domodedovo (DME) and Moscow Sheremetyevo (SVO). It is important to remark that while the highest level of CO_2 emissions per passenger was estimated for British Airways in the flight route LHR-DME (324 kg/pax) the highest daily revenues per CO_2 emissions was calculated for Lufthansa in the flight route FRA-DME (2.71€). For the flight route CDG-SVO, Air France presents the lowest daily revenues per CO_2 emissions (1.81€) and the second lowest level of CO_2 emissions per passenger (202 kg/pax). For short-haul flights considered the differences among airlines are not so significant except in the comparison between British Airways (BA) and Lufthansa (LH) in the flight route LHR-FRA where daily CO_2 emissions per passenger estimated for BA is 38% higher than the amount calculated for LH. On the other hand, daily revenues per CO_2 emissions are very similar in both cases. For long-haul flights from Europe to JFK the differences in both indicators vary between 11% and 22%.

Table 40 Daily key indicators for comparison among most competing airlines in each flight route chosen.

Airline	Flight route	Daily Pax	Daily CO_2 emissions (Kg)	Daily revenue (€)	Daily CO_2 emissions/pax	Revenues /CO_2 emissions (€/Kg)
British Airways	LHR-CDG	759	45818	103,212	60	2.25
	LHR-DME	587	190366	359,608	324	1.89
	LHR-FRA	684	72925	119,944	107	1.64
	LHR-JFK	2294	1611261	1,136,341	702	0.71
Air France	CDG-SVO	590	119078	215,930	202	1.81
	CDG-LHR	865	48798	94.373	56	1.93
	CDG-FRA	678	53981	48,792	80	0.90
	CDG-JFK	1224	952263	803,367	778	0.84
Lufthansa	FRA-CDG	1465	92590	208,184	63	2.25
	FRA-DME	427	82515	223,235	193	2.71
	FRA-LHR	1465	113108	190,049	77	1.68
	FRA-JFK	1650	1411277	1,144,420	855	0.81

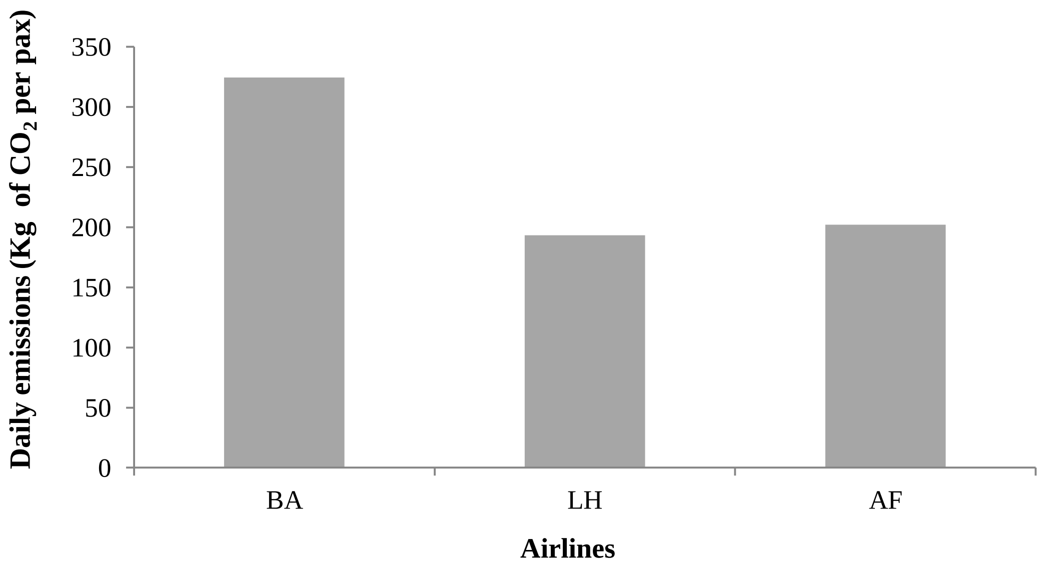


Figure 31 Comparison of daily CO_2 emissions per passenger among flights offered by British Airways (BA), Lufthansa (LH) and Air France (AF) between their hub airports and Moscow Domodedovo (DME) and Moscow Sheremetyevo (SVO).

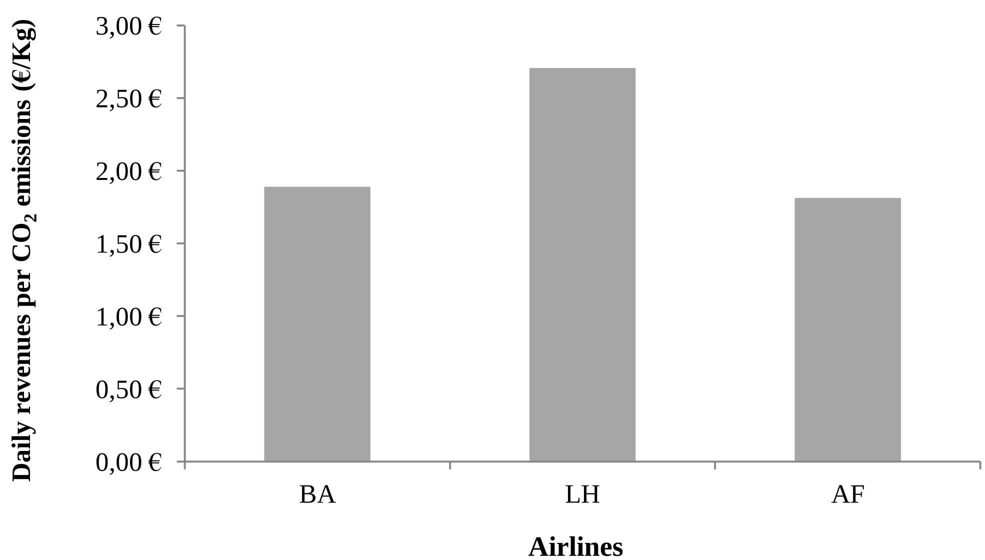


Figure 32 Comparison of daily revenues per unit (Kg) of CO_2 emissions released among flights offered by British Airways (BA), Lufthansa (LH) and Air France (AF) between their hub airports and Moscow Domodedovo (DME) and Moscow Sheremetyevo (SVO).

Furthermore, both PLF and seat configuration were used among other parameters as recommended by ICAO method to provide calculations of fuel burnt and emissions in terms of passenger-kilometre and subsequently, fuel cost per passenger and climate change cost per passenger.

Figure 33 illustrates the differences between aircraft used by British Airways and Air France in terms of carbon dioxide emissions per passenger-kilometre for the flight route between LHR and CDG.

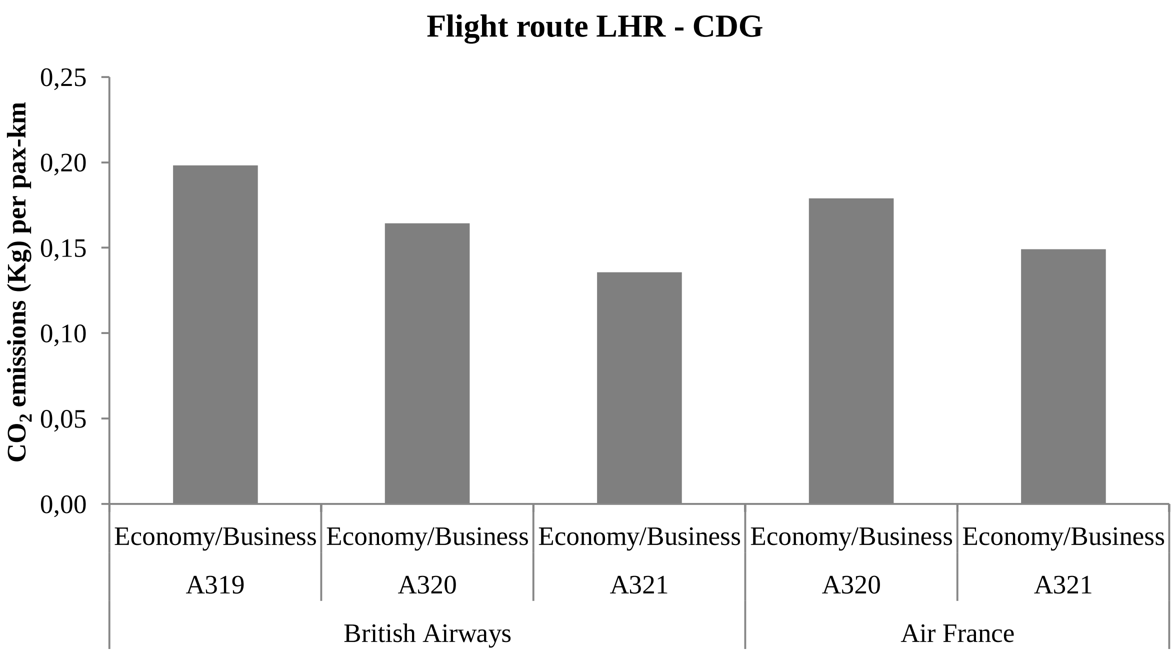


Figure 33 Comparison of carbon dioxide emissions per passenger-kilometre between aircraft used by British Airways and Air France in daily flights between LHR and CDG.

These emissions are proportional to the amount of fuel burnt during the flight. In this flight route aircraft deployed by both airlines have almost negligible difference related to space available for passengers in business class and in economy class as previously shown in table 31. However, in medium-haul flights and mainly in long-haul flights such differences in space between seats in business class and economy class become relevant and even in some aircraft first class seats are available. Such differences in seat configuration result in different values calculated for those indicators highlighted in this section in terms of passenger-kilometre. It can be noted that the differences in CO_2 emissions per passenger-kilometre can be in the range of almost 50% when comparing the aircraft with the highest value (A319 by British Airways) and the aircraft with lowest value (A321 by British Airways).

Figure 34 shows the differences perceived in the same indicator among aircraft used by both airlines for the flight routes LHR – JFK (British Airways) and CDG – JFK (Air France).

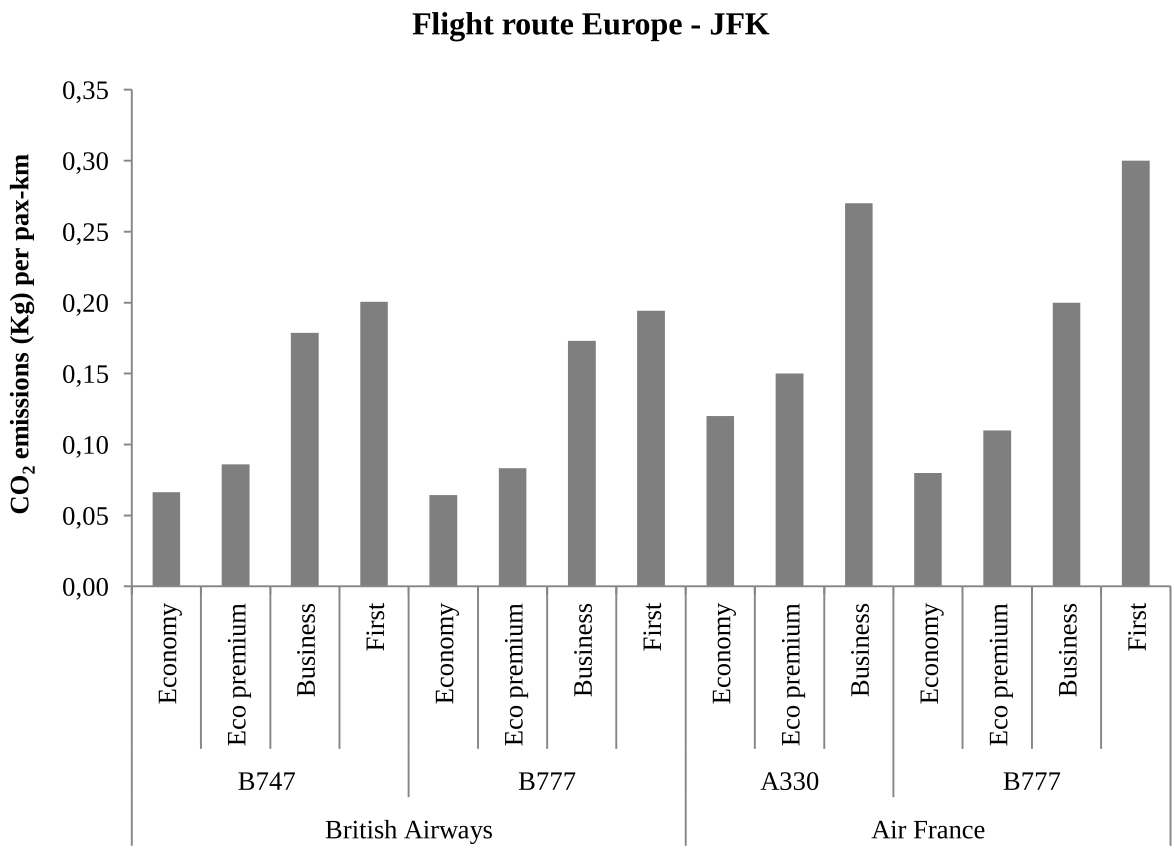


Figure 34 Comparison of carbon dioxide emissions per passenger-kilometre between aircraft used by British Airways and Air France in daily flights from their hub airports to JFK.

In this case the differences are even more significant. The highest value observed (First class B777 by Air France) is five times higher than the lowest value (economy class B777 by British Airways). Even when comparing only these values among economy class passengers the highest value (economy class A330 by Air France) is twice higher than the lowest value. The distance flown from LHR to JFK is about 6391km and from CDG to JFK is about 6732km (measured in terms of great distance circle as previously explained). Therefore, there is only about 341 km of difference in distance flown among these flight routes. Indeed, when proposed functional unit (passenger-kilometre) is adopted substantial differences are perceived in terms of fuel burnt and

GHG emissions, which in turn also result in large difference of fuel cost per passenger and climate change cost per passenger (mainly associated to CO_2 emissions as explained in section 2.3.3). Figure 35 and figure 36 show respectively the differences in fuel cost per passenger and in cost associated to climate change per passenger for the flights offered by both airlines between LHR and CDG. Figure 36 and figure 37 illustrate respectively the differences in fuel cost per passenger and in cost associated to climate change per passenger for the flights offered by both airlines from their hub airports to JFK.

Figure 35 shows that difference in fuel cost per passenger for individual flights between LHR and CDG can reach up to around 46%. The highest value observed is 11.14 € (A319 by British Airways) while the lowest value is 7.63 € (A321 by British Airways).

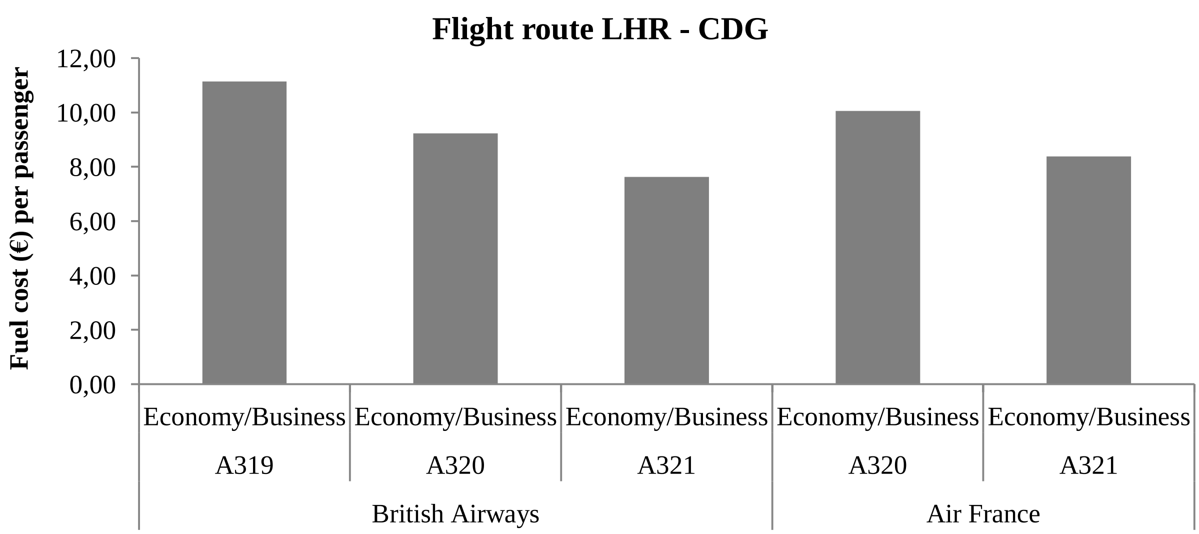


Figure 35 Comparison of fuel cost per passenger between aircraft used by British Airways and Air France in flights between LHR and CDG.

The differences in climate change cost per passenger as seen in figure 36 is lower but still meaningful (around 31%) when comparing the highest value (3.31 € for A319 by British Airways) with the lowest value (2.53 € for A321 by British Airways). These smaller difference in terms of climate change cost is due to the fact that such costs are not only associated to calculated CO_2 emissions (proportionally to fuel burnt by multiplying factor of 3.157) but also to calculated values of water vapour (H_2O) and calculated values of nitrogen oxides (NO_x), which in turn have a multiplying factor related to fuel burnt different for each aircraft type considered as explained in section 2.3.3.

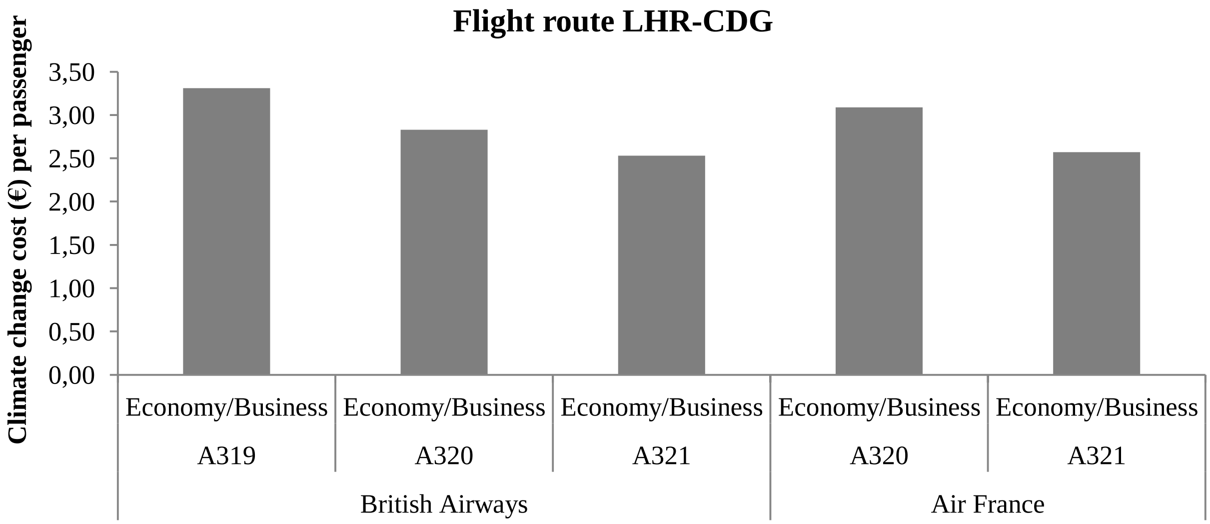


Figure 36 Comparison of climate change cost per passenger between aircraft used by British Airways and Air France in flights between LHR and CDG.

Figure 37 illustrates even larger differences in terms of fuel cost per passenger when comparing different seat classes among aircraft offered by British Airways and by Air France to JFK. The highest value calculated (243.24 € for first class in B777 by Air France) is almost four times higher than the lowest value (66.41 € for economy seat in B777 by British Airways). When climate change cost per passenger is addressed as seen in figure 38 a similar difference is perceived between the highest value (74.67 € for first class in B777 by Air France) and the lowest value (20.78 € for economy class in B747 by British Airways). Furthermore, all possible combinations of aircraft types for the inbound and outbound flights offered by each airline in each flight route considered was inserted in the model in similar manner as presented in table 41 to estimate the overall amount of fuel burnt and CO_2 emissions as well as their associated costs per passenger.

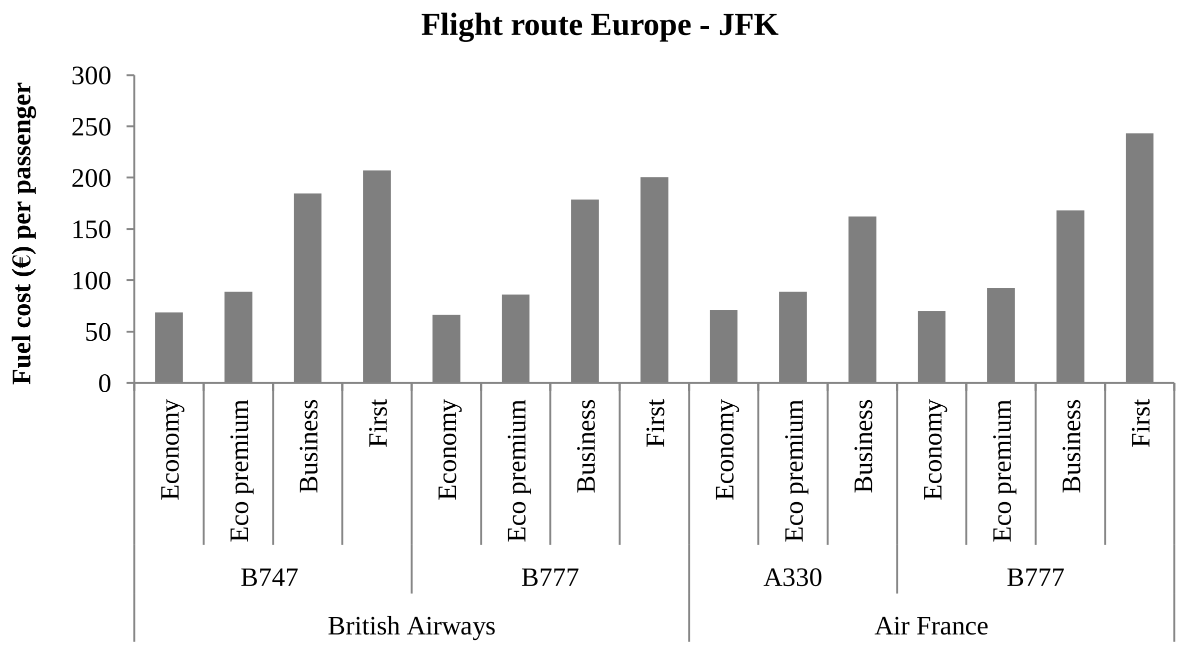


Figure 37 Comparison of fuel cost per passenger between aircraft used by British Airways and Air France in flights from their hub airports to JFK.

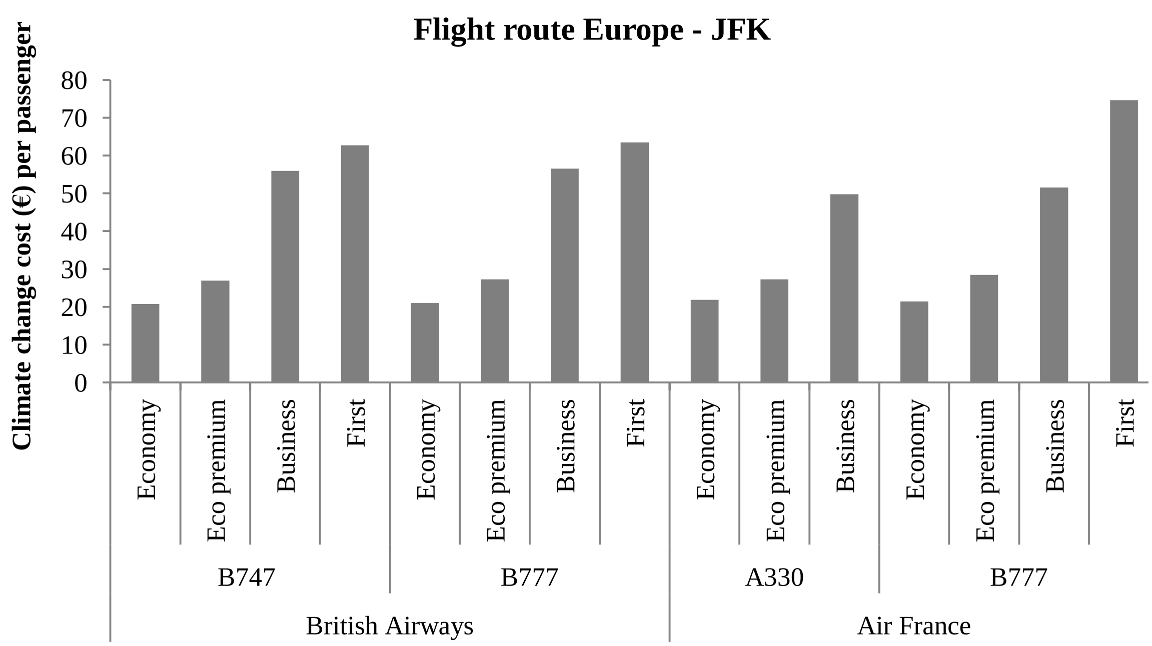


Figure 38 Comparison of climate change cost per passenger between aircraft used by British Airways and Air France in flights from their hub airports to JFK.

It can be observed from the values presented in table 41 that real fuel cost per passenger can vary up to 46% for an air passenger who decides to fly with British Airways from LHR to CDG. This is perceived when comparing the combination of inbound and outbound flights performed by A321 (22.28€, variant 3) with the combination of inbound and outbound flights performed by A319 (15.25€, variant 5). However, British Airways as well as other airlines applies the same fuel surcharge on air passengers who are flying in the same seat class no matter the combination of inbound and outbound flights they choose. In fact, for these short-haul flights there is a negligible difference between fuel consumed per passenger flying in economy class and fuel consumed per passenger in business class. However, British Airways charge 64% higher fuel surcharge on business class passengers (41€) than on economy class passengers (25€). Similar practice is also perceived among Air France and Lufthansa. In all cases the fuel surcharge on short-haul flights is higher than the real fuel cost per passenger. This is a common practice among airlines to compensate on flights with PLF lower than the observed annual average.

Table 41 Calculation of relevant indicators associated to impacts on climate change for outbound and inbound flights daily offered by British Airways between LHR and CDG.

Flight variants	Variant 1		Variant 2		Variant 3	
Flight 1 (in), 2 (out)	Fl. 1 (A320)	Fl. 2 (A320)	Fl. 1 (A320)	Fl.2 (A321)	Fl.1 (A321)	Fl.2 (A321)
Indicator	Value	Unit	Value	Unit	Value	Unit
Fuel per pax.km	0.052	Kg/pax.km	0.048	Kg/pax.km	0.043	Kg/pax.km
CO_2 per pax.km	0.16	kg/pax.km	0.15	kg/pax.km	0.14	kg/pax.km
CG cost per pax	5.67	€	5.37	€	5.07	€
Fuel cost per pax	18.47	€	16.86	€	15.25	€
Real fuel cost/price	11.4%	Economy	10.4%	Economy	9.4%	Economy
	2.6%	Business	2.4%	Business	2.1%	Business

*Note: Calculated based on data provided by airline on their website and on cost per weight of emissions as suggested by previous research by Dings et al. [239] and by Givoni & Rietveld [119].

Table 41 (cont.) Calculation of relevant indicators associated to impacts on climate change for outbound and inbound flights daily offered by British Airways between LHR and CDG.

Flight variants	Variant 4		Variant 5		Variant 6	
Flight 1 (in), 2 (out)	Fl. 1 (A320)	Fl. 2 (A319)	Fl. 1 (A319)	Fl.2 (A319)	Fl.1 (A319)	Fl.2 (A321)
Indicator	Value	Unit	Value	Unit	Value	Unit
Fuel per pax.km	0.057	Kg/pax.km	0.063	Kg/pax.km	0.053	Kg/pax.km
CO_2 per pax.km	0.18	kg/pax.km	0.20	kg/pax.km	0.17	kg/pax.km
CG cost per pax	6.14	€	6.61	€	5.84	€
Fuel cost per pax	20.37	€	22.28	€	18.76	€
Real fuel cost/price	12.6%	Economy	13.8%	Economy	11.6%	Economy
	2.9%	Business	3.1%	Business	2.6%	Business

*Note: Calculated based on data provided by airline on their website and on cost per weight of emissions as suggested by previous research by Dings et al. [239] and by Givoni & Rietveld [119].

It can also be noted that the ratio between real fuel cost and the overall airfares charged by British Airways for these flights varies between 9.4% (variant 3) and 13.8% (variant 5) for economy class seats and between 2.1% (variant 3) and 3.1% (variant 5) for business class seats. Figure 39 illustrates these differences in overall fuel cost per passenger among both airlines between these airports.

Figure 40 compares the overall carbon dioxide emissions per passenger-kilometre among different combinations of inbound and outbound flights offered by both airlines for the same flight route. Differences can be up to 43% when comparing the highest value (0.20 Kg/passenger-kilometre for both inbound and outbound flights performed by A319 with British Airways) with the lowest value calculated (0.14 Kg/passenger-kilometre for both inbound and outbound flights performed by A321 with British Airways). Differences are less considerable among possible variants with aircraft offered by Air France.

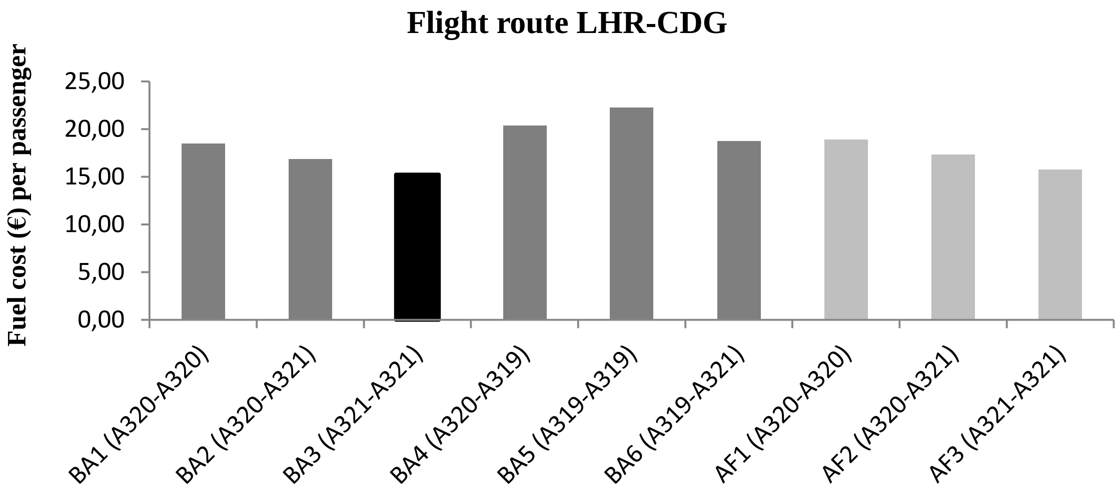


Figure 39 Comparison of overall fuel cost per passenger among different combinations of inbound and outbound flights offered by British Airways and Air France between LHR and CDG.

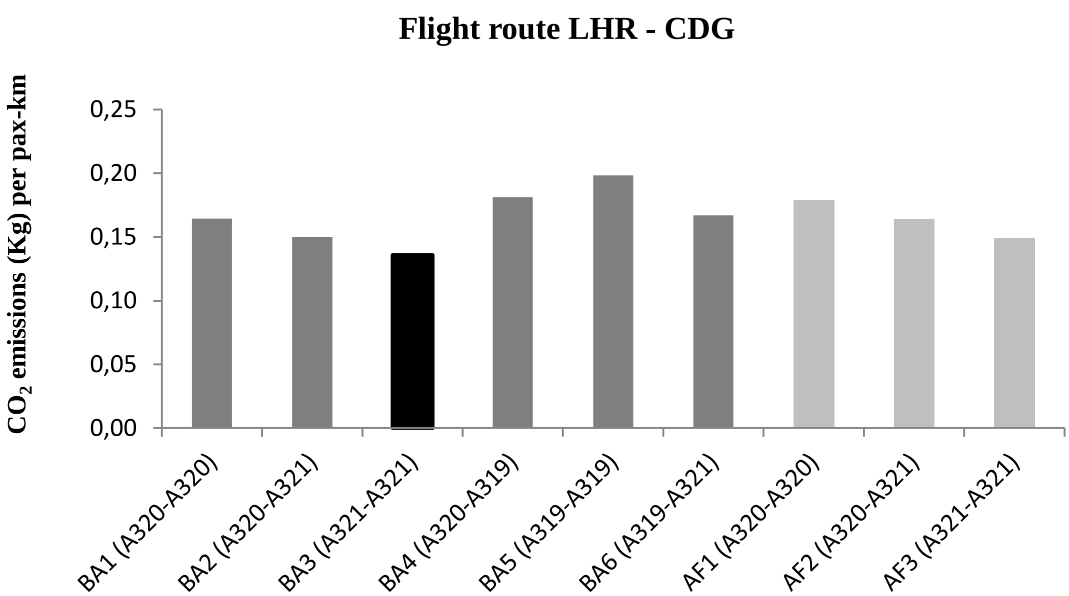


Figure 40 Comparison of overall CO_2 emissions per passenger-kilometre among different combinations of inbound and outbound flights offered by British Airways and Air France between LHR and CDG.

Figure 41 compares overall CO_2 emissions per passenger among different combinations of inbound and outbound flights offered by British Airways, Air France and Lufthansa from their hub airports to JFK. This comparison shows that the highest calculated value (3011 kg by first class seat in combined B777-B777 flights operated by Air France) is almost four times higher than the lowest calculated value (822 kg by economy seat in combined B777-B777 flights operated by British Airways).

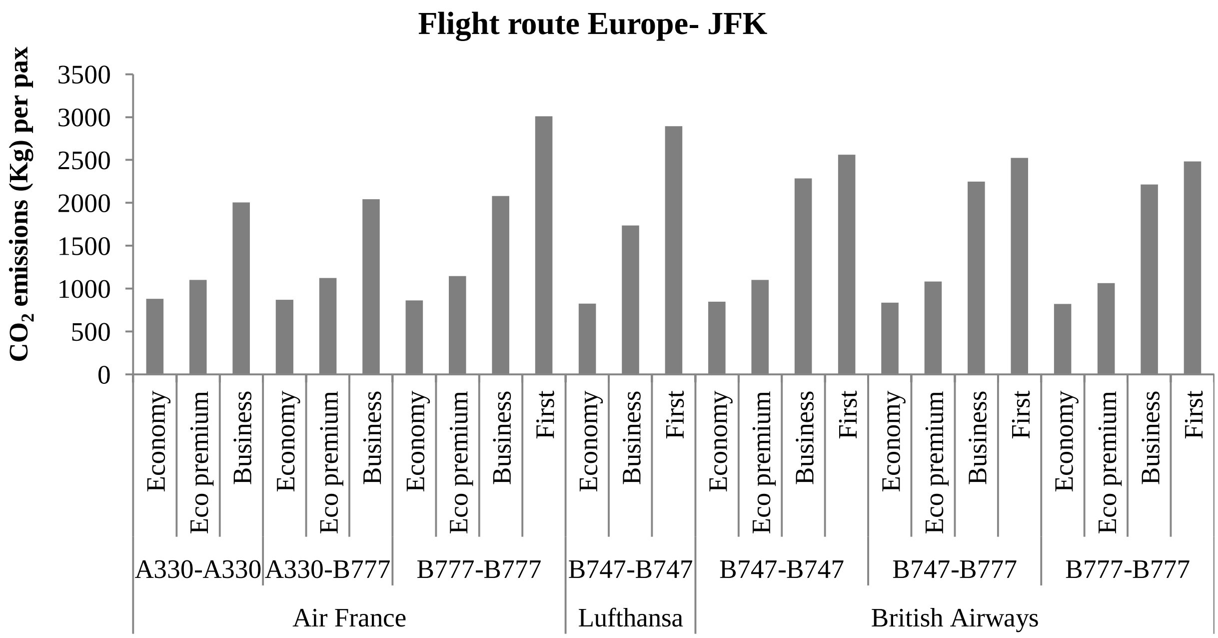


Figure 41 Comparison of overall CO_2 emissions per passenger among different combinations of inbound and outbound flights offered by British Airways, Air France and Lufthansa from their hub airports to JFK.

When comparing fuel cost per passenger among different seat classes of each combined flight between these three airlines as seen in figure 42, the highest value found (486.47€ by first class seat in combined B777-B777 flights operated by Air France) is almost four times higher than the lowest calculated value (132.82€ by economy seat in combined B777-B777 flights operated by British Airways).

The fuel surcharges applied by British Airways on air passengers for daily flights from LHR to JFK were obtained directly from booking simulations in the website of the airline and are presented in table 42 according to the seat class.

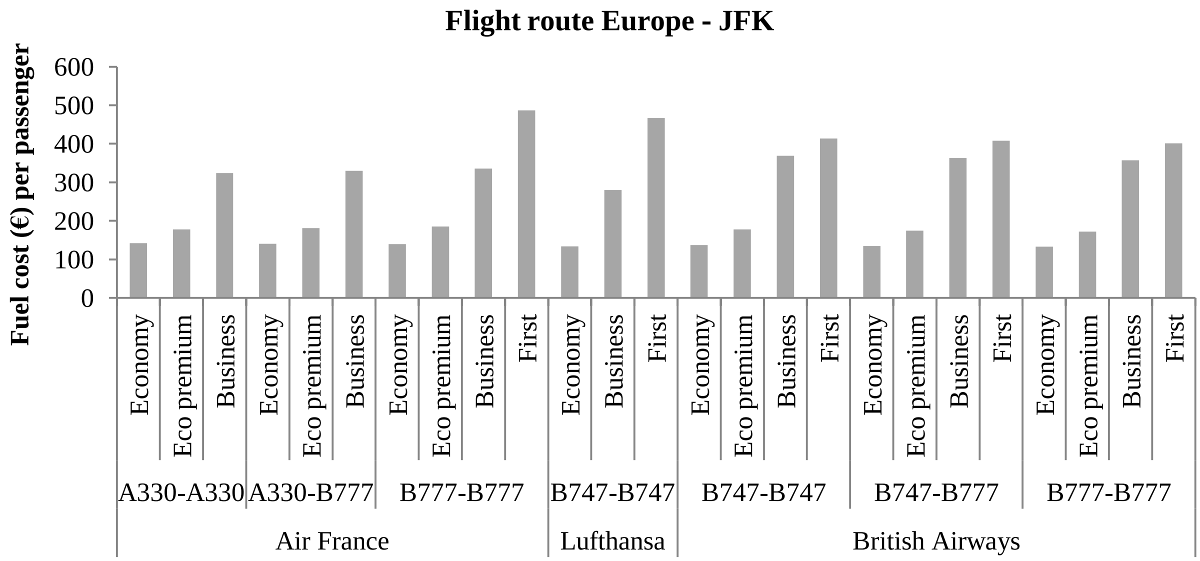


Figure 42 Comparison of overall fuel cost per passenger among different combinations of inbound and outbound flights offered by British Airways, Air France and Lufthansa from their hub airports to JFK.

Table 42 Fuel surcharges applied by British Airways for daily flights offered between LHR and JFK.

	Variant 1		Variant 2		Variant 3	
Seat class	Fl. 1 (B747)	Fl. 2 (B747)	Fl. 1 (B747)	Fl. 2 (B777)	Fl. 1 (B777)	Fl. 2 (B777)
First	377.94 €		377.94 €		377.94 €	
Business	377.94 €		377.94 €		377.94 €	
Eco premium	252.35 €		252.35 €		252.35 €	
Economy	252.35 €		252.35 €		252.35 €	

It can be noted that fuel surcharges applied on air passengers in economy class is almost twice as high as the real fuel cost incurred by each air passenger in that seat class. This ratio between the fuel surcharge and the real fuel cost per passenger decreases gradually with other seat classes. Air passengers on eco premium seat class are charged 50% higher than their real fuel cost. Air passengers on business class are charged almost the amount they incur in fuel cost. Air passengers on first class, on the other hand are charged a bit less than their real contribution in terms of fuel cost. Considering that air passengers flying on business class and on first class are more inelastic in terms of price demand than air passengers on economy class it might be a convenient decision to reduce the fuel surcharge on air passengers in economy class by transferring more of this cost to air passengers flying in first class and in business class. This reduction in fuel surcharge on air passengers in economy class would have to be done in a careful manner in order to ensure that airline would still cover all fuel expenses with the flight. When a reduction on fuel surcharge on air passengers in economy class is possible, airlines can develop marketing campaigns to attract more passengers to these flights by showing in a transparent manner that the passenger pays for what they really contribute in terms of fuel consumption.

These last calculations performed in this section can validate the hypothesis 7 as previously stated in chapter 2 which asserts that “the fuel surcharge on air passengers does not take in account their real contributions in fuel consumption when measured in passenger-kilometre.”

3.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Among all calculation methods presented in this research the use of Petri nets with the support of a LCA software such as Umberto may prove to be the most promising approach since it allows the researcher to consider important parameters that can provide different results even in the case the same aircraft type is used for the same flight route. This was mainly evidenced by the differences in terms of fuel consumption and emissions released by the same aircraft type but different jet engines which have different fuel rates and emission factors for NO_x and CO in each phase of flight. There are further ways to improve the accuracy of this method by using the average elapsed time of each phase of flight for each aircraft type used in each flight route. This data however is not publicly available. It could only be obtained directly from the flight logs of aircraft operated by airlines. Moreover, in further analysis fuel consumption and CO_2 emissions during the flight can also be provided in terms of passenger or passenger-kilometre for each seat class available. In this case, it will be recommended to obtain the PLF and PFF for a specific flight route on monthly basis in the previous year. Then, for each month in a year it can be estimated with more accuracy the average contribution of each air passenger flying in each seat class in terms of fuel consumption per kilometre and CO_2 emissions per kilometre in each flight route considered. By comparing the calculated values per seat class in each month through the year with the annual average fuel consumption per kilometre-passenger and CO_2 emissions per kilometre-passenger, it can be observed if the flight route is being performed in a more fuel efficient manner than the average among all flights routes offered by a specific airline. It also becomes possible to identify in which flight route a specific aircraft used by an airline is being used in a more fuel efficient manner during the year. Finally, a comparison can be done between the specific average values of fuel consumption per passenger-kilometre and CO_2 emissions per passenger-kilometre and the estimated average annual values per passenger-kilometre that should not be exceeded by airline in order to comply with their regulated cap of emission allowances within the EU ETS.

The use of artificial intelligence by means of neural networks or fuzzy logic or even by neuro-fuzzy systems where monthly classification of each aircraft or each flight route performed by airline in terms of CO_2 emissions per passenger-kilometre in relation to the maximum average annual value regulated by the cap (also measured in passenger-kilometre) is previously unknown and there is an interest in learning how to interpret it and classify by means of Kohonen's self-organizing feature maps (KSOFMs).

Figure 43 illustrates how KSOFMs can be modelled in order to cluster the flight routes in terms of their average monthly CO_2 emissions per passenger-kilometre as inspired by previous research undertaken for air quality assessment [173]. In this figure each hexagon would correspond to a specific flight route performed by an airline in a specific month. The number in each hexagon would correspond to the month of the year considered for that flight route. Another KSOFM can be modelled and designed for labelling each flight route with a code. The colours presented in the scale would represent how far or how close that flight route has been performed in comparison with the required cap defined by the annual average CO_2 emissions per passenger-kilometre that would be in compliance with the total allowances provided to the airline within the EU ETS.

This maximum average annual value defined by the cap of an airline within the EU ETS can serve as the main reference or benchmarking for monthly or annual classification of flight routes and aircraft deployed. The darker the hexagon the poorer is the performance of that flight route in comparison with the benchmark for that month considered.

A third KSOFM can be modelled and designed showing each hexagon as a specific aircraft used by airline under analysis. By superimposing one KSOFM onto another a sophisticated assessment structure can be developed to help flight planners to identify the most appropriate aircraft for each flight route and the months in which each flight route can be better performed in terms of CO_2 emissions per passenger-kilometre in comparison with the benchmark. In some cases, a flight planner may consider that certain flight routes will be performed just for few months during the year in order to avoid major deficit in CO_2 emissions in comparison to the required annual emissions cap. Various airlines in Europe offer certain flight routes just for few months but this is done mainly by low-cost airlines that operate with very limited aircraft fleet to seasonal destinations.

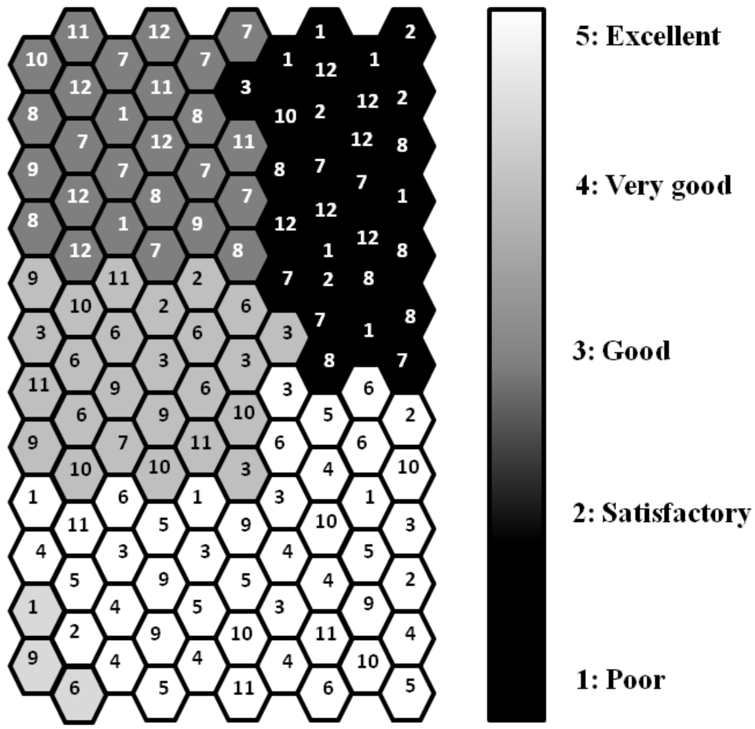


Figure 43 Clustering of the KSOFM by K-means Algorithm (months).

When such sophisticated model is developed a further analysis can involve a comparison between the performance of low-cost airlines and flag airlines in terms of CO_2 emissions per passenger-kilometre in short and medium-haul flight routes covered by EU ETS. By definition, a flag carrier is usually an airline that is owned by a government, even long after their privatization and enjoy preferential rights or privileges accorded by the government for international operations. The airlines considered in this research are flag carriers. It is a fact that usually low-cost airlines operate relatively newer aircraft than flag carriers and they maintain a high daily aircraft utilization rate to increase their revenues, which makes these airlines especially vulnerable to delays. Therefore, it is interesting to analyse in the context of EU ETS if newer aircraft and engines generally used by low-cost carriers can compensate on their higher aircraft utilization rate and delays in comparison to flag carriers in short and medium-haul flight routes.

The sophistication provided by artificial intelligence models may enhance the accuracy in the estimation of the expected CO_2 emissions per passenger-kilometre incurred by each air passenger that will fly on a specific aircraft and seat class in a particular month. These models may bring new opportunities for airlines by facilitating the identification of opportunities to reduce CO_2

emissions by charging lower fuel surcharge on air passengers when they choose flights with lower expected fuel consumption per passenger-kilometre, which in turn also result in lower CO_2 emissions per passenger-kilometre.

In the decision-making process for a more accurate fuel surcharge applied on air passengers based on their real contribution in fuel consumption it is also important to analyze the price elasticity of demand of air passengers by means of econometric models. That means, develop a prognosis of how air passengers demand for each seat class and each flight route would change in reaction to a change in fuel surcharge.

4 CONCLUSIONS

This research shows that despite of increasing pressure on airlines based in Europe to reduce their greenhouse gas emissions there are still meaningful opportunities to reduce their fuel consumption and consequently their CO_2 emissions during their flight operations where most of GHG emissions are released by airlines. This is demonstrated by means of a simplified life cycle analysis conceptual framework oriented to climate change mitigation using passenger-kilometre as the functional unit for comparison of alternatives. Results show that more opportunities for airlines in reduction of fuel consumption and CO_2 emissions are available for short-haul flights than medium and long-haul flights due to the fact that short-haul flights are offered with higher daily frequency, lower average passenger load factor and a wider range of aircraft types used.

Moreover, it is also demonstrated that for every aircraft there is a range of flight distance at which aircraft can perform better in terms of fuel consumption and GHG emissions per passenger-kilometre. Further, it is noticeable that for every aircraft type, there are considerable differences in terms of fuel consumption and CO_2 emitted per passenger depending on the type of jet engines used, being other parameters the same, including flight distance, passenger load factor, seating configuration, among others.

Different approaches are presented in this study with the purpose of illustrating their advantages and drawbacks and their best applicable cases. Although the method of IPCC tier 3A combined with ICAO method seem to be the most applicable case for obtaining an overview of the differences between airlines in terms of fuel consumption and CO_2 emissions on a daily basis, expert systems and artificial intelligence models can be developed and used in order to improve the precision of calculations performed for every individual aircraft considered. In this study, the use of Petri nets within the Umberto software environment (expert system) showed a valuable contribution in this direction and further recommendations are provided for the improvement of the model developed.

In summary, all results obtained and presented from this analysis can serve as an inspiration for an optimized reorganization of aircraft fleet that may contribute to substantial GHG emissions reduction with the support of green marketing initiatives. Last but not least, in order to achieve effective reductions in GHG emissions, it is important to count with the engagement of governments and airports in Europe by rewarding airlines and air passengers with reduced taxes and fees for flights that are considered more eco-efficient than the benchmark of the same flight route.

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Appendices

A. Comparison among largest airlines in Europe in terms of the coverage of environmental reporting.

B. Major achievements in fuel consumption and CO_2 emissions of largest airlines in Europe.

C. Amount of passengers carried by largest airline groups in Europe during the period 2008-2012.

D. Average carbon dioxide emissions released per passenger-kilometre by largest airline groups in Europe during the period 2008-2012.

E. Coefficients used in the calculation of contribution of fuel consumption and CO_2 emissions per passenger based on seat class.

Appendix A - Comparison among largest airlines in Europe in terms of the coverage of environmental reporting

Category	Indicator	Units	Air France-KLM	Lufthansa	IAG
Flight operations	CO_2	tonnes	**Yes**	**Yes**	**Yes**
	NO_x	tonnes	**Yes**	**Yes**	**Yes**
	CO	tonnes	**Yes**	**Yes**	**Yes**
	SO_2	tonnes	**Yes**	No	No
	HC	tonnes	**Yes**	**Yes**	**Yes**
	CO_2 per pax	kg/100 pkm	**Yes**	**Yes**	**Yes**
	NO_X per pax	kg/100 pkm	No	**Yes**	No
	CO per pax	kg/100 pkm	No	**Yes**	No
	HC per pax	kg/100 pkm	No	**Yes**	No
Fuel Consumption	Fuel consumption	tonnes	**Yes**	**Yes**	**Yes**
	Fuel consumption per passenger	l/100 pkm	No	**Yes**	**Yes**

*Note: International Consolidated Airlines Group, S.A. (IAG) is a British-Spanish multinational airline holding company formed in 2011 by merging British Airways with Iberia. Since then reports are released on behalf of both airlines together. The same applies to Air France and KLM since 2004 and to Swiss International Air lines and Austrian Airlines that were acquired by Lufthansa Group in 2005 and 2009, respectively.

Appendix A (cont.) - Comparison among largest airlines in Europe in terms of the coverage of environmental reporting

Category	Indicator	Units	Air France-KLM	Lufthansa	IAG
Ground operations	Water consumption	Thousands m^3	**Yes**	**Yes**	**Yes**
	Electricity consumption	MWh	**Yes**	**Yes**	**Yes**
	Other energy consumption	MWh	**Yes**	**Yes**	**Yes**
	CO_2	tonnes	**Yes**	**Yes**	**Yes**
	VOC emissions	tonnes	**Yes**	**Yes**	No
	HC emissions	tonnes	**Yes**	**Yes**	No
	NO_X emissions	tonnes	**Yes**	**Yes**	**Yes**
	SO_2	tonnes	**Yes**	No	**Yes**
	Non-hazardous waste	tonnes	**Yes**	No	**Yes**
	Hazardous waste	tonnes	**Yes**	No	**Yes**
	Recycled waste	%	No	No	**Yes**
	Global noise energy indicator	10^{12} kJ	**Yes**	No	**Yes**

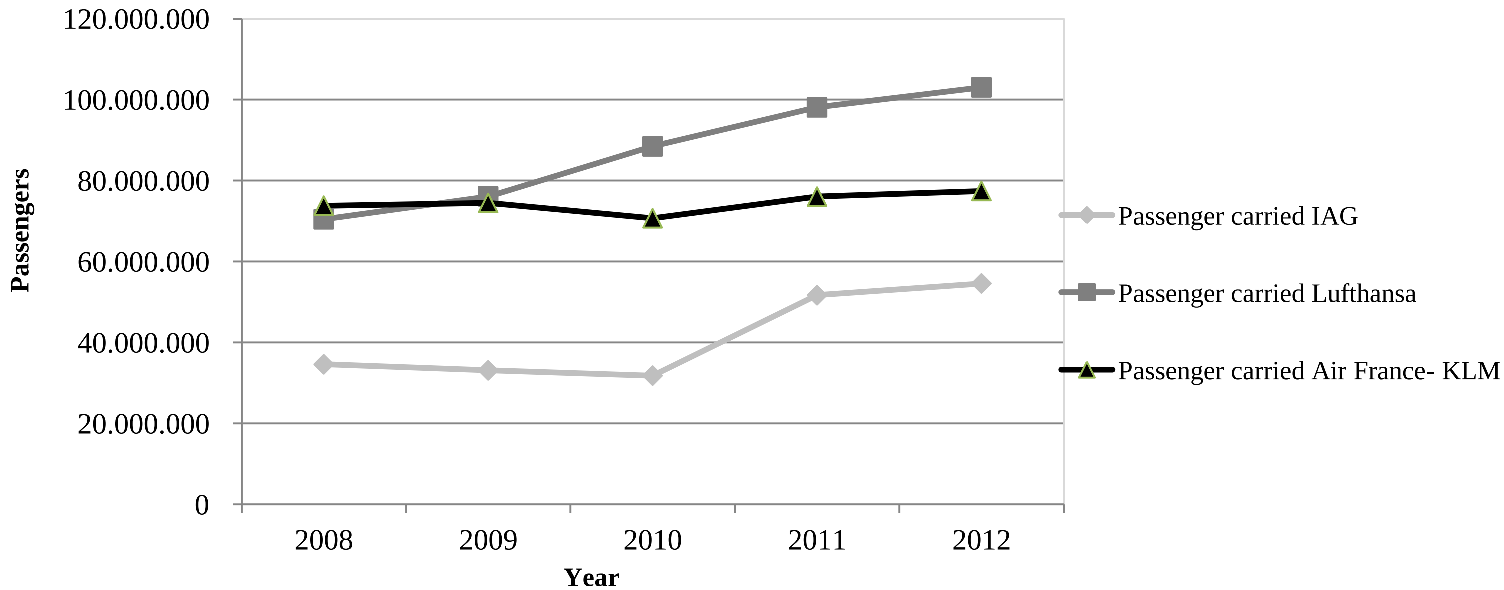
*Note: International Consolidated Airlines Group, S.A. (IAG) is a British-Spanish multinational airline holding company formed in 2011 by merging British Airways with Iberia. Since then reports are released on behalf of both airlines together. The same applies to Air France and KLM since 2004 and to Swiss International Air lines and Austrian Airlines that were acquired by Lufthansa Group in 2005 and 2009, respectively.

Appendix B – Major achievements in fuel consumption and CO_2 emissions of largest airlines in Europe

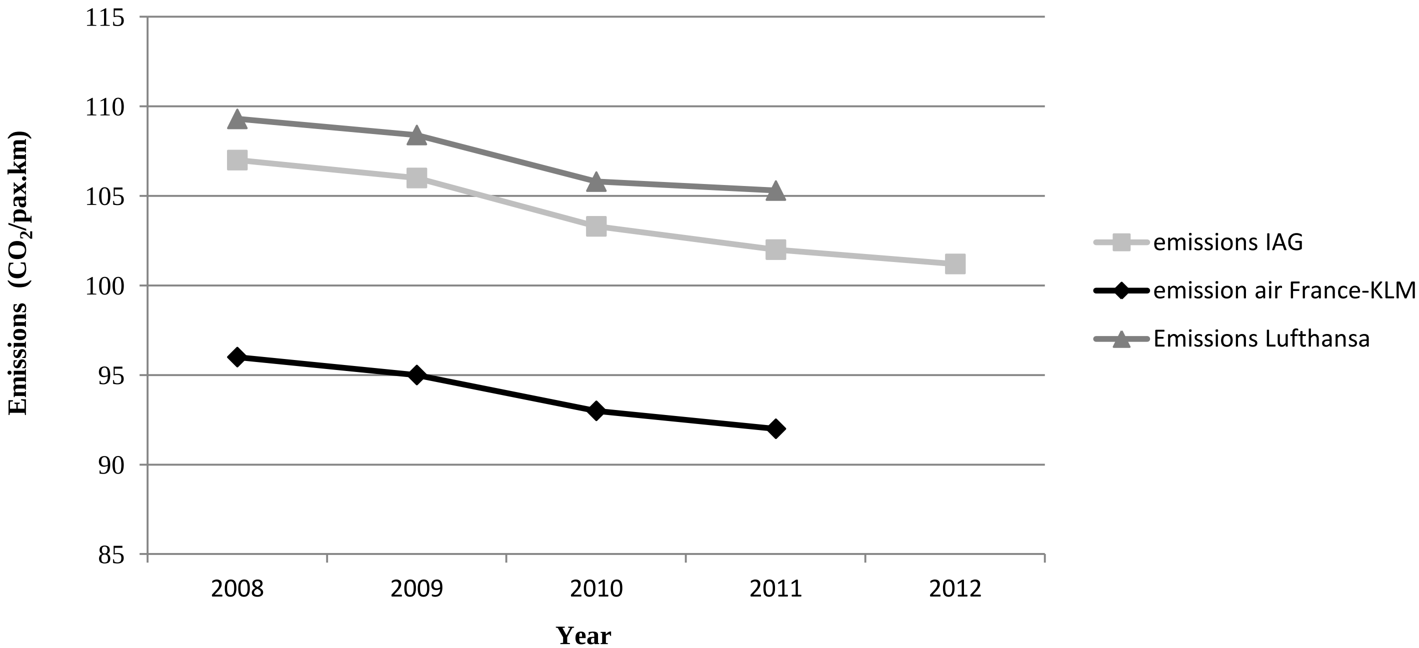
Indicator	Air France-KLM	IAG	LUFTHANSA
Average age of aircraft	Air France has 241 aircraft with an average age of 10.3 years. Since 2009 they acquired nine A380 that contribute to significant reduction in fuel consumption per pax-km in long routes. KLM has 117 aircraft with an average age of 10.5 years.	The fleet of British Airways comprises 264 aircraft with a average age of 12.9 years. There are 40 new aircraft on order/planned. The fleet of Iberia has 75 aircraft with an average age of 8.8 years. The Iberia fleet is one of the most modern fleets in the world.	The fleet comprises 285 aircraft with an average age of 11.7 years. Since 2010 they acquired ten A380s for long routes.
Achievements and targets towards reduction in fuel consumption and CO_2 emissions	Improve energy efficiency by 1.5% per year until 2020. Reduction of fuel consumption from 3.96 litres to 3.81 litres per passenger per 100km between 2008 and 2011, a reduction of almost 4%. The airline group had a previously set target for an average fuel consumption of 3.7 l/pax/100 Km (92g CO2/pax/100Km) by the end of 2012.	A 25 percent improvement in carbon efficiency from 111g CO_2/pkm in 2005 to 83g CO_2/pkm in 2025 (101.9g CO_2/pkm in 2012). 2015 interim goal: 97g CO_2/pkm. 48,000 tones CO_2 reduction due to aircraft fuel efficiency initiatives in 2013. In 2012 achieved savings of 39,336 tones CO_2 due to fuel efficiency improvements. A 5% reduction in ground energy use in our buildings for 2013 against our new 2012 baseline. Achieved 2007 target to reduce ground energy consumption by 20% over five years.	In 2012, the specific kerosene consumption fell to only 4.06 liters per 100 passenger kilometers, after having already reached a record company low the previous year with a value of 4.18 liters per 100 passenger kilometers. This represents a decline of 2.8% over 2011. The specific CO_2 emissions fell proportionally. The Lufthansa Group's absolute fuel consumption declined from 9.02 million to 8.88 million tonnes of kerosene – even though the Group's flying companies transported more payload and carried significantly more passengers to their destinations during the reporting year.

*Note: All data presented in this table were retrieved from CSR and Sustainability report of each airline group.

Appendix C – Amount of passengers carried by largest airline groups in Europe during the period 2008-2012



Appendix D – Average carbon dioxide emissions released per passenger-kilometre by largest airline groups in Europe during the period 2008-2012



Appendix E – Coefficients used in the calculation of contribution of fuel consumption and CO_2 emissions per passenger based on seat class

Aircraft	Seating class	Pitch	Width	Coef.
B747-400	First	78.0	21.0	3.0
	Business	73.0	20.0	2.7
	Eco premium	38.0	18.5	1.3
	Economy	31.0	17.5	1.0
B777-200	First	78.0	21.0	3.0
	Business	73.0	20.0	2.7
	Eco premium	38.0	18.5	1.3
	Economy	31.0	17.5	1.0