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

PH.D. THESIS

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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.

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1. INTRODUCTION

The reports of airlines, airports and previous research has shown that most of environmental impacts of aircraft come from the aircraft fuel consumption and its airborne emissions. This is clearly the case of greenhouse gas emissions (GHGs) which in turn is largely represented by CO_2 released at high altitudes during the cruise stage of flights. In recent years GHGs released by aircraft engine and their contribution to climate change gained major importance among airlines operating across European Union member countries after the inclusion of the civil aviation sector in the European Union Emissions Trading Scheme (EU ETS), when all intra-community flights became subject to emission restrictions with allocated annual emission allowances that airlines will have to comply with. 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.

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 related to LCA of aircraft widely used in civil aviation 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 [1]. For this reason, a life cycle assessment can be simplified for an effective approach 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. It is demonstrated in this research 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. 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. Estimations of emissions are provided within a simplified life cycle analysis conceptual framework that takes in account different phases of flight operation.

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 as described in the practical section within section 3.1. 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. An airline hub is an airport that an airline uses as a transfer point to get passengers to their intended destination. 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 [2].

2. LITERATURE REVIEW

2.1. Methods for calculation of fuel consumption and emissions from aircraft

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 emissions [3].

In this section, author initially explains the three methodological tiers of IPCC for estimating emissions from flights. Subsequently, the method of ICAO is described. Other methods exist such as the method of DEFRA, ClimateCare, Sabre Holdings, among others. Some 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 choice of the ICAO method was the most appropriate for the nature of this research due to its simplicity, accuracy and flexibility for improvements due to availability of input data provided by airlines considered and reports from IATA and ICAO. Moreover, the use of ICAO method within the conceptual approach of IPCC tier 3A is seen as the most convenient for the calculations of average fuel consumption and average CO_2 emissions for a set of selected flight routes performed by largest European airlines. Results are presented in terms of the following parameters:

- Fuel consumption per passenger
- CO_2 emissions per passenger and per passenger-kilometre
- Revenues per CO_2 emissions

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).

2.1.1. 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 landing and take-off cycle (LTO). For hydrocarbons and CO, the situation is slightly different being 30% released during the LTO and 70% released at higher altitudes [4].

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 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 [5] 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 [6]. 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 [7] and [8]; as in AERO2k [9] by the European Commission.

2.1.2. 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 [10] employs a distance-based approach to estimate the emissions per kilometre for every economy class passenger (hereinafter specified as “Y pax”) using data currently available on a range of aircraft types. Emissions are measured in terms of Kg/Y pax.km. 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 per pax.km = 3.157 * (TF * PFF) / (Y-seats * PLF * flight distance) (1)

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 [11], while PLF and PFF correspond to traffic data per route group updated by ICAO and economy class (Y) seat capacity is given by aircraft manufacturers and airlines.

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.

2.2. The use of life cycle assessment in the air passenger transport sector

Within the perspective of European airlines regarding the need of environmental performance improvement 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 [12]. For achieving this goal in environmental management, a commonly used methodological tool is Life Cycle Assessment (LCA), which is defined in ISO 14040 standard [13] 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". 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 [14]. 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.

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 [15; 16].

The following elements are essential in a LCA, according to the international standard ISO 14040 series [17]:

- **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.

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 [18].

Among other applications in the civil aviation sector LCA approach was conducted by taking in account the environmental impacts of the entire aircraft life cycle for Airbus A330 [1] and Airbus A320 [19]. 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 the section 3.1.

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 [20] 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.

3. METHODOLOGY AND THEORETICAL FRAMEWORK OF RESEARCH ANALYSIS

3.1. Research objectives and hypotheses

Several initiatives that can be implemented by airlines in order to mitigate the climate change effects of their operations 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 1 and those that in the scope of this study are highlighted, i.e., those at the operational level of airlines.

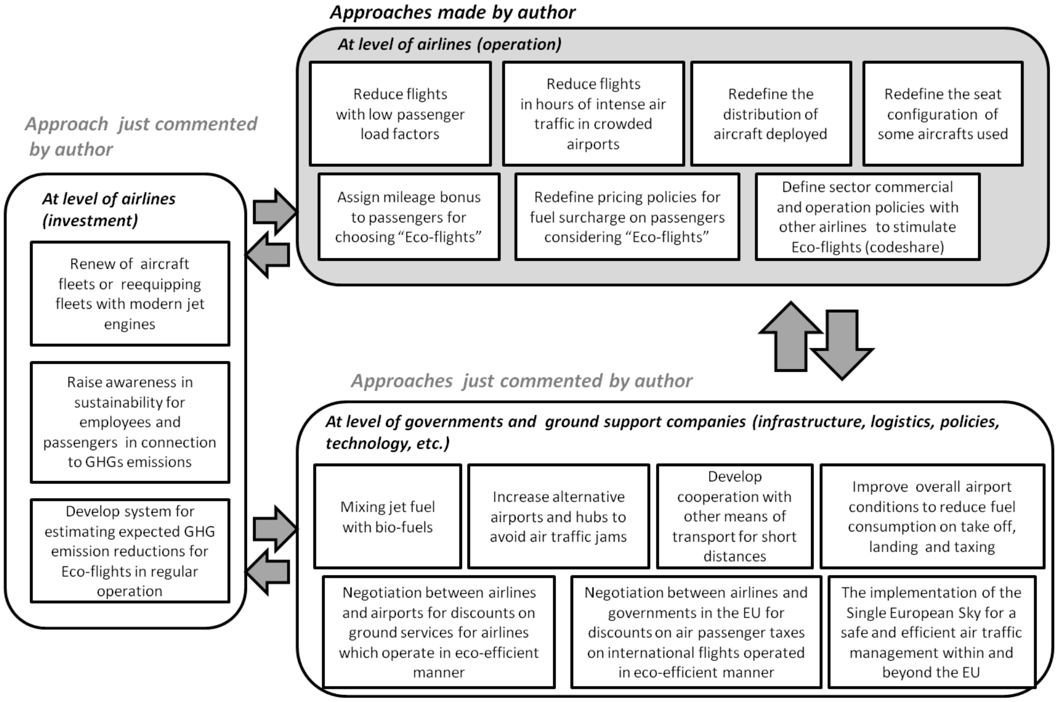

Figure 1 Possible means to reduce GHG emissions per passenger-kilometre by airlines.

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 [21]. 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.

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 a further section. 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 and this is also demonstrated in this study. 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.

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).

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.

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 1 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 intends 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.

3.2. Life cycle assessment oriented to climate change mitigation

This section presents a full life cycle assessment (LCA) focused on the contribution to climate change for two wide-body aircraft regularly used by European airlines in long-haul flights – Airbus A330-200 and Boeing 777-200.

Conventionally, a flight is categorized as long-haul when it covers more than 3,000 km [2]. The contribution of this aircraft type to climate change is estimated for its whole lifespan and is based on the embodied emissions of carbon dioxide equivalent (CO_{2eq}) during their manufacturing and maintenance phases and on the CO_{2eq} emissions released during the operational phase. These three aircraft phases form the system boundaries of the LCA presented in this section. The choice of the functional unit is essential when performing a LCA since it influences the study outcome. The functional unit usually adopted for the passenger transportation sector is: passenger.km [22; 23]. Therefore, CO_{2eq} emissions are analysed referring to the transportation of one passenger, through a travelled distance of 1 km. A comparison is done among each phase of aircraft lifespan in terms of CO_{2eq} emissions per passenger-kilometre (functional unit).

In the subsequent section 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 research 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. Table 1 summarizes the assumptions made in this analysis for each phase of aircraft lifespan. 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 [1]. Nevertheless, this positive contribution in terms of embodied emissions represents no more than 10% of the overall manufacturing phase [19]. 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 [24]. For this reason, this phase of aircraft lifespan is not considered in this LCA.

Table 1 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	Most of aircraft components are produced in the same country of the assembly line.
Aircraft maintenance	Block hours⁽¹⁾ 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 the aircraft. An average PLF of 81.5 per cent is considered An average PFF of 76.95 per cent is considered

Note. Assumptions made by author

(1) 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.

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 measures to be undertaken in the phases of aircraft lifespan where more opportunities are available for mitigating climate change.

Flow diagram

Based on previously described system boundaries, a very simplified flow diagram of aircraft life cycle is shown on figure 2 as proposed by author.

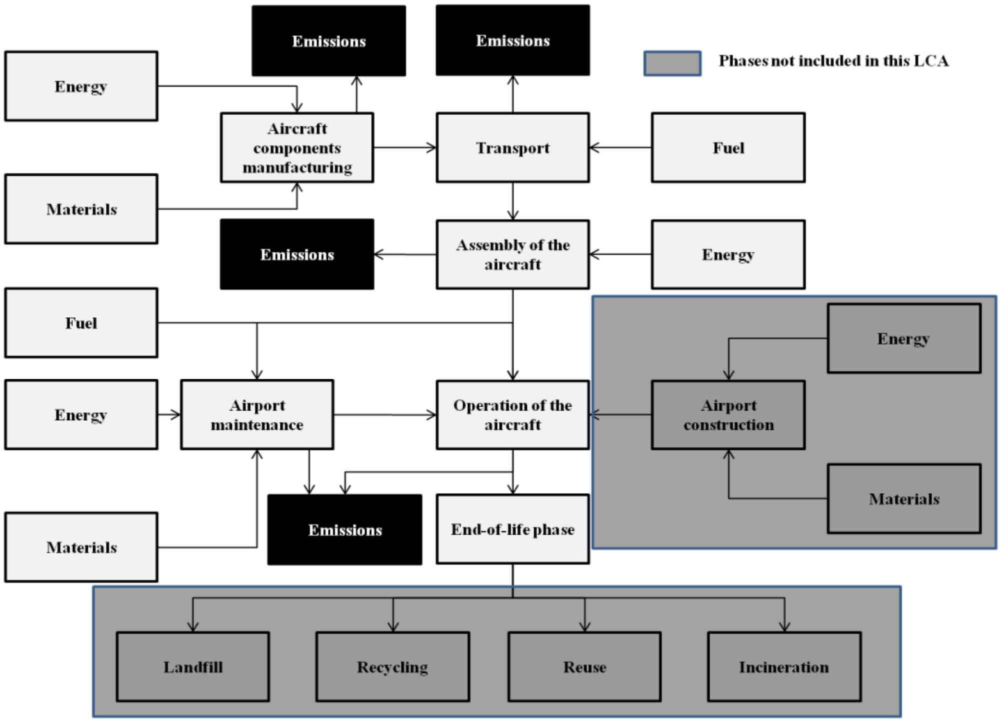

Figure 2 Flow diagram of the full Life Cycle Conceptual Framework for a commercial Aircraft.

Note. Proposed by author.

Although the end-of-life cycle phase is not included in this study, it is also illustrated in this flow diagram. 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 [1].

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.

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. 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 [25]. 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.

The average fuel consumption rate per distance flown was based on the EMEP/CORINAIR Emission Inventory Guidebook [26]. Service life of aircraft is also considered in terms of flight hours for the purpose of calculating the emissions per passenger-kilometre during the whole lifespan of aircraft.

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).

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:

$$\text{Pax-km}_{(LF)} = SL * C * CS \qquad (2)$$

where "SL" is the service life of aircraft, "C" is the capacity of aircraft (varies according to seat configuration), and "CS" is the typical cruise speed of aircraft.

The input values of this equation allowed the final calculation of CO_{2eq} per passenger-km in each phase of LCA.

In the manufacturing phase of LCA the weight of materials used in each aircraft type was calculated based on the operating empty weight and on the percentage of materials used. The values calculated for embodied energy and embodied emissions for virgin materials are based on certain factors and on the weight of each material. These values are aggregated and divided per total amount of passenger-kilometres flown during the lifespan of the aircraft and each seat configuration chosen.

Author adopts from literature the average distribution in percentage for aircraft maintenance cost across airports in Europe due to airframe and components replacement and energy supply. 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. It was estimated the average consumption of electricity associated to aircraft maintenance during its lifespan assuming that all maintenance services are offered by London Heathrow airport. Although it is impossible to estimate the embodied emissions of replaced airframe/components during the aircraft lifespan, it was observed from values calculated that total CO_{2eq} emissions from the manufacturing of airframe and aircraft components can be considered negligible in comparison to the emissions resulting from electricity supply during the maintenance services. For this reason, the estimation of total emissions of CO_{2eq} during the maintenance phase takes in account only the emissions resulting from the energy supply.

The carbon dioxide equivalent (CO_{2eq}) emissions during the aircraft operation phase were estimated based on ICAO methodology. Initially, fuel consumption per pax.km is estimated.

Calculation assumes the average CO_{2eq} emissions per passenger-kilometre for the aircraft type considered for an average flight distance of 3500 nm (approximately 6482 km). The distance of 3500 nm is within the range at which the aircraft flies in a more fuel-efficient manner, i.e. it uses 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. Other parameters assumed include a passenger load factor (PLF) of 81.50 per cent, and a passenger-to-freight factor (PFF) of 76.95 per cent for three different seat configurations as previously described.

ICAO methodology only focuses on 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. Subsequently, energy content was converted to CO_{2eq} by assuming emission factor of 0.0745 kg CO_{2eq}/ MJ [27] and multiplying by 1.9 to take into account the effect of radiative forcing index (RFI).

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 3 and 4:

Energy content per Y pax.km = 46.36 * fuel per Y class pax.km (3)

CO_{2eq} per pax.km = 0.0745 * 1.9 * energy content per Y class pax.km (4)

Interpretation of results

Figure 3 illustrates overall results for embodied CO_{2eq} emissions in each LCA phase analyzed for B777-200. Results were also obtained for A330-200.

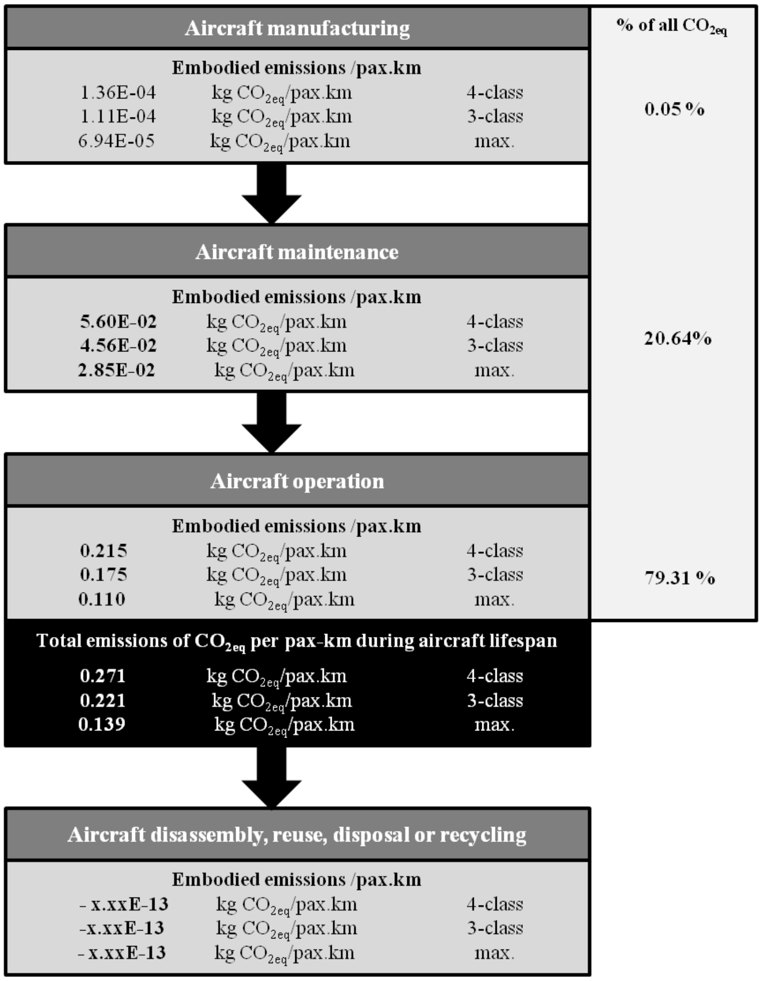

Figure 3 Embodied and released CO_{2eq} emissions during each LCA phase analysed for aircraft B777-200.

Note. Values provided from calculations performed by author.

It can be noted that 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 during the aircraft maintenance phase. Thus, it validates hypothesis 1 stated in section 3.1 of this research. In the operation 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.

The end-of-life scenario (aircraft disassembly, reuse, disposal or recycling) was not included in this analysis. If measured, the results in terms of CO_{2eq} emissions per passenger-kilometre would be negative but in a much lower order (- x.xxE-13) which translate a small positive contribution for all environmental impacts considered.

3.3. 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 3.2 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 [28] 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 [29; 30; 31].

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 [32]. 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 [33]. 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 3.1. 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 are: Lufthansa, Air France and British Airways. 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).

3.3.1. Fuel consumption and GHG emissions for different distances flown

First calculations presented are focused in the fuel consumption and GHG emissions for different distances flown by aircraft. 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). However, author used the emission factors of other greenhouse gases and aggregated the contribution of their emissions during the cruise stage of international flights in order to obtain CO_{2eq} emissions per economy equivalent passenger-kilometre (Y pax.km). These emission factors

Only the emission factors for cruise stage of international flights are considered in these calculations and are presented in table 2. As previously mentioned, 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 2 Emission factors for cruise stage of average aircraft used in international flights **[34]**.

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

3.3.2. Fuel consumption and GHG emissions in different phases of flight

Subsequently, calculations of fuel burnt and more detailed emissions are performed for different phases of flight operation. In this context, author adopted two approaches: firstly, the combined IPCC tier 3A methodological approach with ICAO methodology and secondly, the use of Petri nets within Umberto software environment.

IPCC tier 3A methodological approach combined with ICAO method

In the first approach 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 and average amount of fuel consumption during each part of the LTO cycle according to different aircraft types.

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). 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.

The use of Petri nets within Umberto software environment

Petri nets as evidenced in the second approach are a graphical and mathematical modelling tool that were originally proposed by Carl Adam Petri in 1962 [35] 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 [36]. 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.

Umberto software has 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. The design of model and calculations performed within Umberto environment are based on Petri Nets [37]. 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 [38].

In the calculation procedure within Umberto software environment different amount of fuel consumption and carbon emissions are estimated for the same aircraft type using different engines in the same flight route. The technical sheets of jet engines provides data related to average thrust setting and elapsed time measurements in LTO cycle as presented in table 3. Therefore, the flight time is taken as an important input parameter instead of flight distance. Other parameters as considered in other calculation procedures are maintained.

Table 3. Average thrust setting and elapsed time measurements in LTO cycle [39].

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

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.

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 (BA, British Airways). Then a comparison was undertaken between aircraft types conventionally used by BA in that route (A320 and A321) and a larger aircraft type (A330) with high density seat configuration in terms of fuel efficiency per passenger for short-haul flight routes. 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 3. Table 4 presents an example of calculations of fuel rate and elapsed time for each phase of a short-haul flight operated with a specific engine type.

A material flow network was designed within Umberto software environment based on Petri nets conceptual framework and results are presented within this material flow network in the next chapter.

Table 4 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 **[39]**.

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

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

Finally, calculations of average fuel consumption and GHG emissions per passenger-kilometre are performed for specific aircraft types used by competing airlines in chosen flight routes departing from hub airports considered. These flight routes 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). In this part of the research the ICAO method was again used within the conceptual approach of IPCC tier 3A with a great circle distance (GCD) correction factor in order to include the emissions of distance flown in excess of the GCD, stacking, traffic and weather-driven corrections. Author used the GCD correction factor as recommended by ICAO method.

Results of these simulations are calculated and presented 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.

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 climate change 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.

Table 5 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 London Heathrow (LHR) to Paris Charles de Gaulle (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 5 Aircraft types, seat configuration and frequency of flight offered by British Airways for flight route LHR-CDG [40; 41].

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

The CORINAIR database provides average fuel consumption per distance flown for each aircraft type considered. This was the basic data used to estimate fuel consumption and emissions by aircraft used for the flight routes considered. It is interesting to note that a business class seat in these aircraft used for short-haul flights occupies only 10% more space than a seat in the economy class. For this reason, a factor “1.1” was used for calculating the fuel consumption and emissions per business class seat.

4. RESULTS AND DISCUSSIONS

4.1. Results of calculation for different distances flown

Initially calculations for the fuel consumption and carbon dioxide-equivalent emissions per economy-equivalent passenger-kilometre (CO_{2eq}/Y pax.km) were undertaken for different distances flown by different aircraft types analyzed in this research.

Figure 4 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. Similar calculations were undertaken for 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.

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." Therefore, these calculations evidence that hypothesis 2 is 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.

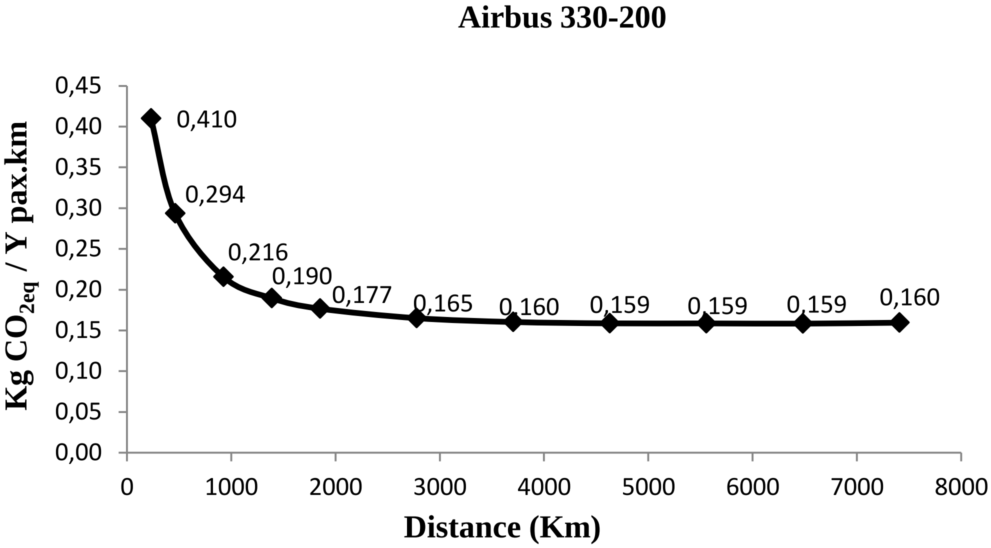

Figure 4 Emissions of carbon dioxide equivalent per Y passenger-kilometre for Airbus 330-200 (Kg CO_2eq/ Y pax.km).

4.2. 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 3.3.2.

4.2.1. 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. The average values of fuel consumed and CO_2 emissions per different ranges of distances flown during the cruise phase for each aircraft type are considered. For the purpose of comparision only the emissions of CO_2 during cruise phase were analyzed 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. Moreover, the aim of this approach 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, i.e. for short-haul and medium-haul flights. Therefore only flight distances up to 4630 km were considered.

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 5 shows the share in percentage of fuel consumed during the LTO cycle in relation to total fuel consumed during the flight for different distances flown. This graph represents the situation for Airbus A330-200. In fact, other aircraft were also analyzed in this aspect and similar conditions were perceived. This evidence serve to test hypothesis 4 as described in section 3.1 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.” 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 as well as for other large aircraft such as B777-200 and B747.

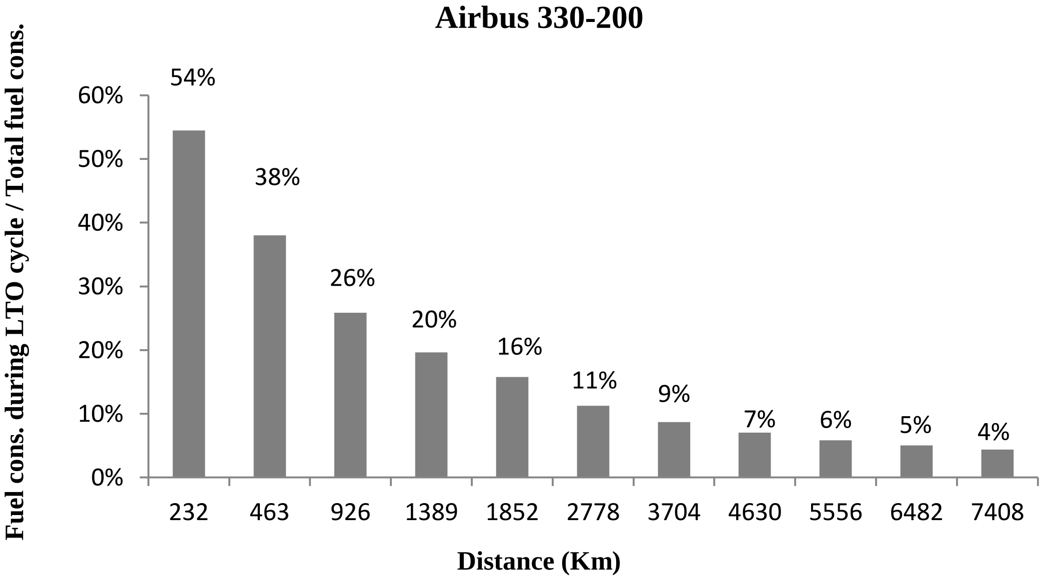

Figure 5. Percentage share of fuel consumed during LTO cycle in relation to total fuel consumed per distances flown for Airbus 330-200.

4.2.2. 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 3.3.2 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. 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 [39].

Figure 6 presents a material flow network based on the conceptual framework of Petri nets as designed within Umberto software environment. The material flow can be visualized using the so-called Sankey diagrams as shown. 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 6 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.

Table 6 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.

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**

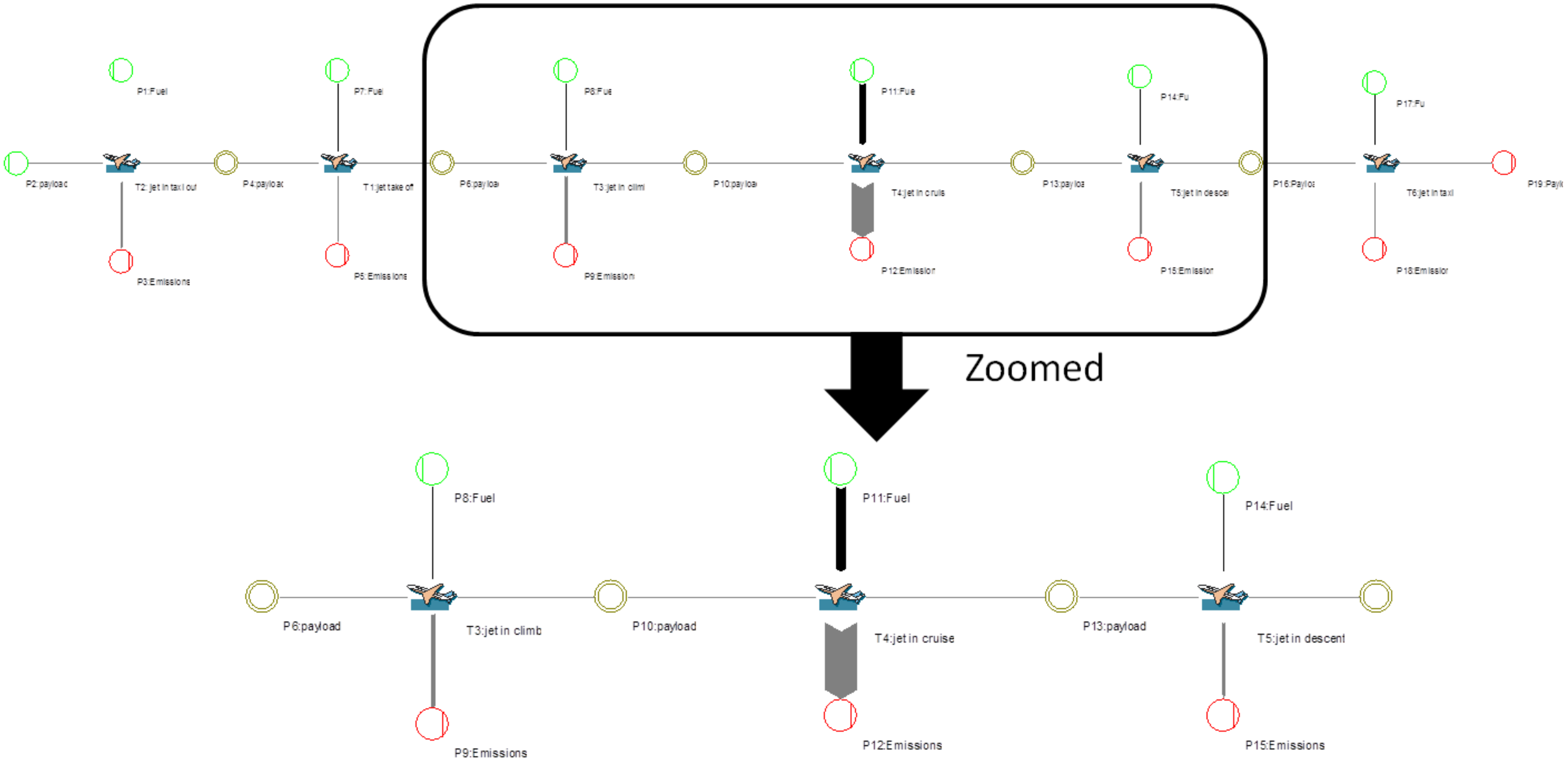

Figure 6. Sankey diagrams represented in the material flow network designed within Umberto software.

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 4. Other values regarding fuel consumption and emissions were also calculated for the same flight route but different aircraft type and different engines. Together they allowed a comparison among different combinations of aircraft used in the flight route in terms of fuel consumption per passenger and CO_2 emissions per passenger. Figure 7 illustrates the differences in terms of total carbon dioxide emissions released per passenger among different types of aircraft with different set of jet engines.

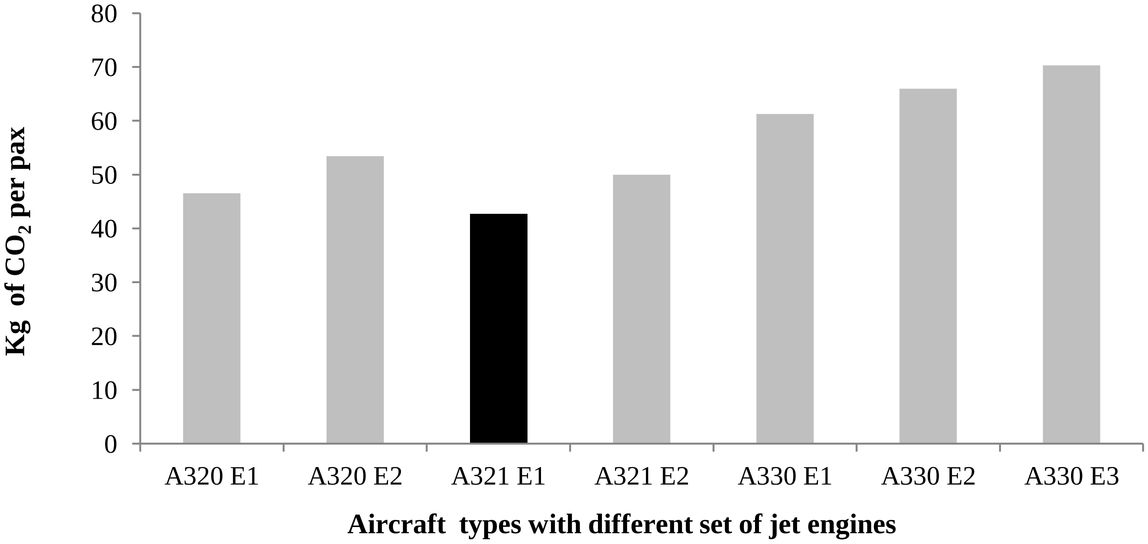

Figure 7. Comparison of total carbon dioxide emissions released per passenger among different types of aircraft with different set of jet engines.

*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

The calculated values evidenced 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. 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). This validates the hypothesis 3 as stated in chapter 3 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."

4.2.3. 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 2 was again used within the conceptual approach of IPCC tier 3A but with the great circle distance correction factors.

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 airlines. The average annual PLF of each flight route was also acquired by consulting the annual reports and online information available about each airline investigated.

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").

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 for selected flight routes 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 was observed that 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.

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.”

In fact 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 as presented in table 7.

Table 7 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%

Alternative 1 as shown in table 7 offers a potential daily reduction of 31% in these indicators when deploying two aircraft A319 (a narrow body aircraft with one single passenger aisle) and one aircraft B777 (a wide body aircraft with two passenger aisles). 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. 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 8 shows the differences perceived in carbon dioxide emissions per passenger-kilometre among aircraft used by British Airways and Air France in daily flights from their hub airports (London Heathrow and Paris Charles de Gaulle, respectively) to John F. Kennedy International Airport (JFK) in New York.

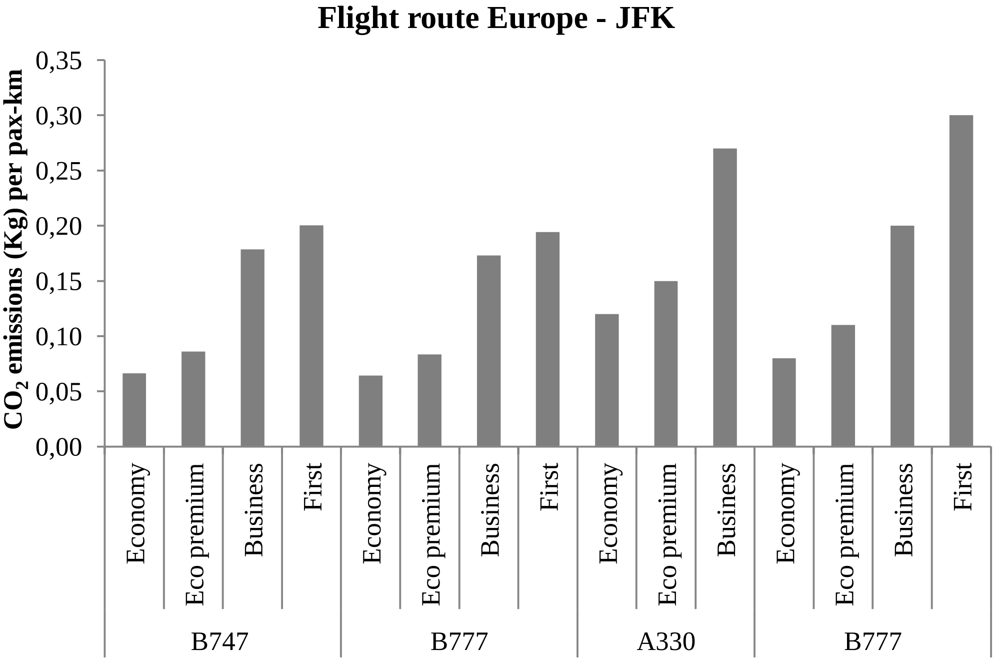

Figure 8. Comparison of carbon dioxide emissions per passenger-kilometre between aircraft used by British Airways and Air France in daily flights from their hub airports to JFK.

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. 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).

When comparing the estimated fuel cost per passenger among different seat classes for flights offered by selected airlines and selected flight routes with fuel surcharges applied by these airlines on air passengers it was observed 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. These last calculations performed in this section can validate the hypothesis 7 as previously stated in chapter 3 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."

5. 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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