CRANFIELD UNIVERSITY

STUART HOWE

ENVIRONMENTAL IMPACT ASSESSMENT AND OPTIMISATION OF COMMERICAL AVIATION

SCHOOL OF ENGINEERING
MSc by Research

MSc Thesis
Academic Year: 2010 - 2011

Supervisors: Dr Athanasios Kolios & Prof Feargal Brennan
November 2011

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ABSTRACT

The aviation industry represents approximately 3% of global greenhouse gas emissions, however with significant growth expected over the coming decades this proportion is expected to increase. Continued governmental and social pressure to reduce global emissions is posing a challenging question to the industry; how to improve environmental efficiency and reduce emissions with increasing industry growth.

The environmental impact of aviation globally is discussed, examining the significant emissions and protocols that exist and their relative impacts both environmentally and economically. The viability of alternative biofuels is discussed, determining the life cycle environmental impact of future replacements to kerosene based jet fuel.

This thesis therefore aims to provide an understanding of the fundamentals of aviation emissions but also most importantly provide possible solutions to assist the industry in reducing its emissions 'footprint'. An important factor in determining efficiency improvements is to understand the impact of particular stages of an aircraft life and the impact they have individually. This was achieved using an established methodology called Life Cycle Assessment (LCA), which is an efficient tool for the analytical consideration of the environmental impact of manufacturing, operation and decommissioning.

The results of a comprehensive LCA study of an Airbus A320 are documented considering all phases of the service life. The study draws useful conclusions, indicating the significance of special materials such as carbon fibre reinforced plastic (CFRP) on the total manufacturing emissions of the aircraft and indicating its operational phase as the one contributing most in its environmental performance breakdown.

The thesis also examines short-term efficiencies for emissions reduction in commercial aviation, focussing on improvements in aircraft routing. The initiation of the EU emissions trading system (ETS) within European aviation will

incentivise airlines to reduce their annual CO_2 emissions. An alternative routing strategy is proposed for selected long haul routes, which introduces multiple stages into the route utilising two aircraft and is shown to reduce total CO_2 emissions by up to 13.7%. Combined with blended biofuel, this reduction was estimated to increase to 16.6% with a reduction in ticket fares estimated to be as high as $19 per passenger per flight.

Keywords:

Environmental Economics, Aircraft Routing, Life Cycle Assessment, Aviation Emissions, Aviation Biofuels

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List of Abbreviations and Acronyms

BA	British Airways
BTL	Biomass to Liquid
CFRP	Carbon Fibre Reinforced Plastic
CH_4	Methane
CO_2	Carbon Dioxide
CTL	Coal to Liquid
DECC	Department for Energy & Climate Change
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
EUA	European Union Allowances
FAL	Final Assembly Line
FAMES	Fatty Acid Methyl Ester
FT	Fischer Tropsch
GHG	Greenhouse Gas
GTL	Gas to Liquid
HC	Hydrocarbon
HFC	Hydrofluorocarbons
HRJ	Hydrogenerated Renewable Jet
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
IPCC	Intergovernmental Panel for Climate Change
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCC	Low Cost Carrier
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Load Factor
LTO	Landing Take Off

MHS	Multiple Hub Spoke
N_2O	Nitrous Oxide
NOx	Nitrogen Oxide
OEW	Operating Empty Weight
PFC	Perfluorocarbon
PM	Particulate Matter
PPT	Point to Point Transit
RFI	Radiative Forcing Index
SHD	Spoke Hub Distribution
SO_2	Sulphur
SURF	Sustainable Use of Renewable Fuels
WTT	Well to Wake

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Chapter 1

Introduction to the Thesis

1 INTRODUCTION

Air Transportation is one of the most important services in the world today, providing global connectivity between millions of passengers and providing employment to millions across the globe. Ever since the de Havilland Comet, the first purpose built airliner entered service in 1952; commercial aviation has experienced unprecedented growth with approximately 18,000 aircraft operating an extensive route network to almost 10,000 airports.

However the growth and success of the industry is not without drawbacks. The ever-increasing volume of air traffic is causing the skies to become congested and airports overloaded. The increased aircraft utilisation is also leading to concerns regarding the industries environmental impact resulting from noise and emissions.

The air transport industry has made significant steps in increasing environmental efficiency with todays jet airliners burning around 70% less fuel than early jets (Peeters P.M, 2005). This is the result of continuous improvement within the industry, with improved aerodynamics and engines with dramatically lower fuel burn. However the fact still remains that air transportation accounts for 2-3% of all fossil fuels burnt.

Therefore aircraft operators are coming under continued pressure to reduce global emissions both through advances in technology and enhancements to airline operating strategies. The International Energy Agency reported that commercial aviation accounts for approximately 12% of carbon dioxide (CO_2) emissions emitted by the transportation sector with this figure expected to reach 19% by 2050 (IEA, 2010). Demand for air travel is predicted to grow consistently with Airbus forecasting an annual growth in traffic of 4.8% between 2010 and 2029 (Leahy, 2010).

Airline operators have not only recognised the environmental need to reduce emissions, but also the commercial benefits that can be gained from improving environmental efficiency. Several airlines have chosen to use ‘green’

credentials as part of their marketing strategy, with low cost carrier easyJet recently claiming that they are greener than rival airline Jet2 due to their newer aircraft fleet (Turner, 2011).

The continued emphasis on reducing greenhouse gas emissions is raising the profile of a methodology called Life Cycle Assessment (LCA). This systematic approach will examine emissions from all stages of the aircraft life including the less researched area of manufacturing, maintenance and decommissioning.

This thesis implements a holistic environmental assessment, examining not only the operation of commercial aircraft but also the additional life stages and their impact upon the overall environmental efficiency. Much focus is directed into the fuel efficiency of aircraft engines during operation and technological advances to airframe structure. Although such developments will undoubtedly assist in the reduction of fuel and emissions, the question must be posed into the aircraft manufacturing process and its overall environmental impact.

The development of new aircraft such as the Boeing 787 Dreamliner and Airbus A350 have been heavily focused on efficiency, with claims of 15% and 25% fuel consumption improvements respectively (Dodge, 2010). The reductions are mainly based on advances in manufacturing materials and techniques with both aircraft constructed from at least 50% carbon fibre composite, offering substantial weight savings over their predecessors.

Less is reported into the greenhouse emissions resulting from manufacturing. The increasing use of carbon fibre composites on airframe structures may have more of a negative impact than first thought. Toyota (Winter, 2010) recently commissioned a study into the environmental credentials of composites and concluded that carbon fibre production creates more CO_2 per pound than any other automotive material.

Should the aviation industry continue its focus into aircraft fuel efficiency improvements as a method of reducing emissions, or does the production and eventual disassembly need to be more closely examined? Perhaps sacrificing

fuel economy in favour of manufacturing more carbon neutral airframes capable of operating with alternative fuels is a greener route?

The majority of existing research into the environmental impact of aviation focuses on new conceptual advances in aircraft technology. This report focuses on environmental improvements that can be made using the current aircraft in operation.

This thesis will first examine the operational phase of an aircraft life, analysing current routing strategies implemented by airlines together alternative solutions that may provide environmental benefits.

1.1 Aims and Objectives

1.1.1 Aim

The aim of this thesis is to identify the key challenges relating to environmental efficiency within the aviation industry by both examining routing strategies, analysing the viability of alternative fuels and conducting a holistic life cycle assessment of a commercial airliner.

1.1.2 Objectives

The objectives of the thesis are as follows:

- Identify the key areas for improvement of aviation environmental efficiency
- Examine routing strategies implemented by airlines, providing an alternative model which offers environmental benefits
- Assess the viability of alternative aviation fuels, detailing the current and future fuels available and their potential improvements to the environmental impact.
- Conduct a holistic life cycle assessment (LCA) of an Airbus A320 airliner, determining the environmental impacts associated with all stages of the aircraft life.

1.2 Thesis Structure

- **Chapter 1** is an introduction to the thesis

- **Chapter 2** describes the environmental challenges and opportunities facing the aviation industry, examining the current and future regulation regarding GHG emissions and the most significant emissions associated with air transportation.

- **Chapter 3** describes the effect of routing upon aircraft efficiency. The chapter begins by examining the science and logistics associated with routing and hub architecture. The second section of the chapter analyses a new conceptual routing strategy that aims to improve environmental efficiency and comparing to existing strategies.

- **Chapter 4** examines environmental credentials of alternative biofuels for commercial aviation. The chapter begins by describing the principles behind biofuel production and the need for alternative energy sources. Current and future biofuels are identified and their environmental impact examined, both during combustion and production.

- **Chapter 5** details a comprehensive life cycle assessment (LCA) of an Airbus A320 commercial aircraft, examining the environmental impact of all stages of the aircraft life (production, operation and disposal). The analysis determines the stages with the greatest environmental impact over a range of different impact factors (fossil fuel depletion, land use change etc). Sensitivity analysis is conducted with the result to examine the impact of alternative materials, fuels and operating practices upon the overall results.

- **Chapter 6** presents the conclusions and future recommendations, summarising the findings and proposing future work.

Chapter 2

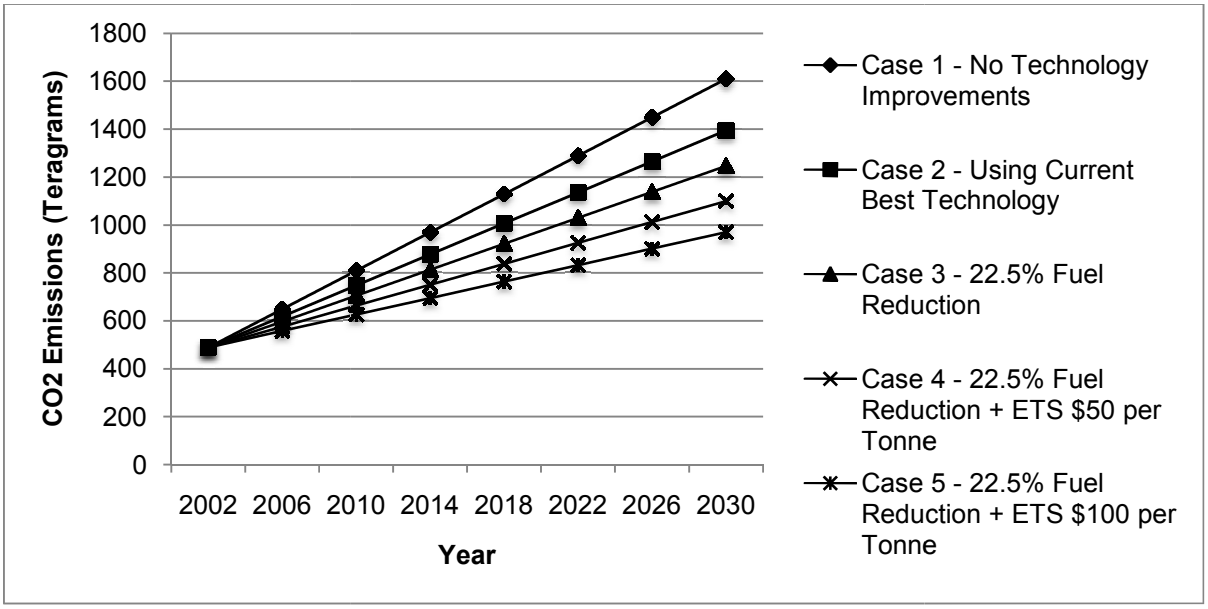
Environmental Emissions within the Aviation Industry

2 ENVIRONMENTAL EMISSIONS WITHIN THE AVIATION INDUSTRY

The developments in aviation during the last fifty years have been unprecedented, with new technology and operating practices contributing to more efficient and accessible transportation. Reductions of 70% fuel consumption have had an important effect on the environmental impact of commercial air transport (Gössling, 2005). Fuel consumed is directly proportional to CO_2 Emissions; therefore the reductions achieved have had an important impact on the industries environmental impact, however the future growth forecasted for the aviation industry is set to pose new challenges regarding the environmental performance of the sector.

Even with increasing environmental efficiency, annual passenger growth of 4.8% forecasted for the next 20 years (Lewis, 2006) is likely to result in continued increases in the level of CO_2 emissions attributed to the industry. The Intergovernmental Panel on Climate Change (IPCC) estimates that 3.5% of the total human contribution to climate change can be attributed to aviation (Horton, 2006). The IPCC's conservative estimate is that this will increase to 5% by 2050, with the highest 'worst case' scenario representing 15%. The aviation industry will also be affected to some degree by the environmental accomplishments of other industries, with the aviation share potentially increasing as a proportion.

Figure 1 below shows the increase in future CO_2 emission levels forecasted for next 20 years and how technological improvements may effect the rate of increase within the air transportation sector.



Source: Compiled from (Horton, 2006)

Figure 1 - CO_2 Emission Forecast based on Technology Scenarios

2.1 The Environmental Impact of Aviation

Climate change can be defined as "*a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period".* (Adhikari, 2011)

Any human activity that involves combustion, results in the release of CO_2 and other greenhouse gases into the atmosphere, contributing to climate change. This is particularly relevant in aviation, which contributes to climate change in several ways. The combustion of fossil fuels during flight is the largest contributor, however other sources of emissions exist including:

- Aircraft Manufacturing
- Aircraft Decommissioning and Disposal
- Aircraft Maintenance
- Emissions generated from the production of energy in Airport Terminals
- Construction of Airport Infrastructure
- Airport Ground Vehicles for Access and Logistics

During the course of this thesis, several of the other contributors will be examined in greater detail. The manufacturing and disposal of aircraft will be analysed using Life Cycle Assessment (LCA) methodology. The emissions resulting from aircraft operation will also be examined, both when using conventional aviation fuels and future alternative fuels.

The impact of aviation can be split into two primary categories; noise and emissions. Aircraft and airport noise is perhaps the most identifiable environmental impact, with landing and take off the highest cause of local noise pollution (Parliamentary Office of Science and Technology, 2003). Aircraft have collectively become quieter over the past 30 years, however increasing utilization is increasing public concern. Noise, although concerning is very much a localized issue. Emissions however contribute globally and it is this category that will be examined during the course of this thesis.

Many forms of emission are released during flight, with CO_2 regarded as the principal emission, which is proportional to the quantity of fuel consumed. At cruising altitudes in the lower stratosphere (30,000 – 39,000ft), fuel burn produces a number of gases and particles, which contribute to the 'greenhouse effect'. Some of the emissions of concern include:

- Methane (CH_4)
- Nitrous Oxide (N_2O)
- Nitrogen Oxide (NO_x)
- Sulphur (SO_2)
- Hydrofluorocarbons (HFC)
- Perfluorocarbon (PFC)
- Water Vapour
- Particulates (PM)

All of the above emissions have differing contributions to the overall environmental impact of flight, with the altitude of flight also said to have an appreciable effect. CO_2 will first be addressed, with the additional emissions following thereafter.

2.1.1 Carbon Dioxide (CO_2)

Carbon Dioxide is a greenhouse gas released naturally through the carbon cycle or as the result of human activity and is the most significant emission that contributes to aviation's impact on climate change. The current fuels used in aviation (JET A/A1) contain 3.15 grams of CO_2 per gram of fuel (Rahmes, 2009).

Increases in CO_2 emissions contribute to global warming which can have a number of unwelcome consequences on the 'health' of the planet including:

- **Sea Level Rise** – Resulting from melting of the ice caps leading to an increase in inhospitable land

- **Reduction of the Ozone Layer** – Increases in high cloud cover during winter leading to warming and depletion of the ozone layer
- **Increased Extreme Weather** – Leading to more droughts and floods
- **Ecosystem Changes** – Range of plant and animal life changing

The heating of the earth's atmosphere is as the result of a phenomenon called radiative forcing which is defined as *"the change in the energy balance of the lower atmosphere by a climate change mechanism"* and it measured in Watts per square metre (W/m^2) (Jardine, 2005)

Radiative forcing is essentially the extent to which the incoming and outgoing radiative energy of the atmosphere is out of balance. Incoming radiation can easily pass through the outer atmosphere to reach earth however the amount that can escape is much more influenced by the concentration of greenhouse gases present in the atmosphere. Therefore the increase in greenhouse gas will result in less radiation escaping from the earth's atmosphere and thus leading to an increase in the earth's temperature (Nodvin, 2007).

Radiative forcing is generally attributed to CO_2, however it can also be used to quantify non-CO_2 warming effects associated with air travel. For non-CO_2 effects, the radiative forcing index (RFI) is used which is the radiative forcing of a gas with respect to carbon dioxide (Jardine, 2005). The radiative forcing levels per emission are shown below in Figure 2.

The radiative forcing index is a ratio between the total radiative forcing of all non-CO_2 emissions and carbon dioxide separately. The IPCC have calculated the change in radiative forcing today when compared to pre-aviation emissions as $0.049W/m^2$, which equals a radiative forcing index of 2.7 times that of CO_2.

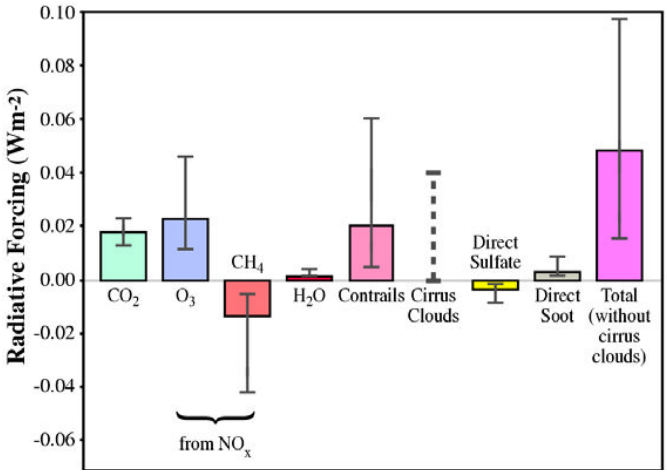


Figure 2 - Radiative Forcing of different Atmospheric Effects (Jardine, 2005)

Figure 2 confirms that CO_2 is only one of several atmospheric effects that can impact on the environmental credentials of aviation. Many other effects assist and whilst they do not receive the same level of scrutiny as CO_2, they are still significant.

2.1.2 Nitrogen Oxides (NO_x)

Nitrogen oxides are a by-product of combustion and have a variety of cooling and warming atmospheric effects, but are less understood than CO_2. The production of NO_x during flight is actually increasing with advances in technology, due to increasing pressure and temperatures from aircraft engines (Greener by Design, 2002). The emission of NO_x forms ozone (O_3) when in the presence of light, which is potent greenhouse gas controlled by atmospheric chemistry and dynamics. NO_x can affect both local air quality and ozone levels in the troposphere. The formation of ozone does however have one benefit in that it reduces the levels of atmospheric methane (CH_4), a dangerous greenhouse gas thus providing a cooling effect.

2.1.3 Water Vapour

Water vapour is natural product of combustion and can be attributed to warming of the atmosphere. Water vapour has a short lifespan in the atmosphere but when emitted at high altitudes can result in contrails (illustrated in Figure 3), which can be seen as cloud like trails from an aircraft. The water vapour, although harmless in composition has been linked to the formation of cirrus clouds. Both cirrus clouds and contrails trap some of the solar radiation reflected by the earth's surface and result in a warming effect.

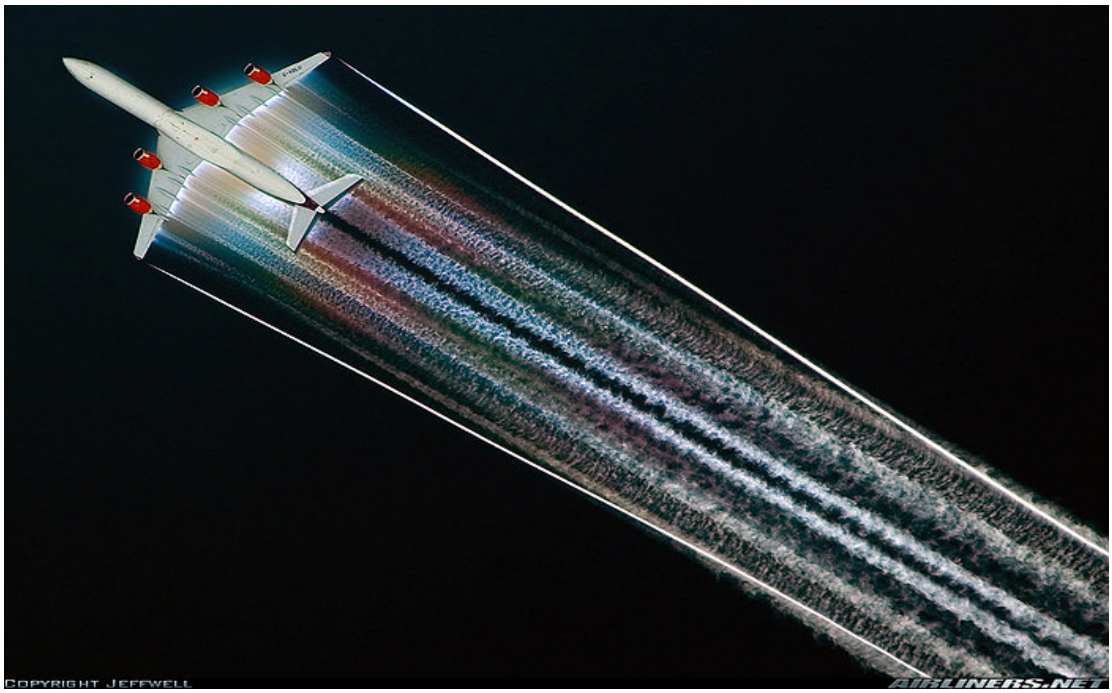


Figure 3 - Contrail from Boeing 747 Aircraft (Jeffwell, 2006)

2.1.4 Soot and Aerosols

Soot and sulphate aerosols released during combustion can have negative temperature effects on the atmosphere (Greener by Design, 2002). Whilst sulphur which is present in aviation fuel, forms aerosols of sulphate compounds which have a small cooling effect due to their reflection of incoming solar radiation, soot traps outgoing radiation and has a small warming effect. They are both said to cancel each other out.

2.1.5 Emission Comparison between different Aircraft types

Aircraft are predominately split into two types depending on the length of flight that they operate; short haul (under 3hrs) using narrowbody aircraft and long haul (above 6.5hrs) typically operated by widebody aircraft. Long haul aircraft will typically operate a greater proportion of the flight in cruise and both types have very different emission values. As part of this thesis, it is important to understand which aircraft currently in operation are the most efficient per seat, with the best indicator being fuel consumption, which is directly proportional to CO_2 emissions.

Figure 4 considers the fuel consumption (kg) of 2 narrowbody and 2 widebody aircraft per seat for a short haul distance of up to 2000nm. Seating capacity is taken as the maximum from (Williams V. N., 2006) negating varying load factors. The fuel consumption figures used take into account all stages of the flight envelope, including landing and take off (LTO), cruise, climb, descent and taxiing.

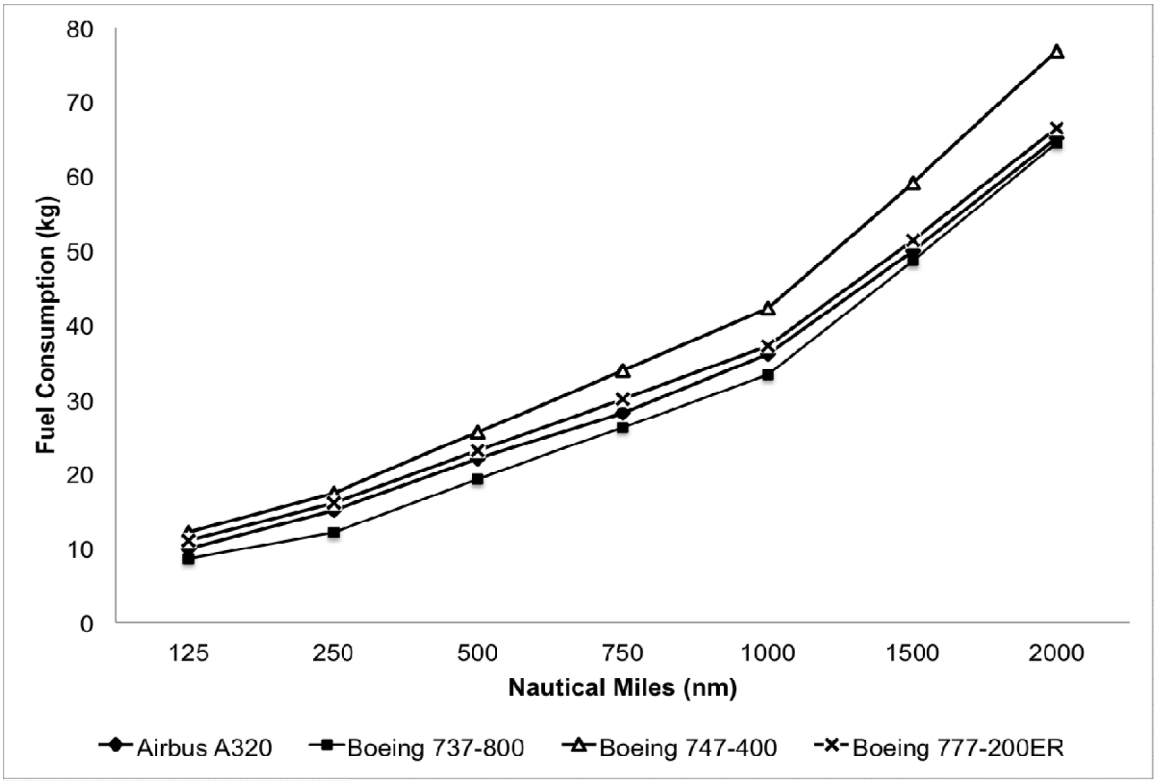


Figure 4 - Fuel Consumption Comparison over 2000nm

Figure 4 shows that over the 2000nm range, both narrowbody aircraft consume less fuel per seat than the 747-400 and 777. Figure 4 shows both the 747-400 and 777 operating over a short haul distance which is uncommon. Considering a 2000nm cruise distance using the 747-400 and 777 without the LTO cycle and comparing to the same distance operated by the A320 over a complete flight cycle, the A320 still consumes less fuel per seat, 14.7% compared to the 747-400 and 1.28% for the 777.

2.2 Aviation Emission Frameworks & Protocols

Many of the world's countries are committed to addressing global climate change through a number of regulatory frameworks. The current system in operation is the Kyoto Protocol, introduced in 1997.

2.2.1 Kyoto Protocol

The Kyoto Protocol is an international global treaty in which developed countries were set targets for greenhouse reductions by 2008-2012 of an average of 5% below those of 1990 (UNFCCC, 1998). The Kyoto Protocol has been signed by all EU member states including the UK, together with a majority of other countries including Russia and China. The United States however has refused to sign the protocol and remains the worlds 2nd highest CO_2 emitter representing approximately 20% of the worlds total (AEF, 2008). The UK had committed to a 12.5% reduction in greenhouse gas emissions by 2010 (BAA, 2006).

The Kyoto Protocol does however have a significant flaw. Although the emissions resulting from airport operation and domestic air travel are included, international aviation is excluded due to difficulties during the formation of Kyoto into how the emissions would be allocated between different countries. This omission is significant, in that a large proportion of the aviation industry is not covered. In 2008, emissions resulting from domestic aviation only represented approximately 5% on the total aviation emissions. Therefore a mechanism that covers both domestic and international aviation is essential going forward.

2.2.2 The Emissions Trading System (EU-ETS)

The Emissions trading system (EU-ETS) launched by the European Union in 2005, is a mechanism aimed at reducing greenhouse gas emissions using the 'cap and trade' principle. The EU ETS operates in 27 EU member states together with Iceland, Liechtenstein and Norway (European Commission, 2010).

The ETS essentially works by 'capping' or placing a limit for the total amount of greenhouse gases emitted by installations in every trading period. An installation is defined as a process producing a net heat in excess of 20MW in energy, covering energy intensive industries and generators of electricity. The EU ETS currently covers more than 10,000 installations, which represent nearly half of the EU's CO_2 emissions and 48% of the UK (Department of Energy & Climate Change, 2011). The mechanism will also require large emitters of CO_2 to annually report their CO_2 emissions.

Within the cap assigned to each installation, emission allowances (one allowance equals one tonne of CO_2) are distributed which can be sold or purchased from other installations/companies if required. This provides an added incentive to companies who address their environmental footprint and reduce emissions, by allowing them to profit by selling to companies who are short of allowances.

At the end of each year, each installation must surrender sufficient allowances to cover the cost of its emissions with heavy financial penalties incurred for non-compliance.

The allowances will be reduced over time to ensure that total emissions reduce, with a target of a 21% emissions reduction by 2020 when compared to the commencement of the scheme in 2005.

2.2.3 EU-ETS Relevance for Aviation

The major drawback with the Kyoto Protocol, is that international aviation is exempt. This is not the case with the EU ETS, with aviation to be included within the mechanism from 2012 (Phase 3). Emissions from all domestic and international flights will be covered from or to any destination in the world that arrive or depart from a EU airport (European Commission, 2005).

The EU ETS scheme covers all commercial aircraft with a maximum take-off weight exceeding 5700kg, with state and light aircraft excluded (Lloyds Register Group, 2011). Operators with very low traffic levels will also be exempt ensuring that developing countries with only limited air traffic links with the EU will not be financially burdened.

There has been a mixed reaction from the aviation and environmental (Lloyds Register Group, 2011) community to the impending ETS commencement. The impact of the scheme is expected to increase the cost of a typical return flight within the EU by between €1.8 and €9, with the cost expected to be passed on to the customer. A spokesman for the Association of European Airlines commented that *"Why would you pay more for your ticket if you can transit through a non-EU hub that avoids the tax that is now the EU-ETS"* (Ares, 2011)

Impact assessments recently conducted also show that the EU-ETS will be almost ineffective at reducing emissions within the aviation industry. An assessment by Ernst & Young (Ares, 2011) concluded that by 2020, non-implementation of ETS would result in an emissions increase of 86%. However ETS will still result in an 83% increase. Whilst the current carbon price of approximately €15 per tonne is significant for ground based installations, this only equates to 3.8 cents per litre of aircraft fuel.

2.2.4 Opportunities for Airlines resulting from ETS commencement

The inclusion of EU ETS does provide strong financial incentives to airlines that adopt aggressive environmental improvements, one of which being the use of alternative 'bio fuels'. Biofuels are excluded from fuel calculations meaning that significant cost savings could be achievable by operating with alternative fuels. A report assembled by environmental consultants EQ^2 (EQ2, 2009), shows that industry assumptions of 15-30% biofuel consumption in 2020 could result in savings for airlines of $2.01 billion rising to $5.84 billion by 2030.

Conversely without the use of biofuels, the allowance expense could represent around 3.6% of an airlines total operating costs. Gregory Elders, director of research for EQ^2 highlights the importance of alternative fuels for future aviation prosperity saying;

If the airline industry is serious about achieving carbon neutral growth from 2020, biofuels offer the only realistic way to do this…..Our research shows that through a committed use of biofuels, where 30% of global jet fuel is biofuel by 2030, the industry would avoid over 400 million tonnes of carbon dioxide a year" (EQ2, 2009)

Alternative fuels are addressed in greater detail in chapter 4, with the latest developments covered in greater detail.

Chapter 3

Introduction to Environmental & Transportation Economics

3 ENVIRONMENTAL & TRANSPORTATION ECONOMICS

3.1 Transportation Economics & Routing

Routing is the process of selecting paths along which to send network traffic and can be applied to a variety of scenarios including electronic data networks and transportation networks. Networks are implemented for all transportation modes and are defined as a collection of points and lines joining these points (Bazargan, 2004).

Figure 5 represents an example of a network.

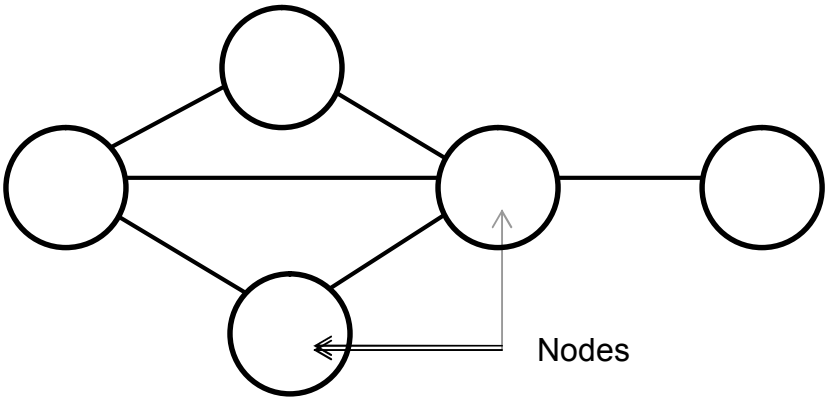


Figure 5 - Basic Elements of a Network (Bazargan, 2004)

Networks and routing can have a significant impact on the financial prosperity of the user, therefore careful and analytical planning is required to ensure the network chosen best suits the business model of the organisation.

Several different transportation models exist and can be seen in various forms throughout all modes of transportation. There are two main models, which are:

- Point to Point
- Hub Network (Hub to Spoke)

3.1.1 Point to Point

The point-to-point network model, sometimes referred to as the fully connected network theoretically is a network linking every city on a route to every other instead of going through a central hub. In reality not every city can be connected to every other.

Figure 6 below shows an example of a point to point model.

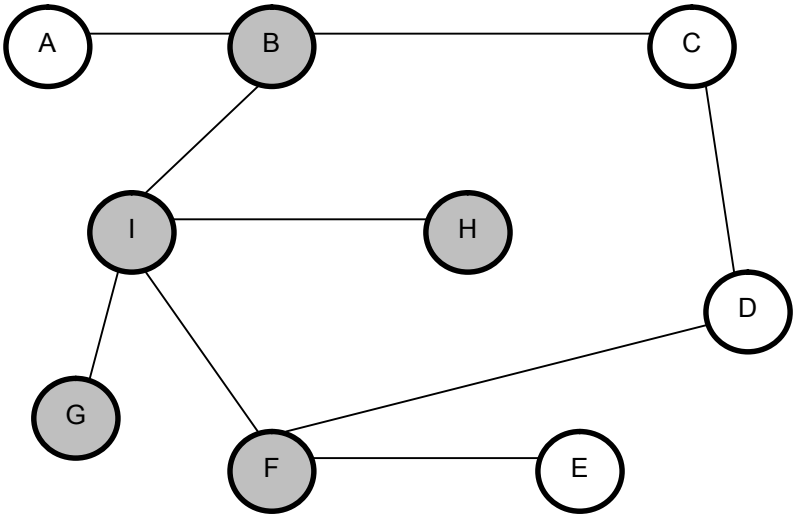


Figure 6 - Example of Point-Point and Hub Network Models (Bazargan, 2004)

The point-to-point model is mainly applied to rail networks and a minority of airlines. Before deregulation in the 1970s, the point to point model was used by the majority of airlines particularly in the US. The issue of network topology was largely ignored and routes were constructed on a demand like basis. The result was that the carrier would have a network pattern similar to that of Figure 6 and with no focal point (hub), the ability to provide an integrated network was limited.

For example a customer wishing to travel from D to G would have to travel in stages (D-F-I-G). The point to point model particularly when used by airlines, is seen as particularly inefficient. The system does not mean that hubs are neglected, however passengers would often have to change between carriers and aircraft. The point to point model is far more suited to rail transportation where more regional travel is used opposed to trips exceeding 1000km more

commonly associated with aviation. Figure 7 shows an example of a US rail network, which uses the point to point model.

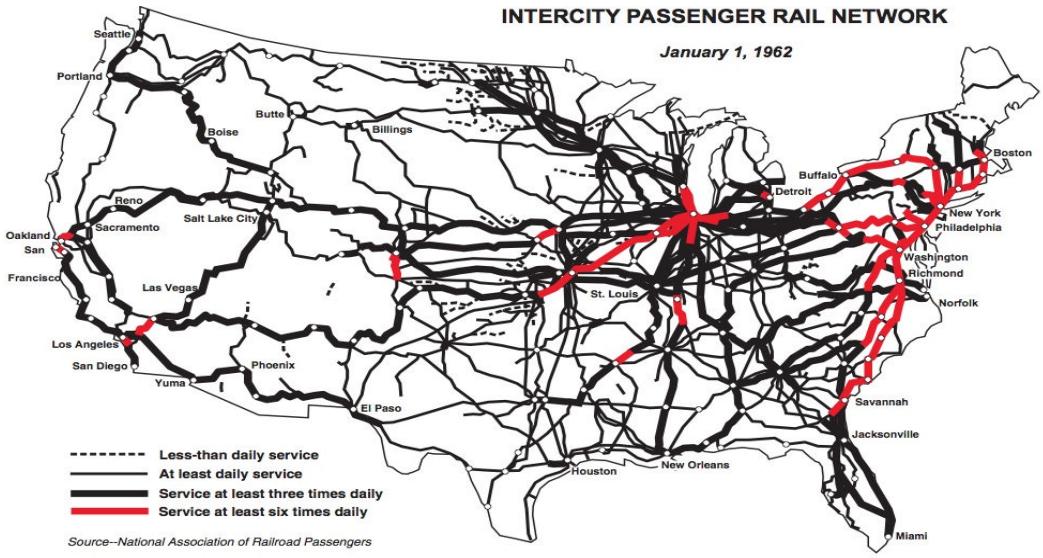
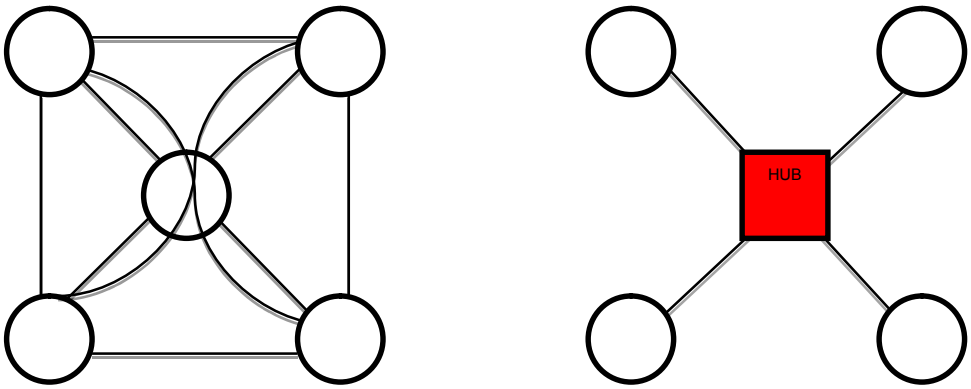


Figure 7 - Point to Point Model Example of 1962 US Rail Network (New World Economics, 2010)

3.1.2 Hub to Spoke

The point-to-point model is the predominately used by maritime and rail transportation, however in aviation it is seen as inefficient for the majority of airlines. The hub and spoke network is the model of choice for airlines due to the efficiencies that it brings. Hub and spoke has been the historic choice for European Airlines and has been adopted by many of the US carriers following deregulation. Figure 8 below illustrates why the hub model is so attractive to carriers.



POINT TO POINT HUB AND SPOKE

Figure 8 - Point to Point and Hub-Spoke Comparison

In the examples shown above, if the circles are assumed to be five cities or airports then by using the hub and spoke model, the number of routes is reduced to 4 instead of the 10 used in the point to point model. This is achieved simply by adding a centralized hub (represented by the red square).

Hub and spoke networks offer significant advantages over the point to point model. Passengers will still often be required to change services/aircraft to complete their journeys, however the hub to spoke strategy works by coordinating the arrival and departure of a large number of services in a narrow time window. Travel times for some passengers will be increased, however fares are traditionally lower and the potential combinations available to any destination are expanded significantly.

Within aviation, the economies available to carriers are considerable. Airlines initially serve routes with larger aircraft due to increased demand but with less intensity, resulting in lower operating costs per passenger and reduced fares. As the fares continue reducing, the demand will increase requiring even larger aircraft, increased frequency and newer routes. This strategy is one of the reasons for aviation's rapid growth, enabling greater numbers of the world population access to affordable air transport.

The structure of an airline network is also of great significance both for passenger convenience and also for the socioeconomic condition of the areas covered by the network.

3.1.3 Routing options available to operators

As mentioned previously, the two main transportation models utilised by commercial airlines are the point-to-point transit (PPT) and spoke to hub distribution (SHD) systems. Both systems have their own benefits and drawbacks, however these mainly focus on economic and sociological issues with negligible thought regarding the environmental impacts of both models.

Spoke and hub distribution is the system currently used by the majority of airlines. It offers the operator many benefits including the centralisation of control to one hub and the likelihood of higher passenger demand and increased LF when compared to smaller 'non hub' airports. British Airways (BA) for example operates to all six continents from its main hub London Heathrow (LHR). The majority of BA's routes are direct to the destination apart from obvious exceptions such as Australia and South America due to distance limitations.

Point-to-point transit systems are less commonly used although they can offer some unique benefits, particularly for passengers who are not required to commute to the central hub. US operator Southwest Airlines uses the system throughout its network (Aris, 2008).

Both networks offer different business models to operators mainly focusing on economic efficiency, however the environmental impact is less discussed. Therefore this paper will propose and examine a third conceptual transportation model, 'multiple hub-spoke'.

3.2 Alternative Aircraft Routing Strategy

The purpose of this study is to examine how the different routing options available to airlines can affect aircraft emissions and other environmental factors. Major airlines operating medium to long haul flights typically operate on a direct routing basis. This means that many aircraft operate directly to major international hubs but also to smaller and less populated airports. The disadvantage of implementing such a routing strategy (point to point transit model) is that whilst routes operating to major hubs will benefit from a consistently high load factor (LF), smaller destination airports may see decreased demand and a subsequently lower LF.

Airline LF is important indicator in determining the economic and environmental efficiency of commercial flights. The aim of any airline is to achieve the maximum LF possible and reduce the number of empty seats to a minimum.

One different option available to operators is reducing the number of long haul destinations and increasing the focus on hub-to-hub routes, with smaller domestic operators completing the route journey from the hub to spoke. The spoke-hub distribution model increases the utilization of smaller domestic aircraft, often used by LCC airlines of whom generally maintain a high LF by offering low cost fares.

Several point-to-point transit routes have been examined for their environmental credentials and LF and will be compared to multiple hub spoke routes. The use of regional aircraft will be analysed to determine if implementing this model can reduce the overall route emissions.

3.2.1 Previous Alternative Routing Literature

The concept involving the splitting of long haul flights is one that is relatively unexamined. The greener by design operations subgroup made up of industry experts, government bodies and research institutions commented in their 2007-2008 annual report (Greener by Design, 2007) that the area required further research.

Two papers have since been published examining the benefits of intermediate stops for long haul aircraft, particularly focussing on the optimisation of a medium range aircraft using sophisticated design synthesis methods for two stage flight opposed to the same route flown directly using a long haul aircraft.

NASA conducted a parametric analysis (Hahn, 2007) undertaking a 15,000km journey in three stages using an aircraft with a design range of 5000km. The analysis predicted that 29% fuel savings could be achieved when using the three stage route.

The second paper follows a similar analysis (Creemers, 2007) using a Boeing 747-400 aircraft with a range of 13,334km as the long haul baseline aircraft. This was compared to theoretical aircraft with the same fuselage and passenger capacity of 420 but with half the design range (6,672km). The result of operating with the theoretical design in two stage flight resulted in a 27% fuel reduction.

Both papers conducted their predictions using a theoretical aircraft with an optimised design range both for use in multiple stage flight. The analysis conducted in the thesis utilises aircraft currently in operation today and does not attempt to split routes into several identical distances as this would be impractical particularly for transatlantic routes.

3.2.2 Multiple Hub-Spoke Distribution System

The multiple hub-spoke (MHS) concept has been examined to determine if hybrid airline routing strategies can have a positive impact on global aviation emissions. The MHS concept is based very closely on the most popular hub spoke distribution networks utilised by most airlines today, however with one major difference.

Currently several hub airports exist in each country with the majority catering for large long haul aircraft such as the B747, A340 and A380. This is of great convenience to the consumer, with the availability of direct flights providing a wide choice of departure locations, reducing destination times and flight transfers. Whilst this is an obvious advantage to the passenger, does this strategy offer the best environmental efficiency? Long haul routes historically have a more sporadic demand with a higher occurrence of empty seats than domestic and short haul carriers operating smaller aircraft.

Smaller aircraft such as the B737-800 and A320 benefit from better fuel efficiency and lower emissions when compared to their long haul alternatives. It is for this reason that the use of such models should be utilised wherever possible as an alternative.

The MHS concept is designed to provide environmental improvements by focussing on two key objectives:

- Reducing the distance of long haul aircraft* to a minimum by utilising ‘super hub’ airports and increasing short haul transfers
- Increasing passenger load factor to a maximum on long haul routes

*(Boeing 747, 767, 777 & Airbus A340, A380)

The idea of the multiple hub-spoke network is to reduce the number of long haul flight destinations to so called ‘super hubs’, focussing more heavily on short haul aircraft to transport passengers from the super hub to their final destination. This concept introduces intermediate stops for long haul routes,

with the aim of using smaller and more efficient aircraft for a section of the journey. An example of implementing this strategy can be demonstrated in the United States and is shown below in Figure 9.

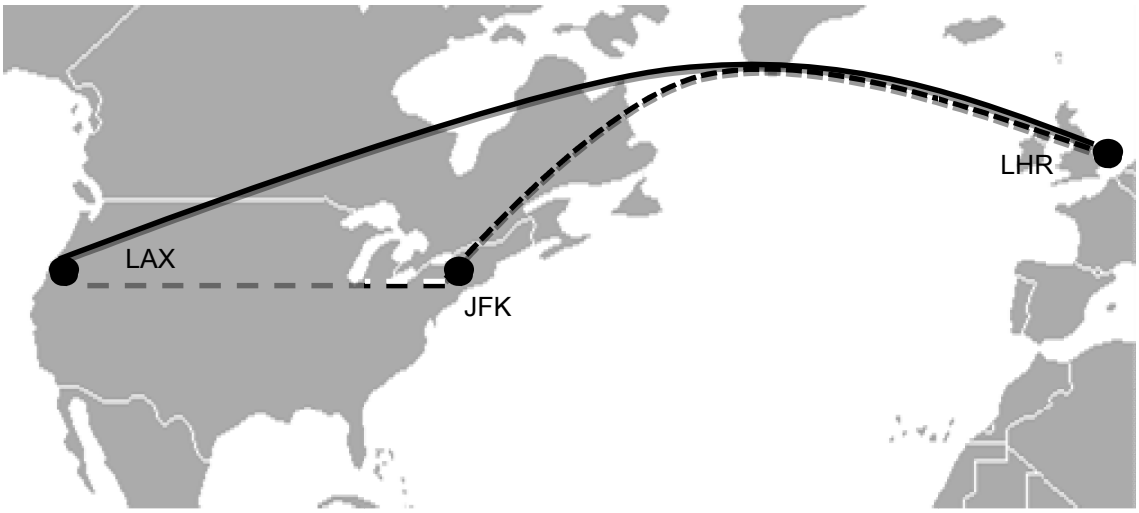


Figure 9 - Non-Stop and Multiple Stage Route Example from LHR to LAX

Figure 9 shows two different flight routes for the transatlantic LHR to LAX route, the solid line representing the 'non-stop' route operated using a widebody aircraft (Boeing 747-400/Airbus A340) and the conceptual routing strategy shown with dotted lines utilizing a widebody aircraft to John F Kennedy, New York (JFK) followed by a narrowbody aircraft (Boeing 737NG/Airbus A320) for the second phase to LAX.

BA and Virgin Atlantic operate daily from LHR to LAX direct using the B747 and A340 aircraft respectively covering a distance of approximately 9550km. The alternative route transfers at John F Kennedy (JFK) in New York using either the A320 or B737 NG to complete the journey to LAX. This route reduces the reliance on larger long haul aircraft by over 35% and utilises domestic routes with traditionally higher LF.

This strategy is already implemented on many routes, however flights originating from LHR can still operate directly to over eight US destinations. The question that this paper hopes to address is how restricting the direct long haul routes to one 'super hub' for example JFK, would impact on the environmental emissions of the overall journeys and the factors that drive any potential

improvement. The pages that follow contain analysis into the aircraft routing options for several different continents.

3.3 Methodology

To be able to make an adequate comparison into the environmental effects of different airline routing strategies, several key data inputs are required. Both the point-to-point transit and hub-hub-spoke models are compared for a variety of routes to estimate the total emissions per flight per passenger.

3.3.1 AMEE

Data detailing the emission levels of different aircraft models is understandably difficult to obtain, however all data used in the following analysis has been obtained courtesy of AMEE. AMEE is relatively new organisation of whose aim is to *"build the largest engine for computing greenhouse gas emissions".* (Butcher, 2010)

AMEE have codified the major greenhouse gas standards and produced emission factors for many different industries and provide accurate emissions data. Customers include small business, multi nationals and governments, with the UK government Department of Energy and Climate Change (DECC) relying on data for policy making and the need to address climate change.

AMEE provide a specific database for jet aircraft which details many of the parameters required for the analysis and a calculator for determining emissions based on the aircraft model and flight distance. When determining route emissions, the ICAO departure and destination airport codes are inputted into the calculator. This calculates the total flight distance taking into account an additional 9% for holding pattern manoeuvres, also calculated is the total CO_2 emissions for the cruise section of the flight. Together with the cruise CO_2, the total CO_2 emitted during taxiing, take off, climb out and final approach is provided from historical data. Figure 10 below shows the results for LHR – JFK operated by a Boeing 747-400 aircraft.

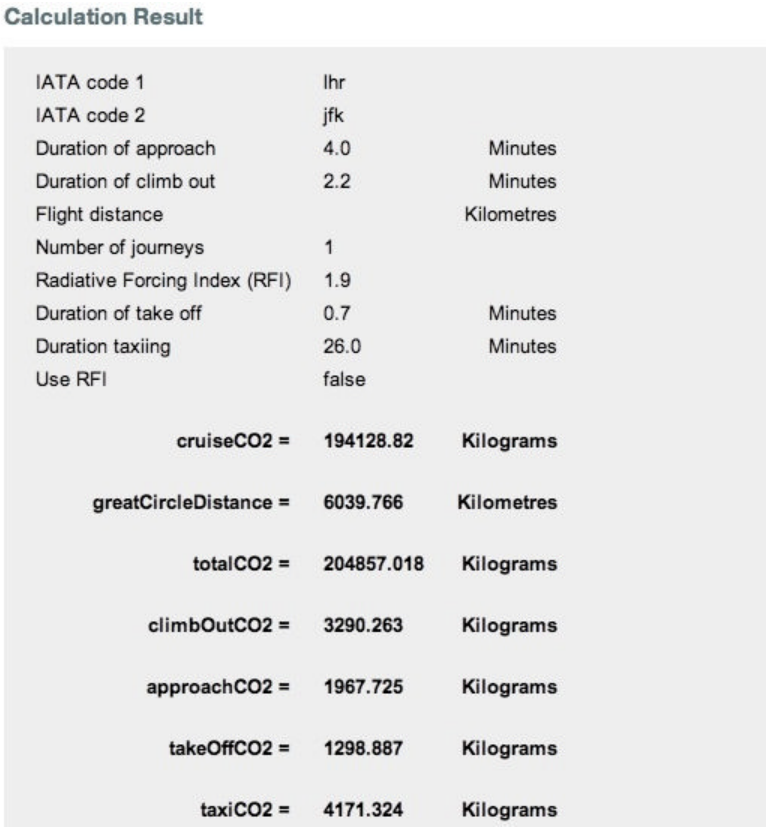


Figure 10 - CO_2 and Distance results for LHR-JFK (B747-400)

The calculator provides the total CO_2 mass and distance of each route, however results for the other significant emissions nitrogen oxide (NO_x) and carbon monoxide (CO) are still required. These are calculated using emission and fuel factors for various aircraft per landing take off (LTO) and distance cruised, obtained from the (European Environment Agency, 2007) (EEA). These factors detail emissions for all flight phases covering a number of standard flight distances for both domestic and international routes (500nm, 1500nm etc). These standard distances can be used to provide an accurate estimation of fuel used, NO_x and CO for any flight distance. An example of the emission factors provided by the EEA and the method in calculating precise emissions is detailed below in Table 1.

Table 1 - Fuel and Emission factors for A320 (Fuel, NO_x)

A320		Standard flight distances (nm) [1nm = 1.852 km]		Standard flight distances (nm)				
		125	**250**	**500**	**750**	**1000**	**1500**	**2000**
Distance (km)								
	Climb/cruise/descent	232	463.04	926	1389	1852	2778	3704
Fuel (kg)								
	Flight total	1644.4	2497.3	3660	4705.0	6027.2	8332.0	10865
	LTO	802.3	802.3	802.3	802.3	802.3	802.3	802.3
	Taxi out	167.3	167.3	167.3	167.3	167.3	167.3	167.3
	Take off	89.9	89.9	89.9	89.9	89.9	89.9	89.9
	Climb out	232.5	232.5	232.5	232.5	232.5	232.5	232.5
	Climb/cruise/descent	842.1	1695.0	2858	3902.7	5224.9	7529.7	10063
	Approach landing	145.4	145.4	145.4	145.4	145.4	145.4	145.4
	Taxi in	167.3	167.3	167.3	167.3	167.3	167.3	167.3
NOx (kg)								
	Flight total	28.0	37.9	56.0	66.8	83.9	109.4	141.1
	LTO	10.8	10.8	10.8	10.8	10.8	10.8	10.8
	Taxi out	0.775	0.775	0.775	0.775	0.775	0.775	0.775
	Take off	2.491	2.491	2.491	2.491	2.491	2.491	2.491
	Climb out	5.450	5.450	5.450	5.450	5.450	5.450	5.450
	Climb/cruise/descent	17.199	27.094	45.12	55.928	73.040	98.550	130.2
	Approach landing	1.344	1.344	1.344	1.344	1.344	1.344	1.344
	Taxi in	0.775	0.775	0.775	0.775	0.775	0.775	0.775

Compiled From: (European Environment Agency, 2007)

The majority of routes do not conform exactly to the standard flight distances listed in Table 1. Therefore calculations must be carried out to determine values relating to the exact flight distance covered. These are detailed below:

X = Total route distance (km)

A = Value of fuel/NO_x/CO for standard distance BELOW ‘D’

B = Value of fuel/NO_x/CO for standard distance ABOVE ‘D’

C = Standard Flight Distance above ‘D’ (km)

D = Standard Flight Distance below ‘D’ (km)

$$\boldsymbol{Total\ Emissions\ Value} = \boldsymbol{A} + (\boldsymbol{B} - \boldsymbol{A}) \times \frac{(\boldsymbol{X} - \boldsymbol{D})}{(\boldsymbol{C} - \boldsymbol{D})}$$

Equation 1 - Iteration Equation for determining Emissions from Flight Distance

3.3.2 – Calculating Average Emissions per Passenger per Route

Now that the emissions data has been calculated for routes of distance X using a specific aircraft, analysis needs to be performed to determine the average emissions per passenger on each flight. As different routes operated by different carriers have different LF, average load factors have been obtained from financial statements of the airlines involved. These are by no means perfectly accurate, however they give the best initial estimate of passenger numbers. For example, BA divide their average LF for each year into their four operating areas (UK/Europe, Americas, Asia Pacific, Africa and Middle East). The LHR to JFK route used obviously falls into the Americas category, with an average taken from two years traffic for a more reliable figure. Figure 11 below shows the complete process for calculating the efficiency of routes.

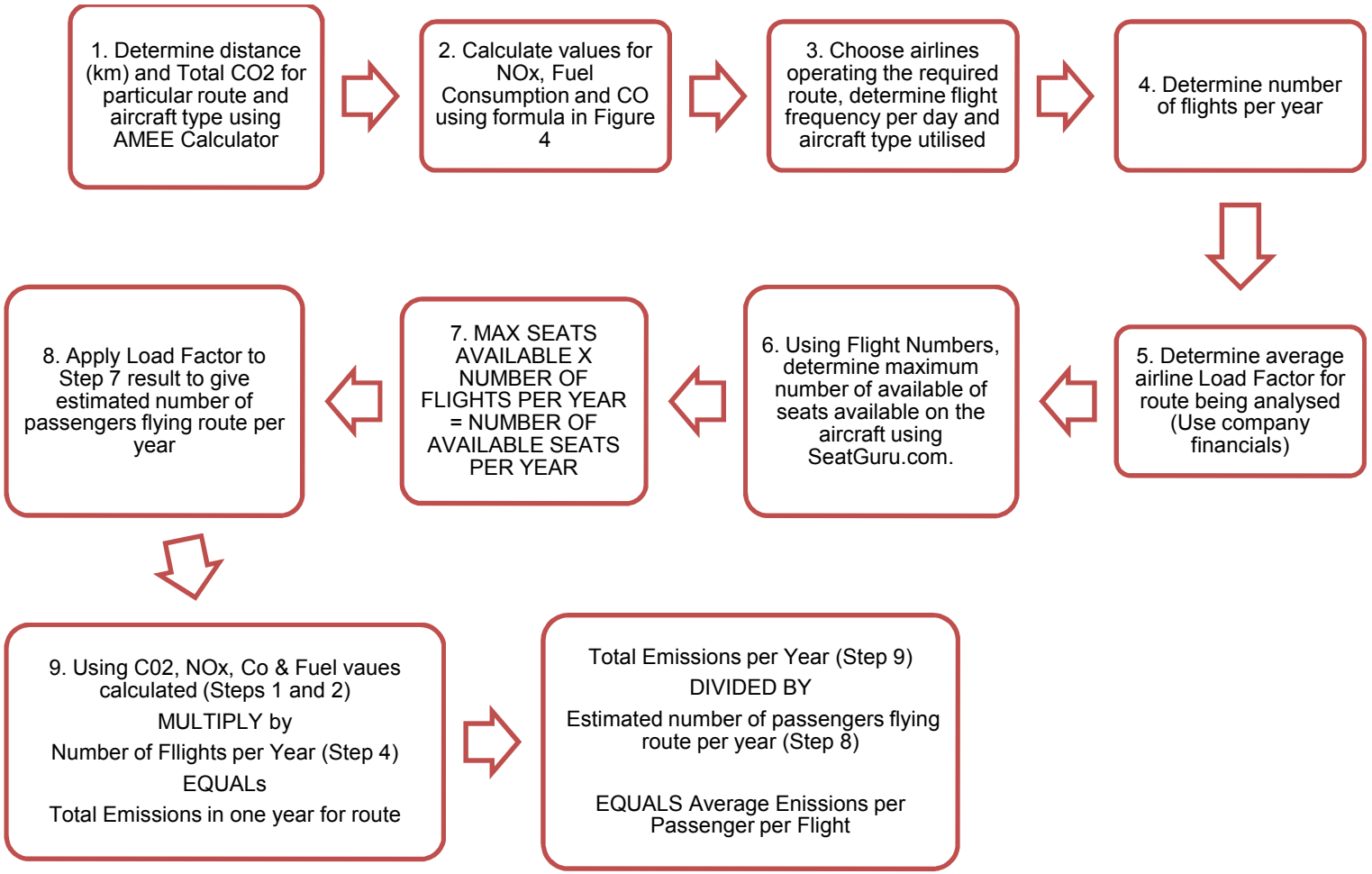


Figure 11 - Emissions per Passenger calculation process

3.4 Route Model Analysis

This study analyses both routing strategies in three different operating regions; North America, Far East Asia and the Middle East. Figure 12 and Figure 13 show the routes analysed in the study.

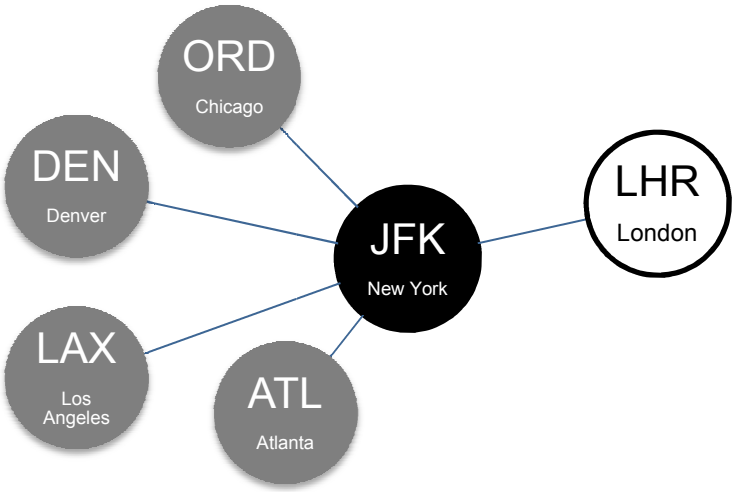


Figure 12 - North American routes analysed

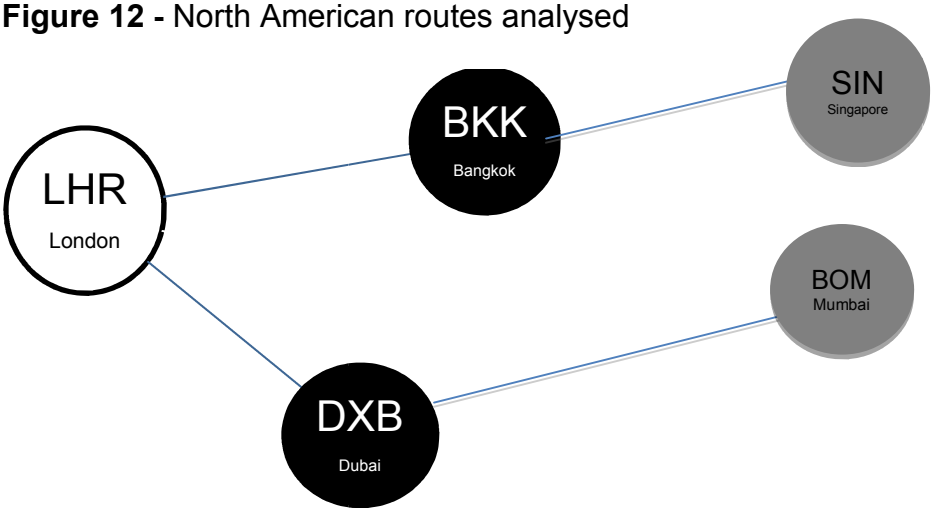


Figure 13 - European, Middle East and Far East routes analysed

The black circles shown in Figure 12 and Figure 13 represent the 'super hub' airports used for the conceptual route model. In Figure 12, the comparison between routes operating from LHR direct to the 4 US destinations represented in grey have been conducted together with the 2 phase flight via JFK proposed in the MHS model. Figure 13 demonstrates the same principle with direct flights

to Singapore (SIN) and Mumbai (BOM) compared with flying to their relevant 'super hubs' in Bangkok (BKK) and Dubai (DXB) respectively. Four parameters were calculated per flight per passenger; fuel consumption, CO_2, NO_x and CO. Figure 14 to Figure 17 show the comparisons for each parameter between direct flights and MHS routed flights. All data used for the production of the charts below can be found in Appendix A.

Load Factor assumptions for each route were made using company financial data from the relevant airlines. Table 2 details the routes analysed including the designated intermediate hubs used, the combinations of aircraft utilised and also the total distance covered in phase 2 of the journey.

Table 2 - Designated Intermediate Hubs and Aircraft Operated

Route	ICAO Symbol	Designated Intermediate Hub	Non Stop Aircraft Used	Multiple Aircraft Combination *	Total Distance covered in Phase 2 (Additional Distance from Multiple Routing)
LHR – Chicago O'Hare	LHR - ORD	JFK	B777	B747-400 / A320	18% (+419km)
LHR - Denver	LHR - DEN	JFK	B777	B747-400 / B757	32% (+712km)
LHR – Los Angeles (1)	LHR - LAX	JFK	B747-400	B747-400 / A320	42% (+822km)
LHR – Los Angeles (2)	LHR - LAX	ATL	B747-400	B777 / B737-700	32% (+1228km)
LHR – Los Angeles (3)	LHR - LAX	ORD	B747-400	B777 / B737-700	31% (+420km)
LHR - Singapore	LHR - SIN	BKK	B747-400	B747-400 / A320	13% (+120km)
LHR – Mumbai, India	LHR - BOM	DXB	B777	B747-400 / A320	26% (+230km)

*** Aircraft combinations based on airline scheduling as of March 2011.**

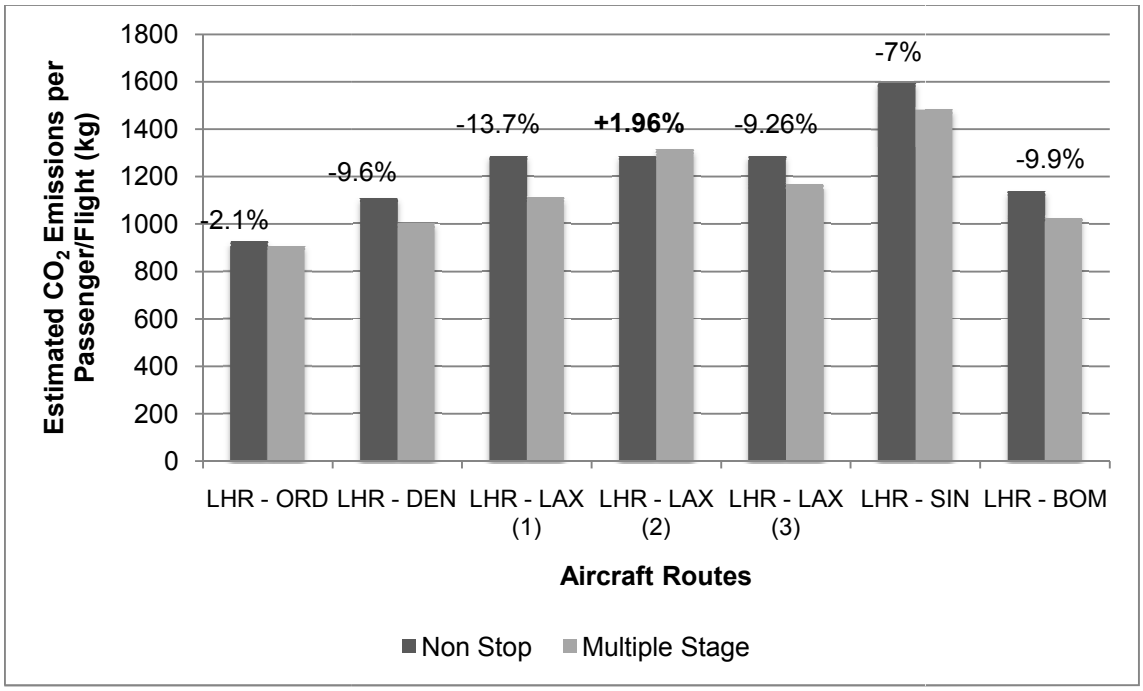


Figure 14 - CO_2 Emission Comparison between Non-Stop and Multiple Stage Flight

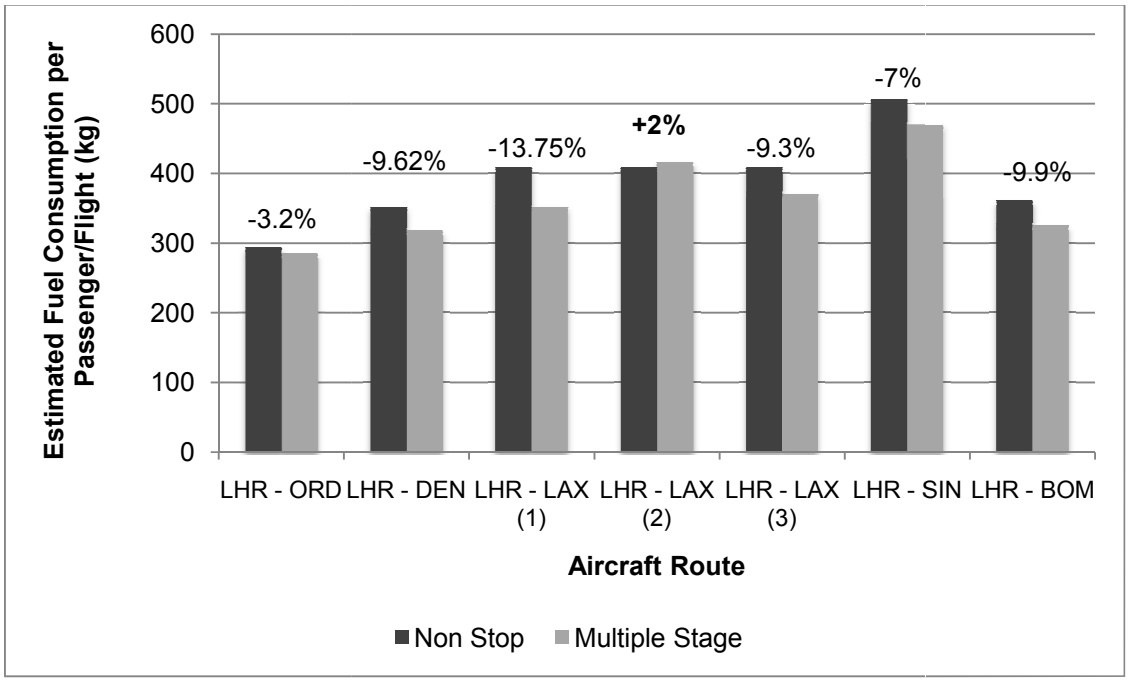


Figure 15 - Fuel Consumption Comparison between Non-Stop and Multiple Stage Flight

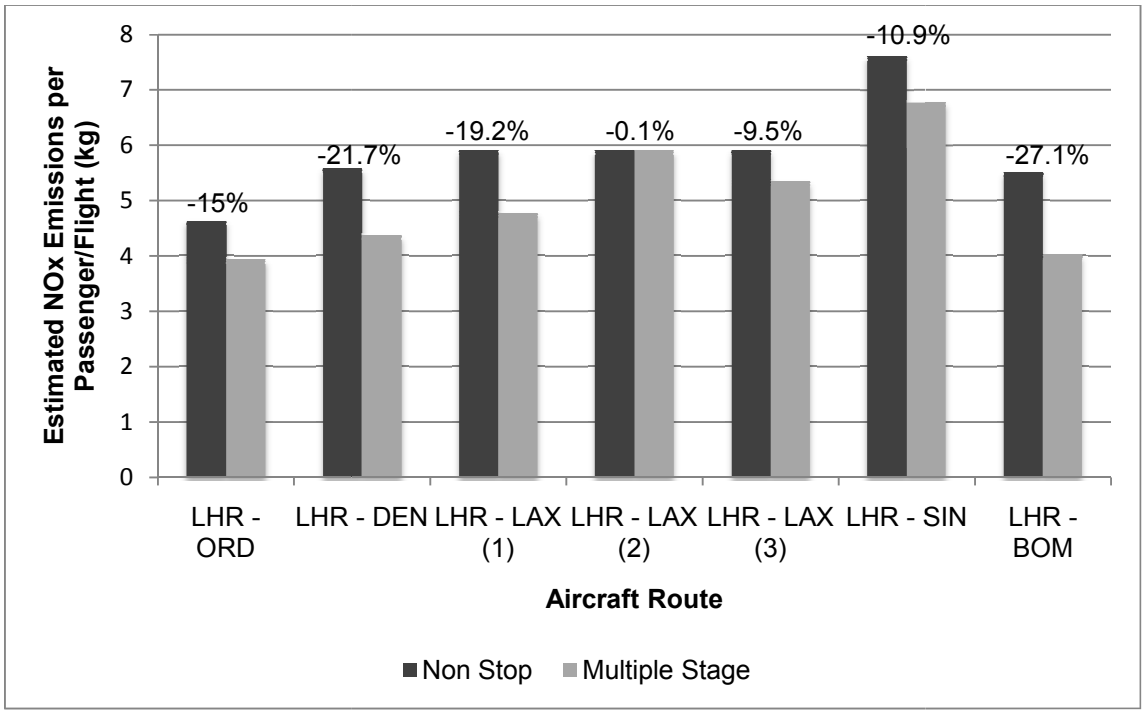


Figure 16 - NO_X Emission Comparison between Non-Stop and Multiple Stage Flight

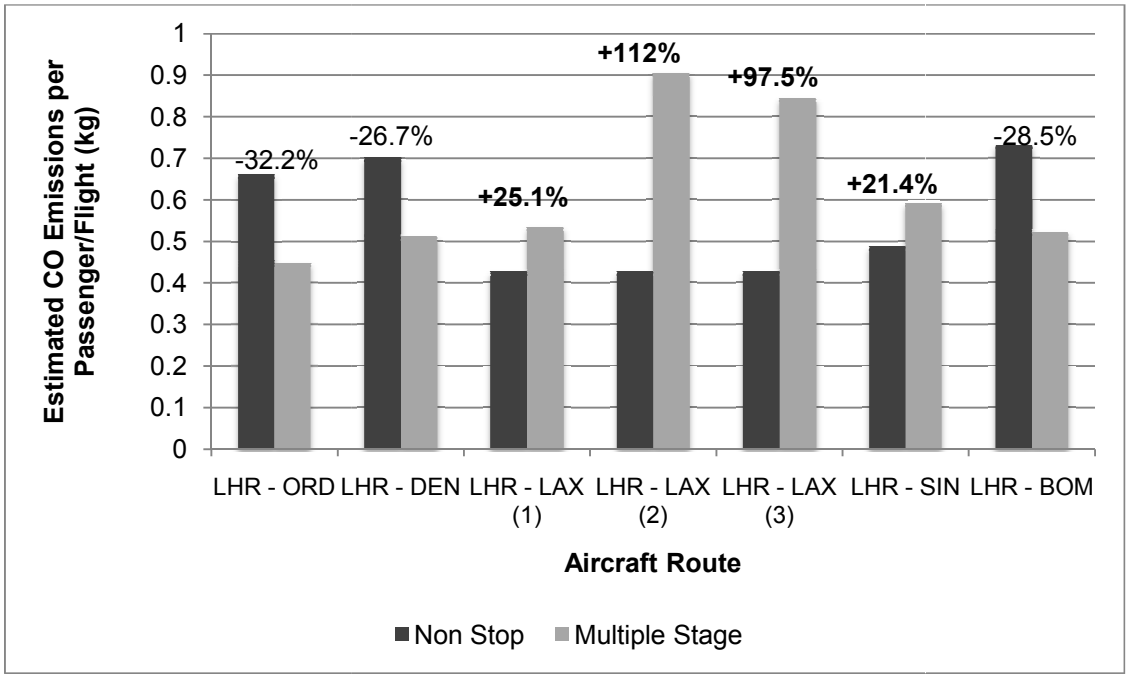


Figure 17 - CO Emission Comparison between Non-Stop and Multiple Stage Flight

3.5 Environmental Impact of Multiple Stage Routing

3.5.1 CO_2

Carbon dioxide emissions are shown to be reduced using multiple stage flight in 6 out of 7 routes analysed, with an average saving of 8.6% achievable despite the multiple stage distances of all 7 routes exceeding the non stop routes distances by as much as 822km (LHR – LAX). This demonstrates the improved efficiency of narrowbody aircraft used during the MHS routes and shows that the type of aircraft utilised during the journey is of equal or greater importance than the distances covered. The LHR-LAX [1] route contains the highest proportional distance covered using a narrowbody aircraft (42%) and this is reflected in a CO_2 reduction of 13.7%. Conversely the LHR – ORD route utilises a much smaller second stage route of 18% and only results in a reduction of 2.1%.

It is important to note that the most efficient period of flight is during cruise (Williams V. N., 2006), conversely landing and take-off is much less efficient. This is confirmed by the LHR-LAX (1) route with a 42% second phase operated by an A320 with a significant cruise phase.

The LHR-LAX route stopping at ATL was the only analysed route to show an increase in CO_2 emissions, however this can be attributed to the additional distance of 1228km covered during the multiple stage flight.

3.5.2 NO_x

All 7 flights analysed operating the MHS routing showed reductions in NO_x emissions averaging 14.8% compared with the non stop alternative. The LHR-DEN and LHR-BOM routes showed reductions exceeding 20%. NO_x emissions produced during combustion are increasing together with higher engine temperatures associated with newer powerplant technology, therefore it is perhaps not surprising that the highest reductions were seen when operating a

B747-400 with the Rolls Royce RB211 engines in place of the newer Rolls Royce Trent 9000 engines, operated by the newer B777.

3.5.3 CO

Carbon monoxide levels are shown in the routes analysed to be associated with the aircraft type operated, with the 4 CO reductions occurring when the B777 is replaced by the B747-400 aircraft, conversely when the B777 is used during the first stage of the MHS routing the CO emissions increased by an average of 105%. This is similar trend to NO_x and is associated to the combustion temperature resulting from more technologically advanced engines of the B777.

3.6 Economic Impact of Multiple Routing Strategy

Operating a multiple stage routing strategy will as demonstrated, result in theoretical CO_2 reductions and fuel savings in six of the seven routes analysed. Taking the LHR-DEN route as an example, operated once daily over the course of one year, introducing the multiple stage routing with an intermediate hub at JFK, could result in a annual saving of 7115 Tonnes of CO_2 and 1.752 million litres of jet fuel.

Taking a current average cost of carbon per tonne of €15 ($21.60) and aviation jet fuel at $125 a barrel, ETS carbon credit savings could amount to $153,690 with a potential $1.37 Million aviation fuel saving. Thus a theoretical operating cost saving of $1.53 Million per annum could be achieved equating to an average passenger saving of $23, however this does not include the costs associated with additional landing and take off costs from an intermediate airport.

3.7 Combination of Multiple Routing Strategy and Blended Biofuel on Environmental Performance

Improvements in operation and routing clearly offer efficiencies in emissions and fuel consumption, however the long-term industry ambition is to operate with neat or blended biofuel and reduce the dependence on kerosene based Jet A fuel. The EU ETS offers an incentive for alternative fuel consumption, with biomass excluded from fuel calculations.

Biomass is considered to be CO_2 neutral with an emission factor of zero meaning that any quantity of biomass consumed will result in a theoretical CO_2 emission level of zero when considered under ETS. However with aviation biofuels more likely to consist of a blend together with conventional fuel, a weighted emission factor would therefore be applied effectively reporting zero CO_2 emissions for the proportion that consists of biomass (Environment Agency, 2011).

For example when considering a 50:50 blend of biofuel and JET A1, the emission factor used would be 1.575 tCO_2/t fuel (3.15 x 0.5).

Several biofuels are currently undergoing testing for eventual certification for commercial flight, with the most advanced type currently as Fischer Tropsch (FT) synthetic fuel (Rahmes et al, 2009), expected to be certified for use as a 50:50 blend within two years.

FT fuel is produced using the Fischer Tropsch process, which enables a cleaner combusting liquid fuel to be created from various carbon rich feedstocks including natural gas, coal and biomass. Life cycle CO_2 savings achievable from 100% FT use have been estimated to be 35.16% (Stratton et al, 2010), therefore 17.58% when considering a 50:50 blend.

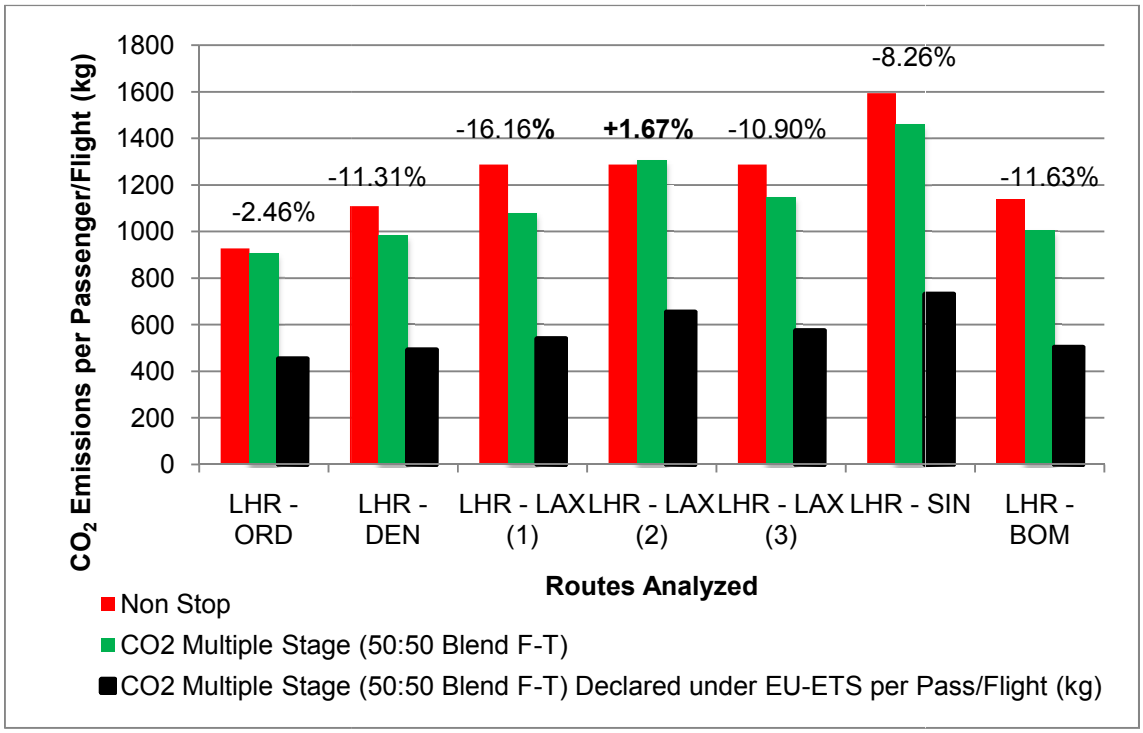
The combination of the multiple stage routing strategy together with a blended 50:50 mix of F-T fuel would therefore lead to significant ETS CO_2 savings.

Figure 18 illustrates the CO_2 reductions available for the routes analysed using the routing and fuel model proposed above.

Note: The theoretical CO_2 emissions per passenger per flight that are required to be declared under the EU-ETS scheme are also shown in black.

Note: The estimated CO_2 emissions resulting from the non-stop routing strategy with 100% JET A1 fuel are represented in red and the CO_2 emissions resulting from the multiple stage routing with 50:50 biofuel is represented in green.

Table 3 includes that data presented in Figure 18 and provides estimated cost savings achievable from using the F-T Fuel blend, multiple stage routing model.



(Percentage values presented in Figure 18 consider the comparison between red and green bars)

Figure 18 - Estimated CO_2 saving per passenger/flight using multiple stage routing and blended 50:50 F-T fuel

ICAO Symbol	Designated Intermediate Hub	CO_2 Emissions per Pass/Flight *(Non-Stop)* (kg)	CO_2 Emissions per Pass/Flight *(Multiple Stage 50% F-T Fuel)* (kg)	Theoretical CO_2 Savings Available per Pass/Flight *(with EU-ETS Biofuel Exemption)* (kg)	Estimated Cost Reduction ($) per Pass/Flight *(EU-ETS Credit Saving)* **Assuming 1 Tonne Carbon = $21.60 (€15)**
LHR - ORD	JFK	927.72	904.92	475.25	10.27
LHR - DEN	JFK	1109.20	983.75	617.33	13.33
LHR - LAX	JFK	1287.13	1079.08	747.58	16.15
LHR - LAX	ATL	1287.13	1308.64	632.81	13.67
LHR - LAX	ORD	1287.13	1146.87	713.69	15.42
LHR - SIN	BKK	1594.25	1462.56	862.96	18.64
LHR - BOM	DXB	1138.05	1005.75	635.18	13.72

Table 3 - CO_2 reductions and estimated cost savings achievable using multiple stage routing and 50% blended biofuel

The CO_2 savings achievable through multiple stage routing and alternative fuel are significant both through emissions and cost savings resulting from EU-ETS exemptions. Due to biofuel use being exempt from EU-ETS, the 50:50 blend used during this analysis results in encouraging savings of between $10-19 per passenger which could be passed on as savings to the consumer and reduce the operators annual carbon credits, allowing additional expansion or the sale to other installations.

3.8 Chapter Conclusions

The study conducted in this chapter has proposed an alternative strategy for current long haul aircraft routing by introducing an intermediate stop, dividing the route into two phases instead on the conventional 'non-stop' method currently used. Implementing such a strategy has been shown in this paper to in certain circumstances reduce the overall emissions of entire journey by between 2% and 13.7%, even when all the routes analysed in this paper resulted in an overall increase in total distance compared to the non-stop alternative. Maximising the utilisation distance of the 2nd phase narrowbody aircraft has been shown to be an important factor in reducing the overall route emissions, for example the LHR-LAX (1) route analysed reduced CO_2 emissions by 13.7% due to 42% of the overall route distance being covered by the A320 aircraft instead of the less efficient B747-400.

The multiple stage routing is not however suitable as an alternative for all long haul flights in current operation. The intermediate airport chosen is a highly important factor and for any potential emissions reductions, the additional route distance covered by the multiple stage route must be kept to a minimum. This is highlighted with the LHR-LAX (2) route that stops at ATL, the additional distance covered is 1228km and thus results in a CO_2 increase of 1.96%. Many long haul routes will not have suitable intermediate airports available for example Russia. However multiple routing has been shown to be highly effective on North American and South East Asian routes departing from European destinations, due to the high availability of suitable intermediate airports. The introduction of the EU-ETS in 2012 will provide a greater incentive for airlines to examine their routing strategies, with the CO_2 savings demonstrated during this paper leading to cost savings that could be passed over to the passenger, with even greater savings available through the use of alternative fuels.

Although transferring in favour of direct flights has environmental benefits, passengers are likely to be less than enthusiastic with having to transfer

through an additional airport en-route to their final destination. The transfer impact on the route will likely add a minimum of 3 hours onto the total flight time with the increased risk of flight delays and lost luggage for passengers to contend with. The likelihood is that if two identical flight routes were offered to a passenger, one being direct and one indirect, the choice would most certainly be in favour of the direct option. However time is not the only factor customer's account for when purchasing their airfare, the highest influence according to a survey conducted by inflight entertainment company digEcor (Williams, 2010) is ticket price. Preliminary analysis into several of the examined routes showed a small increase in ticket fares when flying indirectly. If the multiple stage model is to be implemented, the proposition must be made more attractive to customers by reducing the overall route fare.

Perhaps the most feasible option available is offering economic incentives to consumers for choosing less emitting routes. If direct routes that were shown to produce higher emissions when compared to the indirect alternative were reduced in number together with increases in ticket fares, the assumption is that demand would decrease. Therefore if passenger yields increased on indirect routes, the ticket cost would more likely reduce further with more consistent and higher load factors on the long haul sections.

The recommendation would be increasing the volume of long haul flights between hub routes for example LHR-JFK, LHR-DXB, LHR-BKK. With passengers flying to other destinations incentivised by lower fares, these routes would potentially see increasing passenger yield. This could also have a positive impact on the secondary carriers by increasing their load factor and reducing fares further.

Chapter 4

Current Aviation Fuels & Alternative Fuels

4 ALTERNATIVE FUELS

4.1 Introduction

Increasing environmental awareness and diminishing fossil fuels have lead to an increased focus regarding alternative fuels, which can help to both reduce greenhouse emissions and preserve the planet's natural resources. Alternative fuels, if available in sufficient quantities could assist in reducing the demand for crude oil together with helping to reduce greenhouse gas emissions. In 2003 the European Union introduced the directive 2003/30/EC (European Union, 2003), which sets out the legal framework for the introduction of biofuels into the European market.

Two types of alternative fuel currently exist, biofuels and synthetic fuels. Biofuels are essentially fuels derived from living matter or from the waste that they produce (BBC, 2007). The biomass used is very wide ranging and can include wood, methane from animal excrement and plant material which can be processed to make ethanol or diesel.

Generally, biofuels are produced from renewable sources such as plant material that absorb CO_2 during growth and are most commonly used for transportation, heating and power generation. The absorption of CO_2 is the overriding reason why biofuels can offer such environmental benefits. The use of sustainably produced biofuel results in a reduction of lifecycle GHG emissions as the CO_2 absorbed by the biomass material is approximately equal to the CO_2 produced during combustion. This enables the biofuel to be approximately carbon neutral over the lifecycle when excluding the production and refinery stage. Figure 19 below illustrates the lifecycle of conventional and bio fuels and shows the circular pattern of the biofuel lifecycle.

Figure 19 demonstrates the benefit of replacing fossil fuels with a biofuel; when the fuel is combusted, the conventional fuel releases CO_2 into the atmosphere. Biofuels act in the same way, however the CO_2 emitted during combustion is absorbed by the growing feedstock.

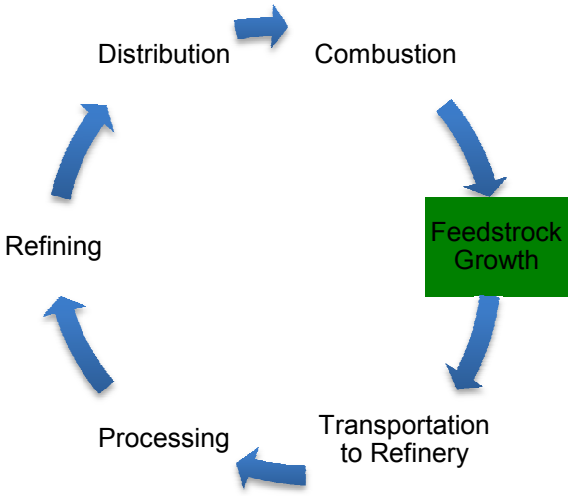


Figure 19 - Biofuel Life Cycle

Biofuels can be divided into four different generations. First Generation biofuels consist of existing alternative fuels such as biodiesel and biogas, which are produced using sugar, starch and vegetable oil. Second generation biofuels have the advantage of being derived from sustainable sources that do not compete for resources (i.e. food stocks) and offer increased environmental benefits. 2nd generation biofuels currently under development are derived from biomass crops such as jatropha and switchgrass.

Third and fourth generation biofuels are less developed than the earlier generations however offer significant environmental benefits. Third generation biofuels are genetically modified crops that capture sufficient CO_2 to result in a carbon neutral fuel. An example of a third generation biomass is algae of which increased yields, non-competition with agricultural land, widespread availability and efficiency of capturing CO_2 make it a highly desirable alternative fuel (European Biofuels Technology Platform, 2011).

The final fourth generation biofuel is a genetically modified crop which is engineered to be carbon negative (the biomass absorbed more CO_2 than is emitted during combustion). Fourth generation biofuels offer the ultimate characteristics for a highly environmentally efficient fuel, both carbon negative and produced from crops that do not compete with the food chain (Zimesnick, 2010).

4.2 Biofuel Applications within Land Transportation

Biofuels are generally used as substitutes for conventional fossil fuels in a variety of different applications including transportation, heating and power generation.

Fuel for transportation is the highest consuming sector, accounting for over 60% (IEA, 2010) of total liquid fuel usage as of 2008 (3502 Mton). The transportation sector includes the energy consumed in moving people and goods by road, air, rail, water and pipeline (U.S. Energy Information Administration, 2010).

Figure 20 illustrates the distribution between the various sectors.

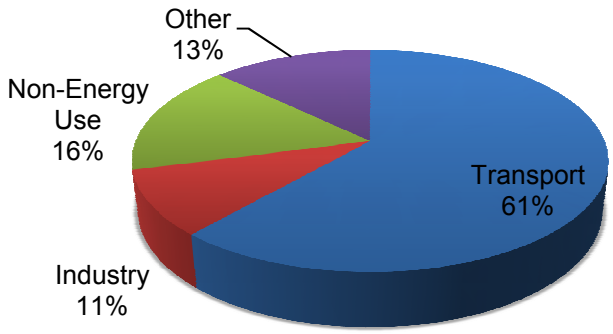


Figure 20 - World Oil Consumption per Sector (IEA, 2010)

Industrial consumption of oil includes the manufacturing and operation of industrial machinery, construction, mining and other energy intensive practices (International Energy Agency, 2008). Non-Energy use covers fuels that are used as raw materials and are not consumed as a fuel or transformed to another fuel (International Energy Agency, 2011). By far the most significant use of liquid fuel however is for transportation. According to the International Energy Agency (IEA) (IEA, 2010), the total fuel consumed as a result of transportation purposes was estimated to be 2150Mton in 2008.

As nearly two thirds of liquid fuel use is attributed to transportation, this sector will now be analysed in greater detail.

Figure **21** below illustrates the consumption of fuel per transportation mode.

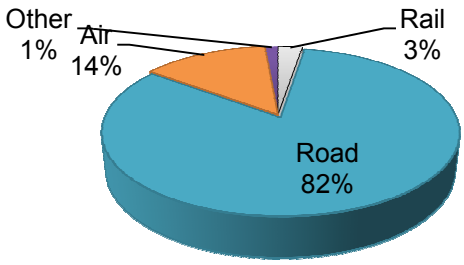


Figure 21 - Fuel Consumption per Transportation Mode (2004) (European Commission, 2008)

From Figure **21**, it can be seen that road travel is the highest sector with 82% of the total transportation consumption. Air travel is the second largest consumer of fuel and it comes as no surprise that alternative fuel research and development is heavily focused on these two sectors.

Biofuel has been produced and used in road vehicles for some time, albeit in lower volumes when compared to the conventional fossil fuels. In 2008, global fuel consumption was 85.43 million barrels per day however the global biofuels market was only 1.7 million barrels per day in the same year, only 2% of the market (Kanes et al, 2010). The EU has set a target of 10% use of renewable energy in transportation fuels by 2020, therefore production has to significantly increase with road transportation receiving the most attention.

The two most common transport biofuels produced commercially are bioethanol and biodiesel. Both are first generation biofuels, meaning that they are primarily derived from crops, which may otherwise be used for food. Biodiesel use is mainly focused in the EU countries with Germany and France producing and consuming the highest volume, approximately 92,000 barrels per day as of 2009 (Index Mundi, 2009). The largest remaining consumers are mainly focused in and around North and South America.

Bioethanol production and consumption however is dominated in the US and Brazilian markets, with both countries accounting for 87.8% of the world's production in 2010 (Banse, 2008).

4.2.1 Bio Ethanol

Bioethanol is an alcohol produced from biomass sources high in carbohydrates such as sugarcane or cereals like wheat or barley. The feedstock crop is fermented into a sugar, to which yeast is added to mash the sugars into alcohol and CO_2. The liquid is then distilled which produces ethanol (next greencar, 2011).

Bioethanol can be handled in a similar way to petroleum and is often used as an alcohol-petrol blend in spark ignition engines. However using pure bioethanol requires modification to the ignition timing together with a larger fuel tank due to the bioethanol's lower energy density (next greencar, 2011). The advantage of an ethanol blend is that it can help reduce NO_x and emissions resulting from smog (NREL, 2010).

In Brazil, one of the leading bioethanol consumers, it is mandatory to operate all light vehicles using an ethanol-gasoline blend of 25% known as E25 (United Nations, 2011). Flexible Fuel vehicles were also developed by Brazilian car manufacturers, enabling them to run on any mix of ethanol-gasoline right through to pure bioethanol. The benefits of bioethanol are wide ranging, particularly the reductions in harmful exhaust emissions. Conventional gasoline produces approximately 2.44 kg/l of CO_2 while bioethanol emits 1.94 kg/l, a reduction of 21% (Popa, 2009). The CO_2 is also absorbed during the growth of the crop and can be used in many existing vehicles.

However there are distinct disadvantages to bioethanol production. Being a first generation biofuel, food sources are being displaced together with the reduction in rainforest to make space for the crop growth. The indirect emissions are considered to be higher than conventional fuels, an example being the growth of soy beans for ethanol in the US. Soy beans, once grown for animal feed is

now being used for bioethanol production. The result is that higher levels of soy beans are produced in Brazil to make up the loss in the domestic market (Gray, 2010).

4.2.2 Bio Diesel

Biodiesel is produced by the esterification of plant oils and animal fats to fatty acid methyl esters (FAMEs), combining alcohol (usually methanol) together with a catalyst which breaks the oil molecules and purifies the fuel (next greencar, 2011).

Similarly to bioethanol, biodiesel is often used as blend with conventional diesel and in small proportions does not require major alteration to the operating vehicle. The advantage of biodiesel is that it has the potential to reduce many of the regulated exhaust emissions such as particulate matter (PM) and sulphur by as much as 75% as demonstrated in (Knothe et al, 2006)

Although many exhaust emissions are reduced, NO_x levels have been shown to increase when operating with biodiesel.

4.2.3 Ethanol & Diesel Suitability for Aviation

Both Bioethanol and Biodiesel are suitable for road transportation however are not applicable for aviation purposes. Although bioethanol is regarded as a mature fuel with high production capabilities, its high vapour pressure would cause problems when operated at high altitudes (Hileman et al, 2009). Although cars can be refueled when required, aircraft ranges would be reduced by 52-66% (Hileman et al, 2009) due to the fuel's lower energy density and result in unsustainable routing difficulties. This would result in a detrimental effect to lifecycle GHG emissions and is better suited to land transportation.

Biodiesels are also unsuitable mainly due to their temperature characteristics. At high temperatures, the compounds and impurities derived from the oils and fats breakdown and leave deposits. This would pose a risk when operated in aircraft fuel systems at commonly high temperatures exceeding 1000^{o}c.

Similarly the lower temperatures experienced during high altitude would also be a safety concern, due to the higher freeze point of FAME fuels.

Due to the high level of specifications required for aviation fuels, other alternatives are being explored that are more suitable for air transportation. These include FT fuels and Hydro-Renewable Treated Jet (HRJ) bio fuels and will be discussed in more detail later in this thesis.

4.3 The Need for Alternative Fuels in Aviation

4.3.1 The Economic Case

Commercial aviation has experienced continuous growth for several decades with aviation becoming both fundamental for the global economy and also a necessity for the travelling public. This growth is expected to increase steadily for the foreseeable future as illustrated in Figure 22.

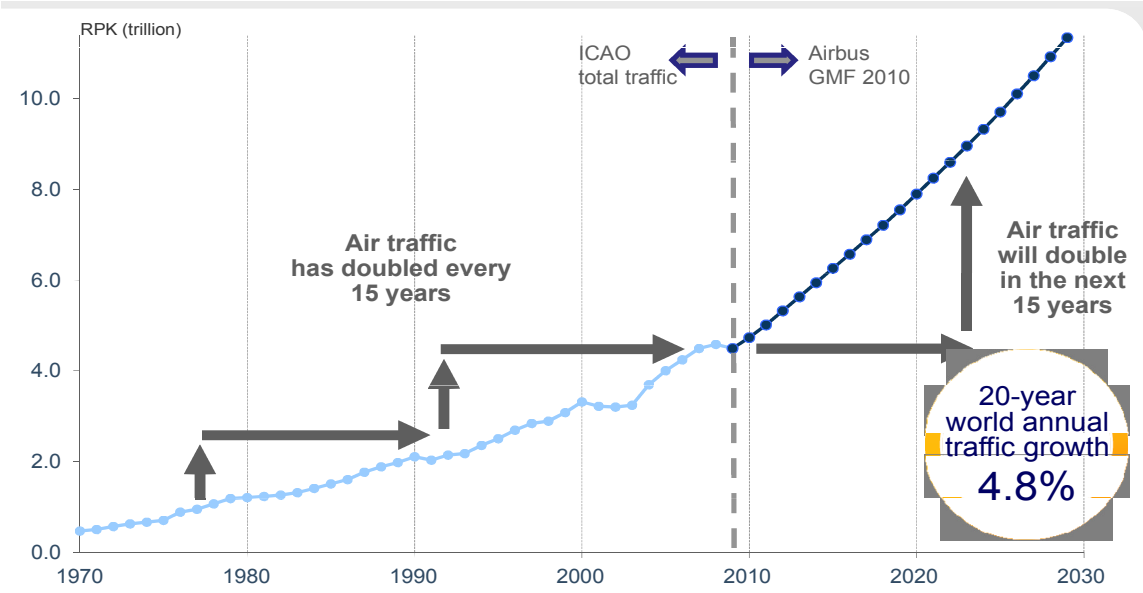


Figure 22 - World Annual Traffic Forecast **(Leahy, 2010)**

The forecasted increases in the demand for air travel can be attributed to several factors. Dynamic growth in emerging economies such as India and China will drive demand together with the expected increase in low cost carriers (LCCs) (Leahy, 2010).

However with this increased growth comes commercial and environmental concerns, namely to price volatility of jet fuel and the climate change concerns relating to increased traffic. Fuel is already an airlines largest operating expense, British Airways (BA) fuel costs in 2010 represented 28.8% of their total expenditure (BA, 2010). Figure 23 highlights the increase in the price of oil, illustrating that apart from a rapid decrease in 2009 as a result of reduced demand, the price of oil is growing consistently.

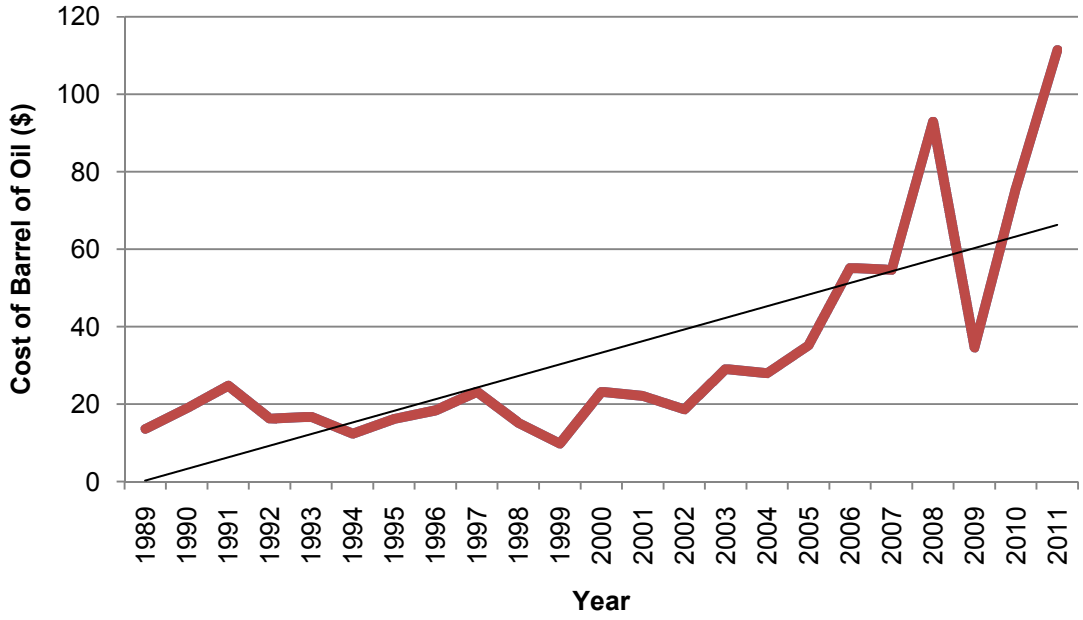


Figure 23 - Global Cost of Barrel of Oil **(EIA, 2011)**

The volatility in fuel prices together with concerns regarding the security of supply are forcing operators to consider their business models and examine alternative fuels in more detail.

Oil prices show no signs of stabilizing and concerns relating to supplies will undoubtedly lead to future increases. Karen Ward, Senior Global Economist for HSBC recently commented that there may only by 49 years worth of oil supply available (Allen, 2011) and with demand expected to increase by around 110% by 2050, alternative energy supply is essential.

4.3.2 The Environmental Case

The aviation industry is under pressure to reduce GHG emissions. Aviation currently represents approximately 2-3% of the global production of GHG emissions (AEF, 2008), however the growth expected over the coming decades may increase this figure. A study carried out by the Aviation Environment Federation (AEF) in 2008 provides a forecast for UK CO_2 emissions, illustrated in Figure 24.

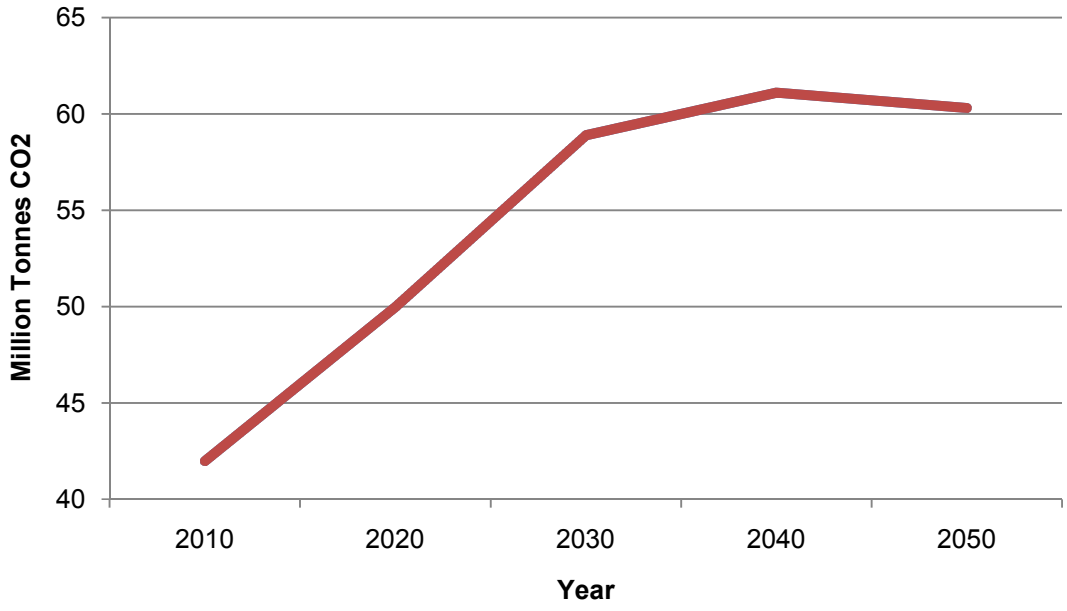


Figure 24 - Total UK Aviation CO_2 Forecast (2010-2050) (AEF, 2008)

The data forecasted by the AEF takes in to consideration, improvements in operational and fuel efficiency however still shows significant growth. CO_2 emissions are subject to the highest level of scrutiny, with the recent arrival of the EU ETS scheme. EU ETS will further pressurize airlines into reducing their GHG emissions, with the threat of significant financial penalties if they fail to meet the targets.

The need for alternative fuels that can reduce CO_2 emissions is essential both economically and environmentally.

4.4 Aviation fuel

4.4.1 Aviation Fuel Requirements

JET A1, the conventional jet fuel used for aviation, is a high performance fuel designed to stand a wide range of operational conditions. Therefore any biofuel replacement must meet the requirements set out in ASTM D1655 'Standard Specification for Aviation Turbine Fuels' (ASTM, 2011). Included in ASTM D1655, all aviation fuels must meet the following criteria detailed in Table 4:

Table 4 - Jet A1 Specifications (ATAG, 2009)

Criteria	Description	JET A1 Specification
Flash Point	The temperature at which the fuel ignites causing combustion to occur	Minimum of 38^{o}c
Freezing Point	The temperature at which the fuel will freeze	-47^{o}c
Combustion Heat	The amount of energy released during combustion/kg of fuel	Minimum of 42.8 Mj/kg
Viscocity	The thickness of a fluid or the ability to flow	Maximum of 8000 mm^{2}/s
Sulphur Content	The Amount of sulphur in the fuel	0.30 parts per million
Density	How heavy the fuel is per litre	775-840 kg/m^{3}

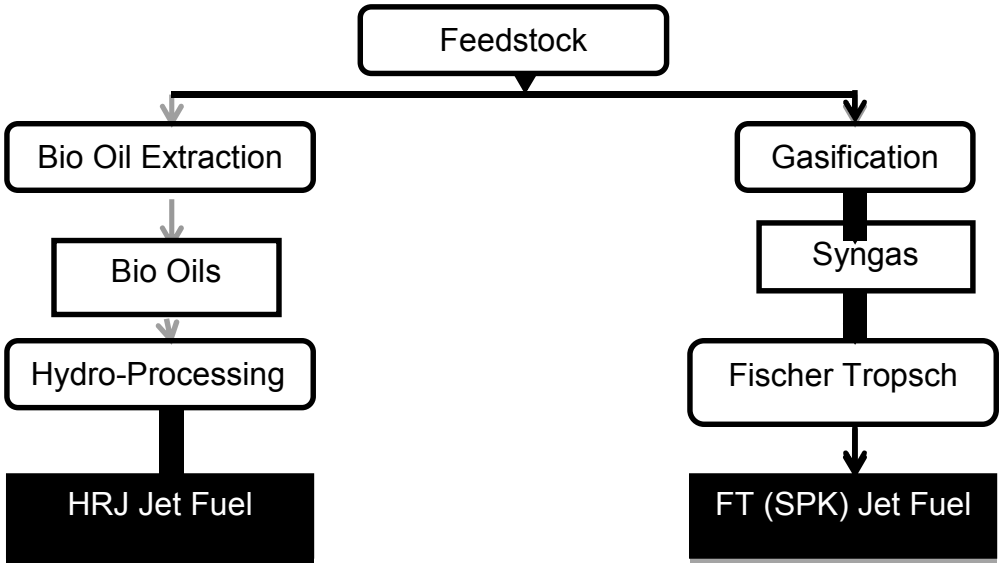
The criteria detailed above, highlight why biodiesel and bioethanol are both unsuitable for aviation purposes, due to inferior flash and freezing point characteristics. Any replacement to JET A1 should both burn correctly at all stages of flight, but also be able to operate as a "drop-in fuel". This ensures that the alternative fuel can operate with existing aircraft engines and fuel systems, requiring no modification.

There are a number of alternative fuel options available for aviation. The possible candidates to be explored in this report are listed below:

- Fischer-Tropsch Synthetic Liquid Fuels (Synthetic Paraffinic Kerosene)
- Hydrotreated Renewable Jet (HRJ) Bio Fuels

The two candidates listed above have differing production processes, GHG emissions and stages of development. Other options such as hydrogen powered aircraft are only at a conceptual stage but will be mentioned during the course of this report.

Figure 25 illustrates the pathways for “drop-in” biofuels and the processes involved in the production of the fuels.



Derived from (Hileman , 2010)

Figure 25 - Biofuel Pathways

Both of these pathways result in a hydrocarbon fuel with similar properties to traditional jet fuel.

4.5 Fischer-Tropsch Synthetic Fuel (SPK)

4.5.1 Introduction to F-T

SPK fuels are produced using the Fischer-Tropsch (FT) process. The FT process enables liquid fuel to be created from various carbon rich feedstocks including natural gas, coal and biomass.

The F-T process was developed by German scientists Franz Fischer and Hans Tropsch in 1923, originally as a method of making liquid fuel from coal. The result is a cleaner combusting fuel, which is colourless, odourless and low in toxicity (EPA, 2002).

There are typically three steps involved in the production of FT fuels (Saynor, 2003):

- **Syngas Generation** – The original feedstock is converted into synthetic gas (Syngas), which consists of CO and H_2.
- **Hydrocarbon Synthesis** – "Synthetic crude" is created by catalytically converting the syngas into a mixture of liquid hydrocarbons and wax. The stage is the Fischer-Tropsch synthesis process.
- **Upgrading** – The mixture of liquid hydrocarbons is upgraded through hydrocracking and isomerization and then fractionated into the desired fuel.

FT fuel also benefits from good compatibility and operation within current aircraft systems. FT fuels have a much lower aromatic content than JET A1, this results in neat FT fuels having a 3% lower energy density and 2% higher specific energy. In terms of performance, this allows the aircraft to fly further using the same weight of fuel. FT fuel benefits from very low levels of sulphur when compared to JET A1, however has comparable levels of CO_2 released during combustion (Hileman, 2009). Life cycle CO_2 emissions are very much dependent on stock used, with biomass potentially offering better lifecycle GHG emissions when compared to coal.

Coal is the world's most abundant hydrocarbon resource with reserves estimated to last between 200 to 225 years however crude oil and natural gas reserves are only expected to last for 40-60 years (Sasol, 2005).

4.5.2 Phase of Development & Current Operation

FT fuel is already used commercially in specific areas of the world particularly for automotive purposes, however it is still in the preliminary stages for aviation use. South Africa current leads the field in coal to liquid (CTL) production; Sasol operates two facilities, which produce the equivalent of 160,000 barrels of oil per day (Hileman, 2009).

Fuel can also be produced from natural gas using the FT process. Gas to liquid (GTL) was first commercially produced by Shell in Malaysia in 1993 and currently produces approximately 15,000 bpd (Hileman, 2009). Sasol is also a producer of GTL, opening a facility in Qatar in 2006 with a capacity of 34,000 bpd.

Biomass to liquid (BTL) fuel is very much in the early stages of development, however is the most promising FT fuel due to its use of non fossil fuel stock in production. One of the leading BTL developers is the US based company Solena Group. Solena currently are constructing their first commercial scale BTL plant in Gilroy, California with the purpose of producing high quality automotive fuel from waste material (letsrecycle, 2010).

In 2009, Solena announced a partnership with British Airways to investigate the possibility of developing a BTL fuel facility to convert waste material destined for landfill into aviation fuel (letsrecycle, 2010). The facility is likely to be built in East London, within close proximity to Heathrow and London City Airport and is expected to convert 551,000 tons of waste into 16 million gallons of aviation fuel per year (Nusca, 2010). The plant intends to use new technology known as a plasma arc gasification unit to perform the Fischer Tropsch process function. The benefit of such technology is that 20-50% more of the carbon based waste materials are broken down to ensure gasification and the use of a metallic

catalyst to spread the heat impact results in a greater processing area (letsrecycle, 2010).

The hope for the plant is that not only will it provide a significant quantity of aviation fuel, but also provide sufficient energy to operate the plant by internally producing 20MW of electrical power (letsrecycle, 2010).

4.6 Hydrotreated Renewable Jet (HRJ)

4.6.1 Introduction to HRJ

HRJ fuels are produced from plant oils, animal fats or waste grease to produce a fuel that is similar to FT fuel and suitable for aviation use (Stratton, 2010). The production process involves hydrotreating to deoxygenate the oil with subsequent hydrocracking to create normal and isoparaffinic hydrocarbons that fill the distillation range of Jet A1 (Hileman, 2009).

HRJ fuels are similar in composition to FT fuels and therefore share similar emission and operation characteristics. Where HRJ fuel is different is the use of feedstock used. The main raw material in HRJ fuel is triglyceride oil (Holmgren, 2010), found in many oils and fats such as soy and canola together with non-food energy oils such as camelina, jatropha and algae. The main challenge relating to HRJ production is finding a feedstock that ideally is abundant and does not compete for other important uses such as food production. The limited availability of such feedstocks when compared to crude oil is why HRJ fuel is currently between 50 and 100% more expensive (Holmgren, 2010). Increased planting and higher yielding feedstocks are required that do not compete for resources such as camelina and algae.

4.6.2 Phase of Development & Current Operation

HRJ together with FT fuel has undergone various flight and ground tests over the past several years to determine if the fuels are both safe to operate and environmentally beneficial. Flight tests have been particularly encouraging, with many of the HRJ fuels performing to the same or better standard when

compared to JET A1 (Rahmes et al, 2009). The United States Air Force recently certified their C-17 Globemaster III aircraft for unlimited use of HRJ fuels (Dowdel) when blended as a 50:50 mix with JP-8, the North American equivalent to Jet A1.

Several major airlines have also tested HRJ with commercial aircraft, a selection of which are detailed in Table 5. Air New Zealand, Contintental Airlines and JAL have all tested 50:50 blends using a mixture of jatropha, algae and camelina feedstock HRJ fuels together with Jet A1 (Hileman, 2009).

Carrier	Aircraft	Date	Biofuel	Blend
Virgin atlantic	B747-800	February 2008	Coconut & Babassu FAME	20% one engine
Continental Airlines	B737-800	January 2009	Algae & Jatropha HRJ	50% one engine
TAM AIRLINES	A320	November 2010	Jatropha HRJ	50% one engine
Lufthansa	A321	May 2011	Biomass to Liquid (SPK)	50% one engine

Table 5 - Selection of Previous Biofuel Test Flights by Commercial Airlines

4.7 Environmental Credentials of Alternative Fuels

Suitable future alternative fuels not only have to demonstrate a minimal environmental impact during combustion, but also be produced at a low cost with high yielding feedstock. The choice of feedstock is highly important in the overall life cycle impact of the fuel. The majority of first generation feedstocks such as ethanol are produced from corn, thus competing for land with food crops and potentially resulting in deforestation (ATAG, 2009). Certain criteria for feedstocks are desirable as listed below:

- Fast growing, non food plants taking minimal land to grow and cultivate
- Do not require large quantities of pesticides, fertilizer or irrigation

- Provide socio-economic value to the local communities
- Result in a lower life cycle carbon footprint than conventional fuels

4.7.1 Life Cycle GHG Emissions of Biofuels

Comprehensive studies have been conducted by several environmental organisations (Hileman, 2009) (Stratton, 2010) (Hileman, 2010) into the complete life cycle impacts of candidate aviation biofuels. Both FT and HRJ fuels have been analysed, with the results of both following. Figure 26 below shows the "well to wake" steps of a biofuel life cycle.

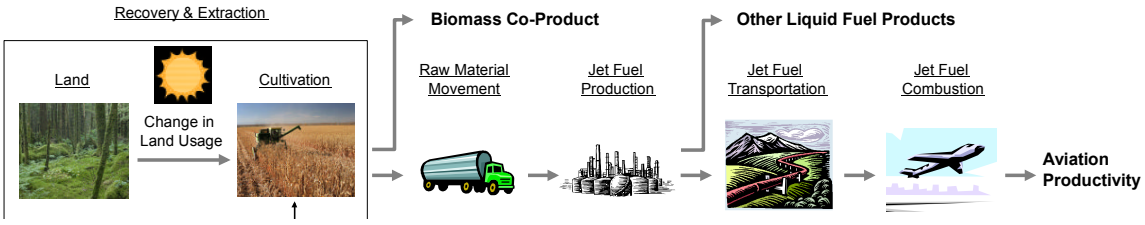


Figure 26 - Biofuel lifecycle steps (Stratton, 2010)

For each step of the lifecycle conducted by (Stratton, 2010), the GHG emissions considered are CO_2, CH_4 and N_2O. For all phases excluding combustion, NO_x, SO_x and soot are neglected but will be mentioned using flight test data from additional sources.

Many of the biofuels have a "biomass credit" which offsets the CO_2 emissions released during combustion. As the benefit of biofuels is the ability of the feedstock to absorb the combusted CO_2 during growth in a "cycle" process, a mechanism is required to consider this. The biomass credit is essentially the "*difference between the biomass and fossil fuels in terms of their GHG emissions"* (Stratton, 2010).

The following results were collated from (Stratton, 2010) with the life cycle GHG emissions presented using a metric (g CO_2e/MJ) that captures the mass of GHG per unit of energy consumed by the aircraft. The two fuel types to be considered are FT and HRJ fuel. The following feedstocks analysed in (Stratton,

2010) and included in this study are listed below in Table 6 together with conventional jet fuel.

Table 6 - Alternative Fuels Considered (Stratton, 2010)

Source	Feedstock	Recovery Method	Processing Method	Final Product
Petroleum	Conventional Crude	Crude Extraction	Crude Refining	JET A1
Natural Gas	Natural Gas	Natural Gas Extraction and Processing	Gasification, F-T Synthesis and Upgrading	**SPK Jet Fuel (F-T)**
Coal	Coal	Coal Mining		
Biomass	Switchgrass Corn Stover Forest Waste	Biomass Cultivation		
Biomass – Renewable Oil	Soybeans Palm Algae Jatropha Rapeseed	Biomass Cultivation & Extraction of Plant Oils	Hydroprocessing	**SPK Jet Fuel (HRJ)**

Nine categories referring to different life cycle phases and emissions have been analysed, with an overall value of g CO_2e/MJ calculated to enable comparisons to be drawn between the different types of aviation fuel.

The nine categories are listed below:

- Biomass Credit
- Recovery
- Feedstock Transport
- Processing
- Fuel Transport
- Combustion
- Well to Tank (WTT) N_2O
- Well to Tank (WTT) CH_4
- Land Use Change

The “well to tank“ category includes all the emissions of N_20 and CH_4 produced from all the phases leading up to but not including combustion. The combustion

category will be complimented with other data obtained from various flight and ground tests to provide a comprehensive evaluation of the environmental merits of each candidate fuel.

With each of the biofuels requiring feedstocks, (Stratton, 2010) formulated several different land use change scenarios to measure the impact when using different types of land masses. Table 7 below details the different scenarios used.

Table 7 - Land Use Scenarios for Candidate Biofuels (Stratton, 2010)

LUC CODE	Land Use Change	Scenario 0	Scenario 1
LUC-B	Switchgrass	None	Carbon depleted soils converted to switchgrass cultivation
LUC-S	Soy Oil	None	Grassland conversion to soybean field
LUC-P	Palm Oil	None	Logged over forest conversion to palm plantation field
LUC-R	Rapeseed Oil	None	Set-aside land converted to rapeseed cultivation
LUC-H	Salicornia	None	Desert land converted to salicornia cultivation field

Figure 27 below displays the results of the PARTNER life cycle study in a graph, highlighting the impact of the various categories on the total life cycle emissions of each fuel.

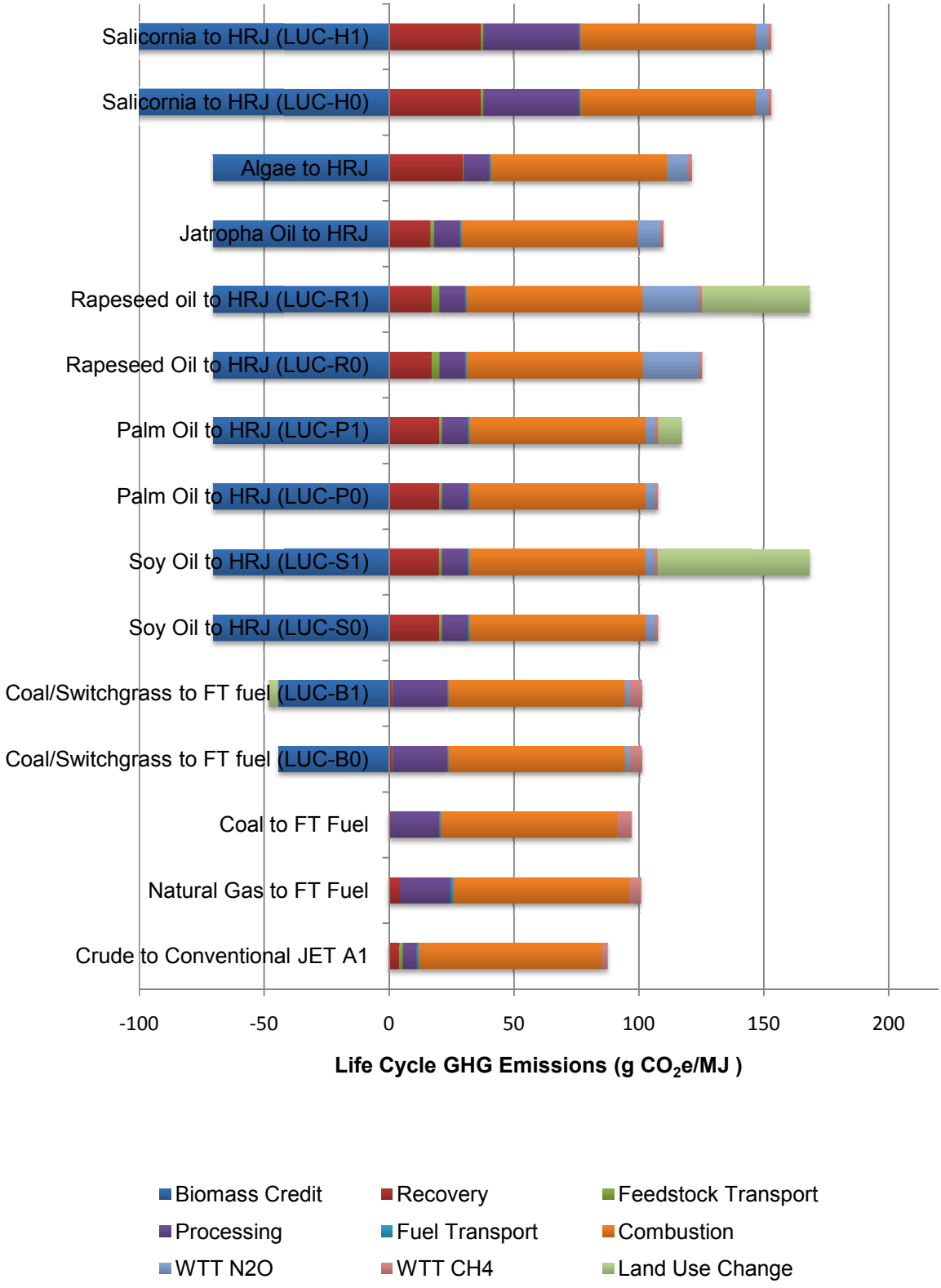


Figure 27 - Life Cycle GHG Emissions for Alternative Fuels (Derived (Stratton, 2010)

Figure 28 illustrates to same results as a sum of all nine categories.

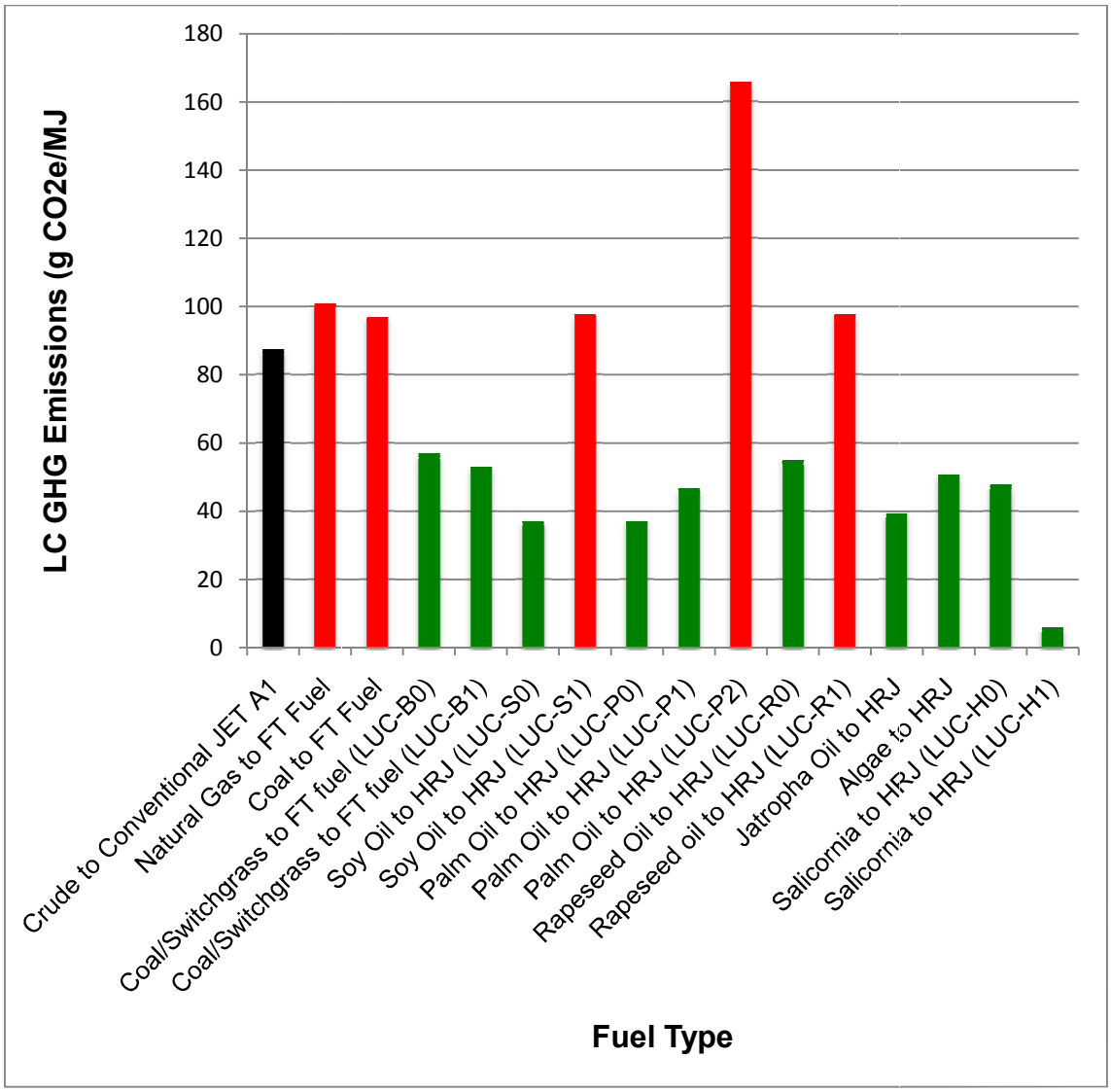


Figure 28 - Total Life Cycle GHG Emissions of Biofuels (Stratton, 2010)

Red and Green symbolise increases or decreases in GHG emissions respectively when compared to the baseline JET A1 (black).

Figure 28 summarises the lifecycle impact of each fuel, however these results alone do not determine the suitability of each fuel. Other factors such as feedstock yield and competition with food sources have to be considered. The following section examines FT and HRJ fuel in more detail together with data obtained from ground and flight combustion testing.

4.7.2 F-T Fuel GHG Emissions

From Figure 28, it can be seen that the source of FT fuel is significant when comparing the lifecycle emissions to Jet A1. FT fuel derived from natural gas results in estimated life cycle GHG emissions 15% higher than Jet A1, mainly attributed to higher processing emissions. Coal derived FT fuel is similar in emission characteristics to natural gas, with 11% higher GHG emissions.

The only benefits of natural gas and coal derived FT fuel appear to result from improved combustion emissions, however the use of biomass in combination with coal shows significant improvements in lifecycle GHG emissions. The combination of coal and biomass has been shown to be beneficial in several studies (Hileman, 2010) both by reducing life cycle GHG emissions and achieving greater economies of scale during production.

Biomass stocks used in FT production can include corn stover and non-food crops such as switchgrass. Figure 27 and Figure 28 provide estimated results for a combination of switchgrass and coal, with the encouraging results. Coal and Switchgrass derived FT fuel is estimated to provide a 35% baseline lifecycle GHG reduction as a result of its 2nd generation feedstock. Switchgrass is an ideal candidate for a biofuel feedstock due to its versatility growing in most climatic variations (Dunn, 2006). Switchgrass provides a very high yield of between 5-10 tons per acre, with little use of pesticides and a low production cost (Dunn, 2006).

FT fuel combustion emissions are similar despite differing sources (coal, gas, biomass) and were all estimated in (Stratton, 2010) to be 4% lower than the baseline Jet A1.

FT fuels exhibit several promising characteristics. Firstly FT fuels contain very low levels of sulphur and have a low aromatic content, leading to potential improvements to local air quality (Hileman, 2010). Tests have also shown improvements in PM emissions with reductions of up to 77% (Timko, 2010) available depending on the engine power condition. CO and NO_x emissions

were found to be similar to Jet A1 (ICAO, 2009). The “smoke number”, a dimensionless term quantifying smoke emissions was found to be significantly reduced when using both blended and neat FT fuel, with 40% reductions seen at all engine settings.

CO_2 released during combustion of neat FT fuel has been shown to be comparable to JET A1 (Timko, 2011), therefore CO_2 reductions will only be achieved with FT fuel derived from biomass feedstock, when looking at the lifecycle emissions instead of just combustion.

4.7.3 HRJ Fuel GHG Emissions

Figure 28 highlights significant variations in HRJ fuel life cycle GHG emissions with palm oil derived fuel produced in certain land use scenarios estimated to be 160% more environmentally damaging than Jet A1 (LUC-P2). Conversely using salicornia as a feedstock with a positive land use scenario could potentially result in a 94% reduction in lifecycle GHG emissions when compared to JET A1.

The wide ranging figures are as the result of land usage and the competition of natural resources. Both soybeans and palm are food crops that require fertile land for cultivation (Stratton, 2010) and the production of biofuels could result in significantly high land use change emissions of CO_2. According to (Hileman et al, 2009) certain feedstocks for example corn could result in taking 93 years to repay the carbon debt caused by land use change emissions. Land use change is an important factor in the environmental credentials of an alternative fuel, Figure 29 illustrates how when excluding land use change, the lifecycle GHG emissions of HRJ are 50% lower than Jet A1.

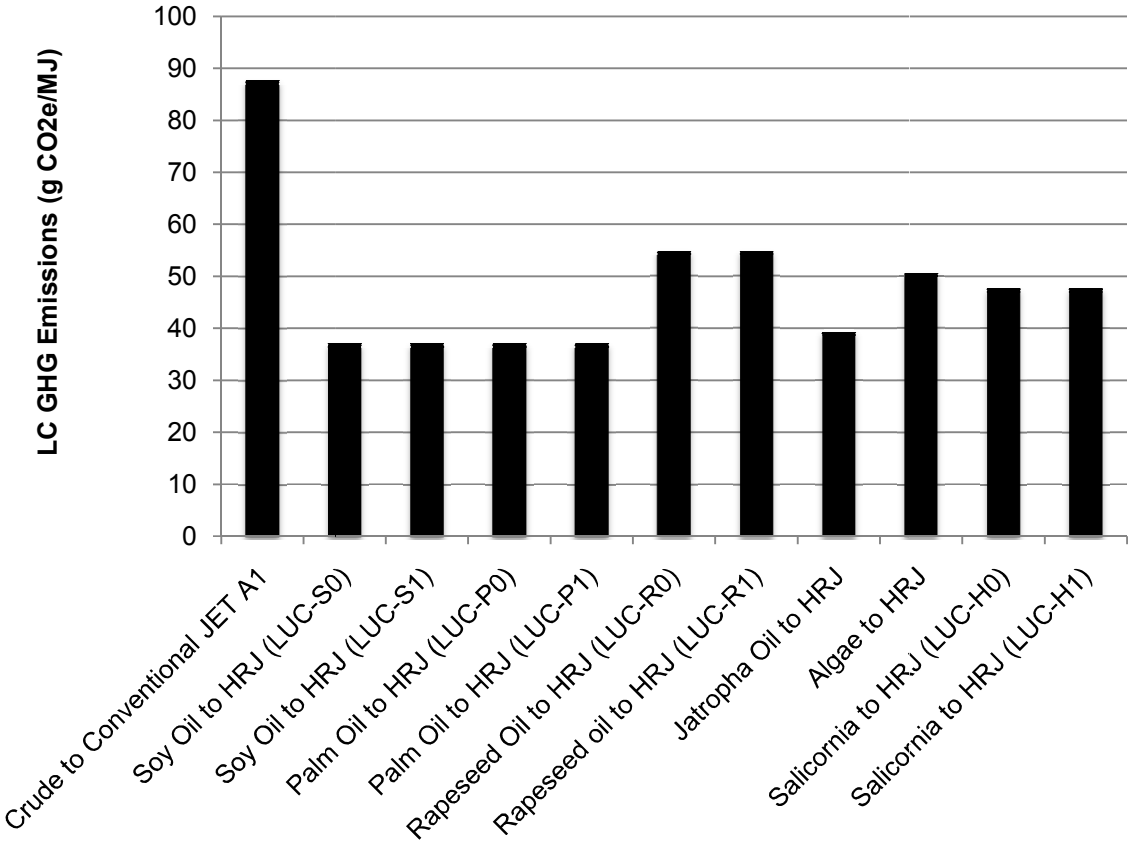


Figure 29 - Life Cycle GHG Emissions for HRJ Fuels (Excluding Land Use Change)

The most promising feedstocks for HRJ fuel are algae and salicornia. Both plants benefit from high yields and both can potentially be grown in salt water. Algae has the benefit of been produced with a negative carbon mechanism meaning that net carbon is taken out of the atmosphere.

Algae have far superior potential yield volumes per acre of production when compared to crop based biofuel sources. Exxon Mobil estimate that algae could yield more than 2000 gallons of fuel per acre of production per year (ExxonMobil, n/a), this is compared to:

- Palm – 650 gallons per acre per year
- Sugar Cane – 450 gallons per acre per year
- Corn – 250 gallons per acre per year
- Soy – 50 gallons per acre per year

The challenge of harvesting algae into aviation grade jet fuel in commercial volumes is one that is receiving substantial research from a number of leading universities and organisations. The Sustainable Use of Renewable Fuels (SURF) is consortium made up of airlines including British Airways and Finnair, Manufacturers Airbus and Rolls Royce, the IATA and Cranfield University (Cranfield University, 2010). SURF aims to address several key issues relating to algae fuel production including processing, capacity and distribution, commercialization, legislation and regulation. Cranfield University currently have a pilot facility which is growing and harvesting algae with the ambition of initiating an ocean based facility with the ability to grow at a commercial scale.

Salicornia is a form of algae that grows in salty waters and has the benefit of "seawater aquaculture", the process that involves feeding the salicornia with fish faeces and this thus eliminates the need for fertilisers which can have detrimental effects on the biofuels carbon dioxide balance (Sandru, 2010).

Combustion characteristics for HRJ are similar to those of FT fuels (Stratton, 2010), with reductions in PM and sulfur. Ground testing was carried out at GE Aviation's testing facility in Ohio in 2008 (Rahmes, 2009), to examine the impact of jatropha and algae based HRJ fuel on engine performance, operability and emissions. The testing was conducted using a CFM56-7B engine operating with:

- Jet A – Baseline Fuel
- 25% Jatropha/Algae Mix
- 50% Jatropha/Algae Mix

Emissions of NOx, CO, hydrocarbon (HC) and smoke were measured for each fuel type using gas analysis equipment. The results depicted in Figure 30 show the change in emissions when compared to Jet A.

The results show a slight reduction in NO_x of between 1-5% and an increase in CO of 5-9%. The addition of biofuel also increases the hydrogen/carbon (HC) ratio

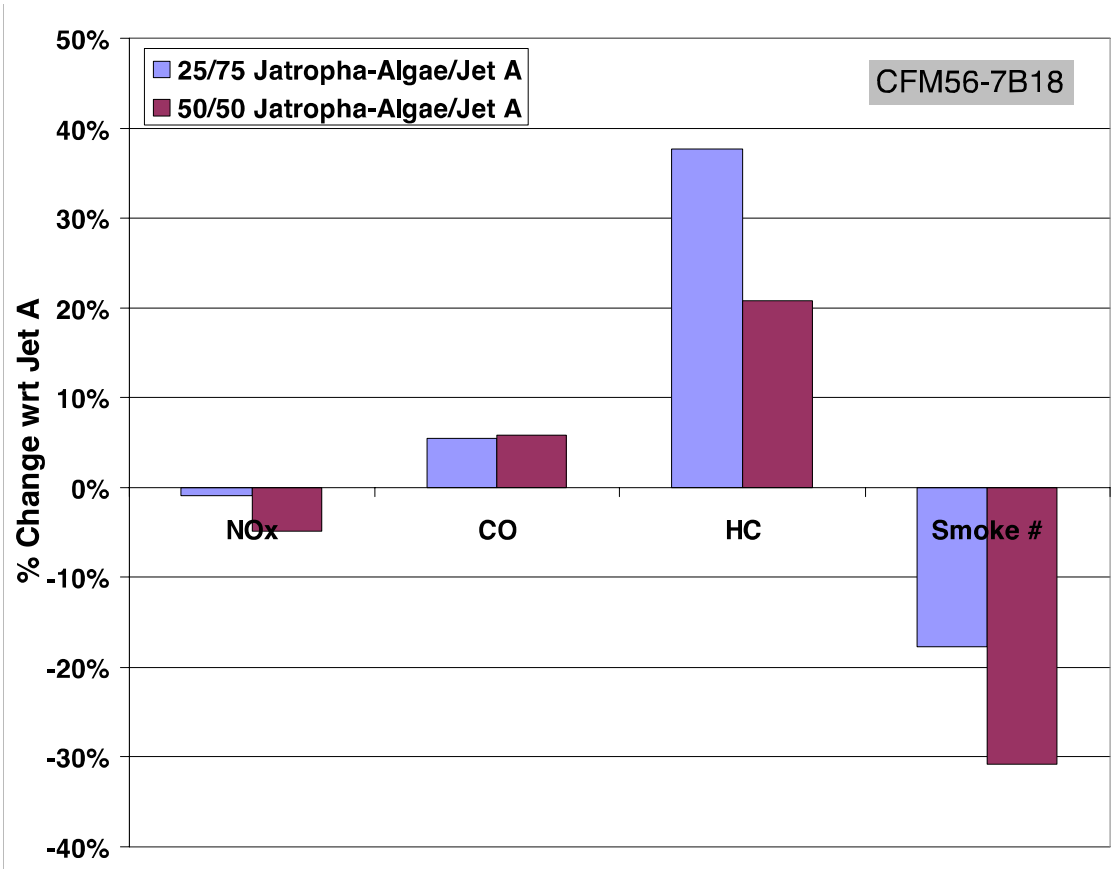


Figure 30 - Emissions for HRJ Test Blends when Compared to Jet A (Rahmes, 2009)

4.8 Emission Reductions Available on Commercial Routes

From the alternative fuel options examined in the previous section, it is apparent that the most promising pathways are:

- Fossil Fuel & Biomass Combined F-T Fuel
- Algae/Salicornia HRJ Fuel

Both fuels have demonstrated satisfactory emission and operational results in ground and flight testing, together with significant improvements in life cycle GHG emissions. The following analysis was conducted to highlight the possible improvements available from replacing traditional Jet A1 with both biofuels.

4.8.1 Route Emission Savings Available

The following example takes a British Airways 747-400 aircraft, operating from London Heathrow (LHR) to John F Kennedy (JFK), New York. From (European Environment Agency, 2007) the following emissions in Table 8 are known to be emitted per flight.

Table 8 - LHR to JFK Emissions from Boeing 747-400

Emission	Total Emitted per Flight (kg)
Total Fuel Consumed	64955
CO_2	204857
NO_x	903
CO	83

The carbon traded price is expected to reach €30 (~ £26.50) per tonne in 2012 (Ares, 2011). The EU ETS will dispense credits to airlines at low cost, however the opportunity arises to sell “unused” European Union Allowances (EUA) to other emitters. Biofuels are excluded from fuel calculations under the EU ETS,

therefore using a 50:50 blend of either FT or HRJ fuel could represent a carbon saving comparable to £2714 per flight.

CO_2 emitted during the flight will as highlighted earlier, be similar to that of Jet A1 with ~5% savings achievable. The biofuel powered LHR-JFK flight could potentially reduce NO_x by 81kg with only a 4kg gain of CO.

If the lifecycle CO_2 emissions are considered during the flight, operating with FT or HRJ fuel could reduce CO_2 levels too:

- Coal & Biomass FT = (35.16% reduction in CO_2) = 132829 kg
- Algae Derived HRJ = (42.24 reduction in CO_2) = 118325 kg

Therefore considering the LHR-JFK route operated by BA (approx. 5 per day) in a one year period using a 50:50 blend or biofuel, the savings achievable are:

- £4.95 Million EUA allowances available for alternative routes by BA or for sale to other EU ETS installations
- Approximate 65700 Tonnes of lifecycle CO_2 saving

Chapter 5

Environmental Life Cycle Assessment of A320 Aircraft

5 ENVIRONMENTAL LCA OF AIRBUS A320 AIRCRAFT

5.1 Introduction

The environmental impact of aviation is becoming increasingly relevant, with continued social and regulatory pressure placed on aircraft operators and manufacturers to improve their life cycle emissions. Historically, much focus has been placed on the operation phase of the aircraft and the emissions that result. This is understandable due to the length of service and fuel consumed, however the other stages of an aircraft service life are seldom discussed.

LCA is a powerful technique that can be used to assess the environmental impacts of a product, process or service throughout its lifecycle from 'cradle through to the grave'. In this analysis LCA has been utilised to study the environmental impact of each of the life phases of a passenger aircraft; Manufacture, operation and decommissioning, in order to determine the impact of each phase and examine their overall contribution to the aircraft life cycle. Operation is expected to be the major contributor of emissions, however this study will determine the significance of the other life phases, particularly that of production and disposal. Among the several subassemblies a number of different materials are used, each subassembly will be examined to establish the areas and materials which have the highest environmental impact.

5.2 Life Cycle Assessment

LCA provides a useful methodology that can be followed to assess the environmental impact of a process, product or service from design through to disposal using a holistic 'cradle to grave' approach. LCA can be implemented for a variety of different applications such as policy decision-making and support of environmental marketing claims. Companies such as Unilever (Unilever, 2011) have used LCA to allow assessment of the impact of their products. LCA is also highly effective when used internally to assist strategic planning or process design and optimisation. The LCA process according to International Organisation for Standardisation (ISO) 14040/14044 (British Standards, 2006)

consists of four interdependent phases as demonstrated below in Figure 31. These stages include the initial goal and scope definition, inventory analysis, impact assessment and finally interpretation of results.

The goal sets out the context of the study and the audience that the results will be presented to. The scope section details how the study will be performed, including the allocation procedures to be considered, the assumptions made, limitations that exist and the boundaries of the study. The system boundaries detail which unit processes will be included in the study and the levels of detail that will be applied. Due to time and data constraints, it is unfeasible to include every process. ISO 14044 (British Standards, 2006) does however state that the omission of stages, inputs or outputs and processes is only permissible if they do not significantly change the overall conclusions of the study. The initial phase also details the methodology to be used including the impact categories and characterisation models.

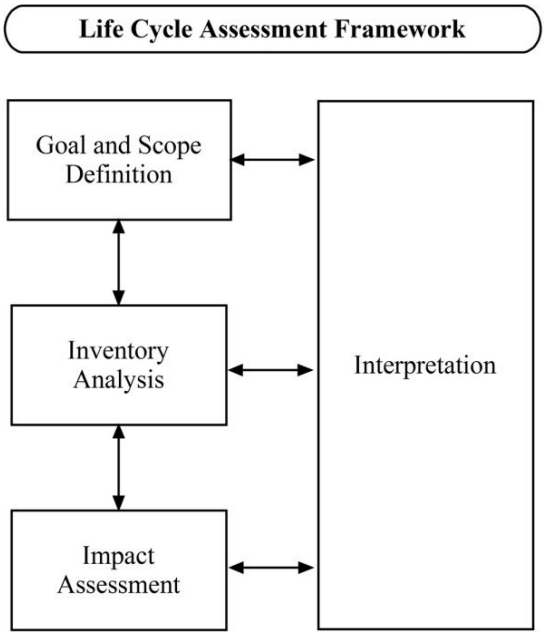


Figure 31 - Stages of Life Cycle Assessment (British Standards, 2006)

The plan for conducting the inventory analysis is defined in the goal and scope section and consists of collecting all the data required to complete the study. This can include inputs of energy, materials or raw materials and is typically constructed using a flow model diagram. Data for this stage can be collected by variety of means; typically questionnaires are used to collect accurate information regarding inputs.

The purpose of the Life cycle Impact Assessment (LCIA) phase is to evaluate the significance of potential environmental impacts based on the results from the life cycle inventory. The LCIA stage consists of several key mandatory elements:

- Selection of impact categories, category indicators and characterisation models
- Assignment of LCI results to the selected impact categories (classification)
- Calculation of category indicator results (characterisation)

Impact categories reflect a particular set of environmental issues such as acidification and climate change. For this particular study, the Eco-Indicator 99 characterization model will be used. This considers damage to human health, ecosystem health and damage to resources. Characterisation models describe the relationship between the LCI results and impact categories, deriving characterisation factors. Characterisation factors are used to quantitatively model the impact from all emissions and resources within the inventory.

Characterisation is a mandatory part of the LCIA procedure, however several optional elements exist that can be implemented to improve the assessment process. Normalisation is the calculation of the magnitude of the impact category results relative to some reference information such as the total inputs and outputs for a given regional area. Normalisation helps to increase understanding of the relative magnitude for each impact category. Weighting is a useful tool in presenting the relative magnitudes of each impact sector by

aggregating the characterisation or normalisation scores into on environmental score.

Weighting is a different practice, based on value choices, which are not scientifically based. The values are based on the opinions of different individuals and organisations, providing an opinion into the magnitude and importance of each impact category. The final stage of an LCA is interpretation, where the analysis is evaluated to identify significant issues arising from the results of the LCIA and to evaluate the completeness of the study. Conclusions and recommendations would also be completed at this stage.

5.3 LCA of A320 Aircraft

5.3.1 Goal and Scope of Study

The goal of this study is a comprehensive life cycle assessment of an Airbus A320 during each of its life phases. As discussed earlier, substantial research has been conducted into the environmental impact of aircraft operation. However the impact of aircraft production and disposal are much less examined. This study aims to address this gap in understanding and determine how influential the additional life phases are to the overall environmental impact. The analysis conducted will highlight particular components, materials or processes that significantly affect the overall environmental impact of the aircraft. The increased use of advanced materials such as carbon fibre reinforced plastic (CFRP) have assisted in reducing weight and improving fuel consumption, however the emissions created during production and disposal need further examination to determine if the move from more conventional materials represents a positive environmental output (Arnold, 2011).

The Airbus A320 is a single aisle narrow body aircraft, typically operated on short to medium haul routes. The A320 was selected for a number of important reasons; there are more than 4530 aircraft in active service with the aircraft ranked as the world's fastest selling jet airliner (abc News, 2010) in comparable size to the competitive Boeing 737. Continued growth, particularly in the Asia-Pacific region will drive demand for new aircraft to over 100% by 2029 (Leahy, 2010). Single aisle aircraft are expected to account for approximately 69% of new aircraft deliveries with nearly 18,000 expected within the next 20 years. The A320 aircraft can be operated with different power plant configurations, however for this study two CFM56-5B engines will be considered.

SimaPro v7.1.8 (PRe Consultants, 2008) will be used to conduct the analysis together with the EcoInvent Version 2 database (EcoInvent, 2007).

5.3.2 System Boundaries

This study considers the complete life of an aircraft over a 20-year service life. The LCA will be modeled in second order, ignoring capital goods involved during production. An average large commercial aircraft will consist of millions of parts and components (Scott, 2009), which would be unfeasible to model due to time and data constraints. Therefore the A320 has been separated into major structural components which can be divided into separate sub-assemblies. For the purpose of this study, 6 assemblies and 75 sub-assemblies have been considered. Figure 32, illustrates the breakdown of the A320 and a selection of sub-assemblies.

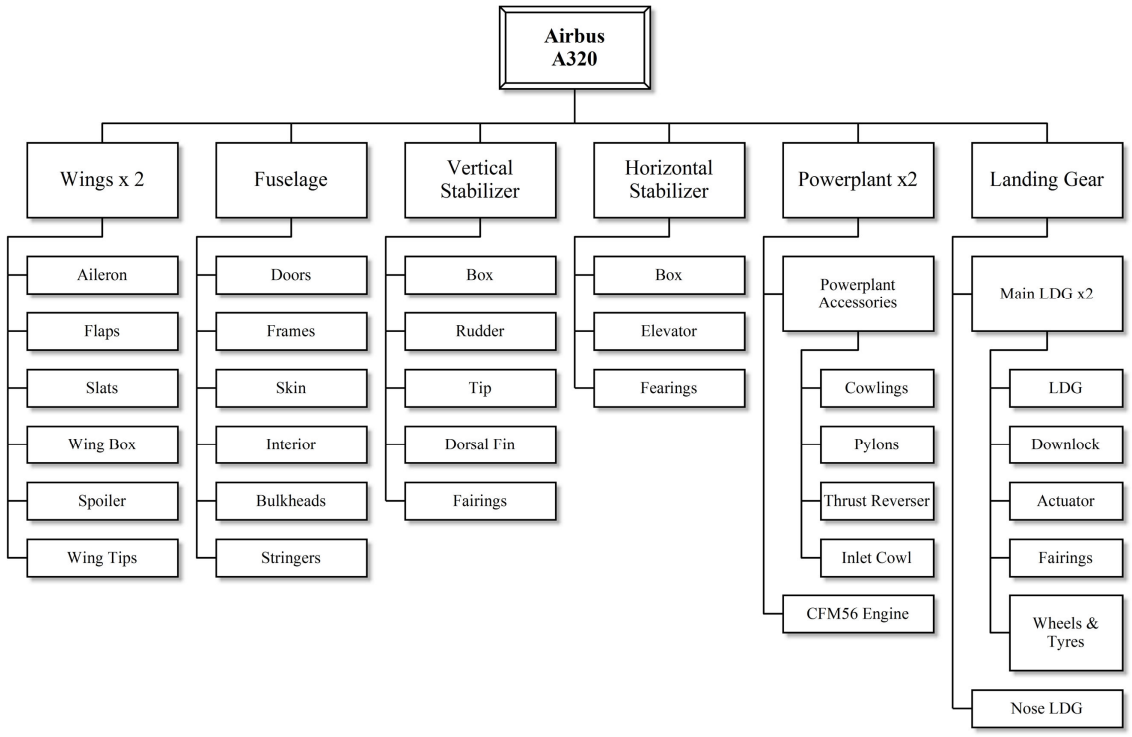


Figure 32 - Component Breakdown of A320 including Sub-assemblies

The major structural components of the A320 are manufactured in several different European locations and then transported to the final assembly line in Toulouse, France. Transportation, excluding the engines, has been considered in the overall LCA, with average distances calculated from each manufacturing base to Toulouse. Disposal will be included for the aircraft involving recycling, incineration and landfill, data of which is discussed in the following sections.

There are a number of unavoidable limitations involved in this study, one being that aircraft systems and internal components have not been considered. Systems such as flight deck instrumentation, hydraulic systems, and batteries are often manufactured by third parties thus limiting the availability of accurate data. Manufacturing processes involved in the production of the A320 also may vary from the processes established in the Ecoinvent database. However methods continually evolve, with processes today varying from those during the infancy of the A320.

The reliability of the study depends greatly on the conformance of data quality requirements within ISO/14044 (British Standards, 2006). All process and material data has been obtained from European Union (EU) unit processes within the Ecoinvent 2.0 database (EcoInvent, 2007). The Ecoinvent database contains over 4000 Life Cycle Inventory (LCI) datasets and has been used exclusively for all but two unit processes. CFRP and aviation biofuel material processes are currently not available in the leading LCI database packages. Therefore custom processes were created using sources for biofuel and CFRP (J. R. Duflou, 2009) (Suzuki, 2005), both being important data gaps and areas for future research.

5.3.3 Life Cycle Inventory Analysis

It is paramount for the credibility of such a study, that the data used is as commercially accurate and updated as available. However data relating to aircraft development and production can be notoriously difficult to obtain for sensitivity reasons. The A320 lifecycle is illustrated in Figure 33.

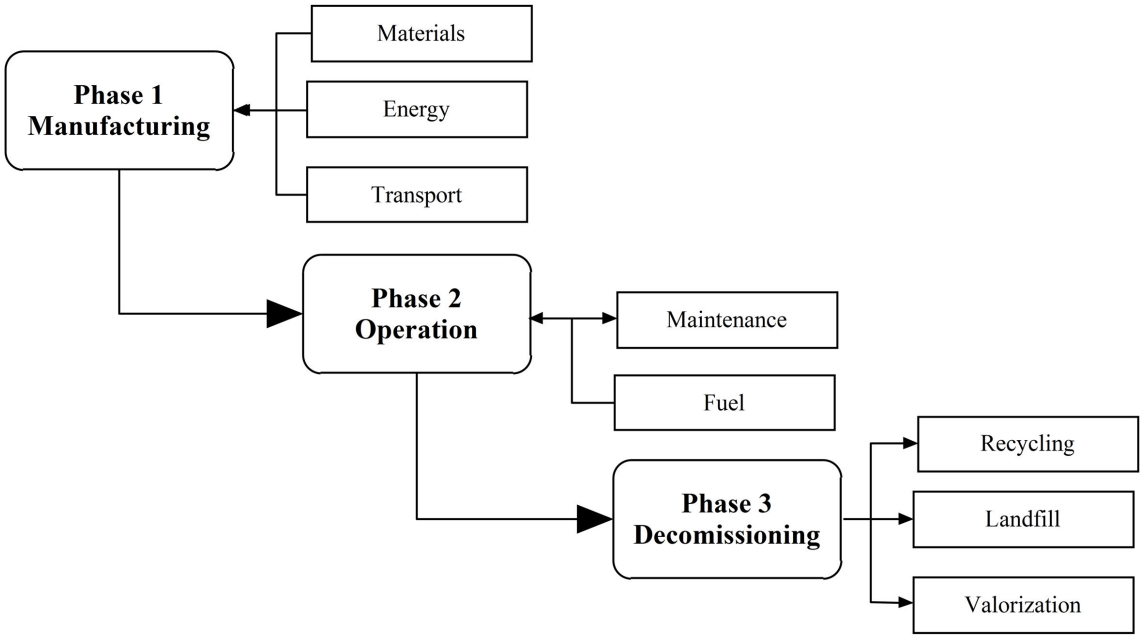


Figure 33 - Life Cycle Flow Diagram for A320

5.3.4 Manufacturing Stage

The sub-assemblies of the A320 consist of a number of different materials and corresponding masses. With the scarcity of data containing precise mass and material compositions, a number of educated assumptions had to be made. The Operational Empty Weight (OEW) of the A320 is 41,244kg (Airbus, 2005), which includes the weight of the structure, power plant, furnishing, systems and all other operators' items such as life vests and engine oil.

All systems aboard the A320 have been neglected from the study and have been assumed to account for 10% of the overall OEW. Therefore the mass of the A320 analyzed in this study will be 39,181 kg. Each CFM56-5B engine has a basic dry weight of 2380kg (CFM, 2010) therefore the structural mass excluding engines is 34,420 kg. Figure 33 details the sub-assemblies considered in this study, while Table 9 summarises the assumptions relating to the mass of each assembly. Table 10 includes the proportional content of each major material in the A320 structure.

Table 9 - Assembly Masses used in Study

A320 Assembly	Proportional Mass Used (kg)	Total Assembly Mass (kg)
Wings (x2)	35%	13713
Fuselage	30%	11755
CFM56-5B (x2)	18%	7052
Main Landing Gear	10%	3918
Horizontal Stabiliser	3%	1175
Vertical Stabiliser	3%	1175
Nose Landing Gear	1%	392
		39,181

Table 10 - Material Composition data for the A320 (Rendigs & Knuwer, 2010), excluding CFM56-5B engines

Structural Material	Percentage Composition	Approximate Mass Content (kg)
Aluminium	68%	23,405
Composites	15%	5163
Steel	9%	3098
Titanium	6%	2065
Miscellaneous	2%	689
		34,420*

Aluminium is clearly the major constituent, however composite materials are expected to be the most important for this analysis due to the fact that they are more energy intensive to manufacture and with challenges relating to disposal (Suzuki T, 2005), therefore their LCA impact during production is expected to be significant. The major composite constituent is CFRP, of which the content in each assembly has been modeled from (Airbus, 2005), illustrated in Figure 34. The assumptions relating to composite content in each of the A320 assemblies is presented in Table 11.

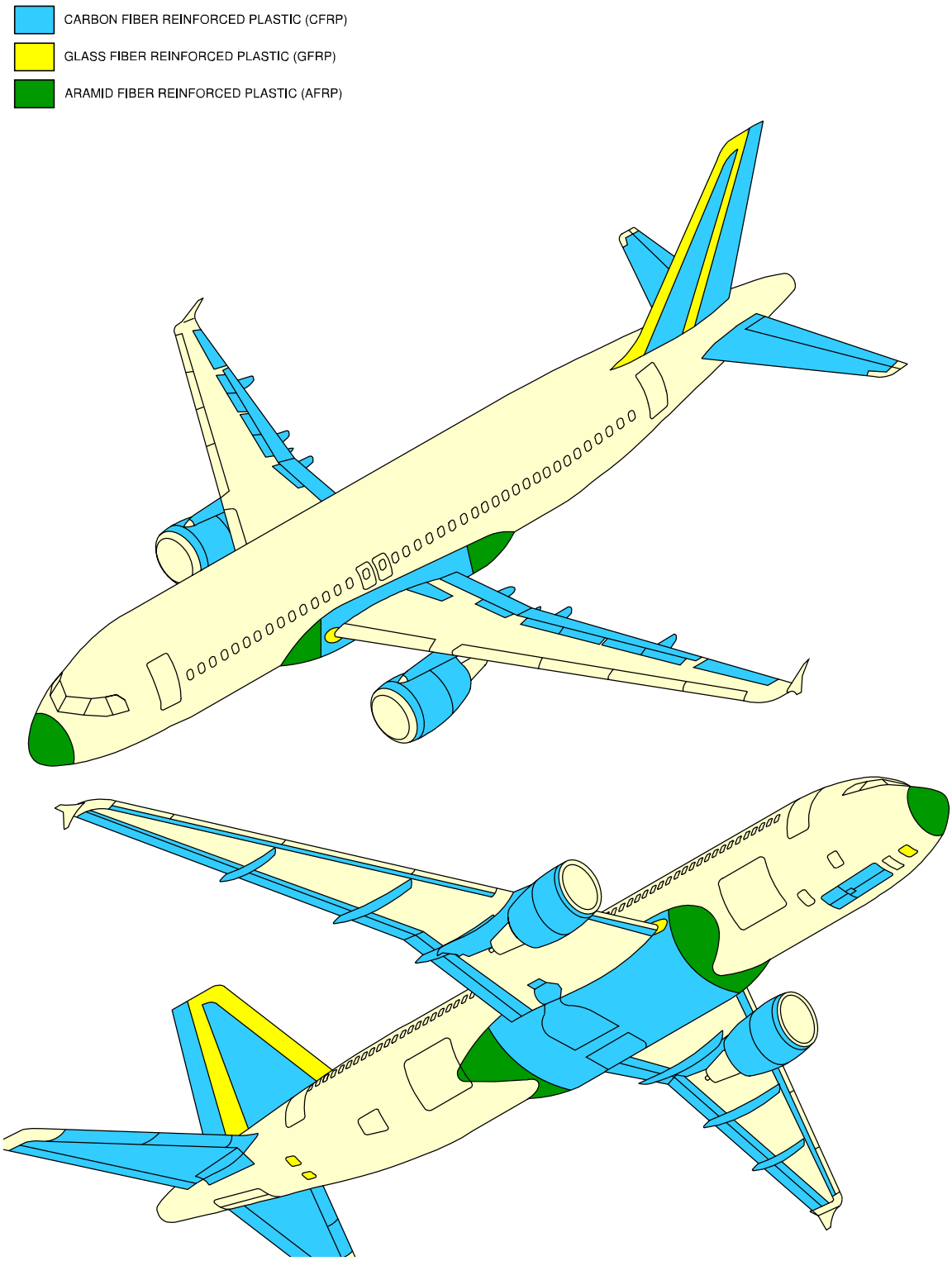


Figure 34 - Location of Composite materials on External Surfaces of A320 **(Airbus, 2005)**

Table 11 - Assumed Quantity of Composite Material per Assembly

A320 Assembly	Proportion of Composite Used (kg)	Total Composite Mass (kg)
Horizontal Stabiliser	99%	1163
Vertical Stabiliser	96%	1128
CFM56-5B (x2)	9%	635
Wings (x2)	8%	1097
Fuselage	7%	823
Main Landing Gear	2%	78
Nose Landing Gear	0%	0

Table 11 establishes the assembly masses that will be used during the LCA analysis with each of the assemblies consisting of sub-assemblies of varying mass and material compositions. Sub-assembly materials were obtained from Figure 34. Of the 75 sub-assemblies, the masses of 60% were precise, representing one third of the total structural mass and obtained directly from the manufacturer (Airbus, 2005). Of the 29 remaining sub-assemblies masses were estimated, however these will only be significant when analysing particular components and will not affect the overall LCA output. Masses for internal assemblies such as seating and galleys were obtained from (Airbus, 2002). Material profiles for CFRP are not currently available in any LCI databases including Ecoinvent. Therefore a custom entry was modeled, data of which was obtained from (Duflou J, 2009) (Suzuki T, 2005).

As previously mentioned the assemblies of the A320 are manufactured at separate locations and transported to the Final Assembly Line (FAL) in Toulouse (Airbus, 2011). Manufacturing locations are split across several European countries, with differing methods of transport used. Assembly lines vary with different structural sections, of which components used within the

sections often come from separate locations. A typical example is that of the wings, which are assembled at the Airbus plant in Broughton, UK. The assembled wing is then transported to the Toulouse FAL using the Beluga transport aircraft. The air transport between the two assembly plants is included in the LCI, measured in kg/km and using Ecoinvent airfreight models and average distances. The sub-assemblies are also considered, an example being the wing boxes, which are transported from Nantes, France by road to Broughton. The transportation of each sub-assembly has been considered from production to final assembly. Table 12 shows the assembly locations for each major structural component and the method used for transport to the FAL. The total estimated transportation used to relocate all assemblies and sub-assemblies to the FAL has been calculated to 1.67E4 tn/km via airfreight and 1.37E4 tn/km via road transport.

Table 12 - Transportation of Major Structural Sections

Assembly	Assembly Location	Transportation to FAL
Wings	Broughton, UK	Beluga Aircraft
Fuselage	Toulouse, France	-
Vertical Stabiliser	Stade, Germany	Beluga Aircraft
Horizontal Stabiliser	Getafe, Spain	Road
Main Landing Gear	Bidos, France	Road
Nose Landing Gear	Bidos, France	Road

A comprehensive breakdown of all the components used in the study including masses, material types and transportation methods can be found in Appendix B.

5.3.5 Operation Stage

The baseline data used for the LCA analysis was an A320 aircraft in one class layout with a maximum of 152 passengers (Airbus, 2011) operating over a 20-year period with an average load factor (LF) of 81.5%. The LF used was the average obtained from all UK registered A320 aircraft utilised during 2010 (CAA, 2010), operating an average distance of 1485 km per flight. LF has a direct impact on fuel consumption per passenger. Thus a measurement of 0.0270 kg/passenger/km was calculated by (Carbon Independant, 2007):

$$Fuel\ Consumption\ (kg/km/pass) = \frac{Fuel\ Consumed\ in\ Average\ Flight\ Distance\ (kg)}{Aircraft\ Max\ Capacity\ (Passengers)\ \times\ LF\ \times\ Average\ Flight\ Distance\ (km)}$$

Equation 2 - Fuel Consumption per passenger km equation

The fuel consumed during flight was obtained from (European Environment Agency, 2007), passenger numbers were obtained by applying the average LF to the maximum passenger capacity.

5.3.6 Decommissioning Stage

The final phase of an aircraft life requires data concerning the re-use, disposal or recycling of all components and sub-assemblies. Data concerning precise disposal scenarios is scarce; however the assumed disposal scenario is detailed below with a more detailed breakdown in Appendix C. Assemblies and components that may be re-used are detailed in (PAMELA, 2008), a joint EU and Manufacturer study into aircraft decommissioning. Although no precise data is given regarding proportions of material recoverable, the study does highlight particular materials and assemblies and the disposal conditions that may apply. Each assembly falls into any number of four categories; Landfill, Incineration, Recycling and Re-use. Table 13 details the assumed disposal scenario per material, referring to the main material constituent in each assembly.

Table 13 - Disposal Scenario per Material

Assembly Material	Disposal Scenario
Aluminium	75% Recycled, 25% Landfill
Titanium	75% Recycled, 25% Landfill
CFRP	50% Landfill, 50% Incineration
Steel	75% Recycled, 25% Landfill
Interior Trim	50% Landfill, 50% Incineration
Rubber (Tyres)	75% Recycled, 25% Landfill

Currently no commercially viable composite recycling activity exists although efforts are ongoing to achieve reasonable recycling rates (Pickering, 2005). Therefore CFRP has been modeled to have no positive disposal impact together with interior trim, which is made up of thermosetting plastics. Aircraft tyres are generally retread dependent on condition, with 75% savings resulting from recycling opposed to production of a new tyre (VRAKKING, 2011).

Dependent on condition, the engines and landing gears should be suitable for reuse so this has been modeled in the study by re-using 75% of the mass and land-filling the remaining 25% (PAMELA, 2008). Figure 35 illustrates the disposal scenario for the entire assembly. The proportion of positive to negative disposal compares favorably to current decommissioning practices resulting in landfill and incineration rates of 40-50% (PAMELA, 2008).

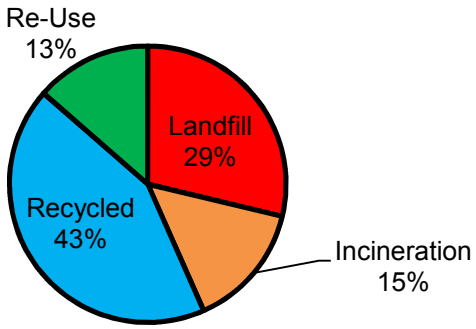


Figure 35 - Assumed Disposal Scenario for A320

5.4 Life Cycle Impact Assessment

This section of the study aims to determine the significance and magnitude of the environmental impact over the life cycle of the Airbus A320. The environmental impact of the individual life cycle phases are first being examined, followed by a complete life cycle impact assessment. Appendix D shows a tree diagram representing the A320 impact assessment.

5.4.1 Manufacturing Phase Emissions

Over a 20-year operational period, the manufacturing phase of the A320 represents only a 0.0889% contribution to the overall environmental impact with the disposal scenario providing a 10% positive return. Manufacturing has been shown to represent a small impact in the overall lifecycle, however this phase is still significant and will be examined in detail. The modeling of the manufacturing phase has been conducted using the Eco-Indicator 99 (H) method, which aggregates each process impact into a single score.

CO_2 will be of particular interest to manufacturers operating within the European Union, due to regulatory obligations under the EU emissions trading system (ETS) (European Commission, 2010). The ETS scheme provides annual ‘carbon credits’ to all emitting companies, with those exceeding their allowance having to purchase additional credits. The overall impact of each assembly over the manufacturing phase is displayed in Figure 36, with the CO_2 emission proportions also displayed.

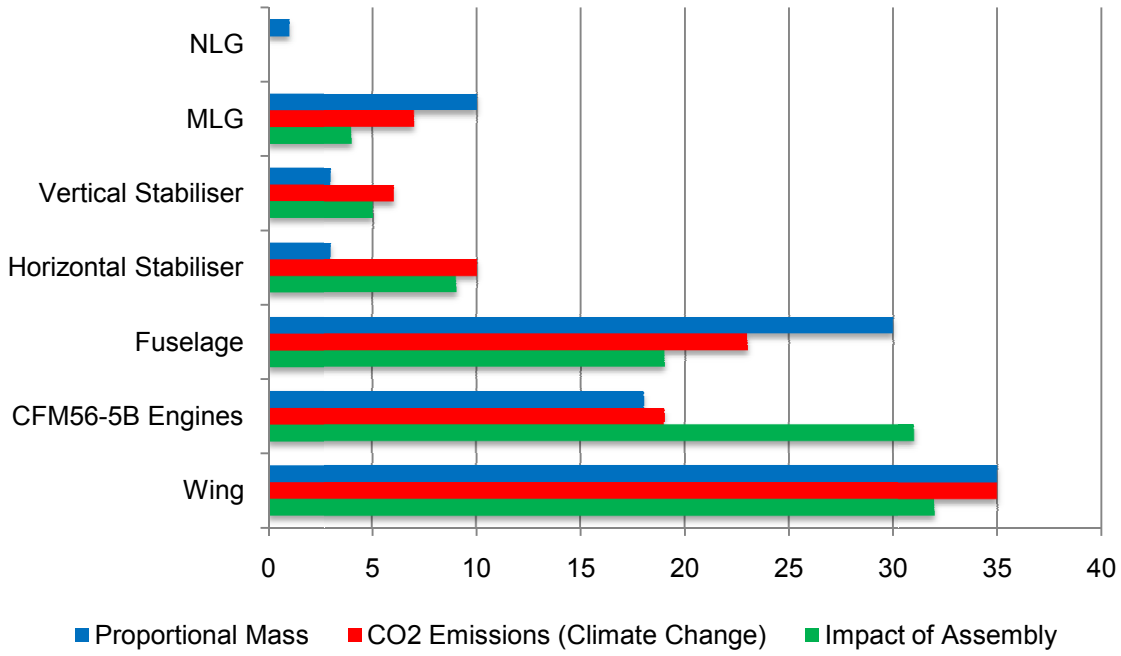


Figure 36 - CO_2 Emitted, Total Impact & Proportional Mass per Assembly

From Figure 36 it can be observed that the wing assembly and engines have the highest environmental impacts and together represent nearly two thirds of the total emission score. The impact compares similarly to the mass of the wing (35% of total mass) with a 32% impact. However, the fuselage although similar in mass to the wing is significantly lower with a 19.3% total impact contribution. The horizontal stabilizer assembly also shows a similar trend to that of the wing. The overriding factor for this increase in environmental impact is the choice of material. The use of CFRP represents almost half of the total process contribution (45.4%) compared to only 18.4% for aluminium alloy, despite aluminium representing nearly 70% of the total material content. Figure 36 shows an interesting trend, assemblies such as the fuselage which are predominately aluminium have a relatively low impact to mass proportion. However assemblies using higher levels of composite material such as the horizontal stabilizer show the opposite trend with the total impact significantly higher than the proportional mass. The impact of the power plant assembly is one of the highest environmental contributors, despite being almost half the mass of the wing assembly. This can again be attributed to the high levels of CFRP, titanium and nickel when compared to aluminium.

To better quantify the overall impact of composite parts in the manufacturing lifecycle all CFRP was replaced with its metallic equivalent which is aluminium. CFRP is predominately used in aircraft manufacturing due to significant weight reductions of more than 25% (Achternbosch, 2011). Therefore the alternative A320 model without CFRP has been modeled as 30% heavier to standardise the results. Figure 37, illustrates the impact of CFRP, when used instead of conventional materials, converting all the LCI data into a single score for each impact factor. The environmental significance of CFRP is highlighted by the vertical and horizontal stabilizer assemblies; both conventionally contain over 90% composite material; however the replacement to aluminium improves the environmental efficiency of both by over 80%.

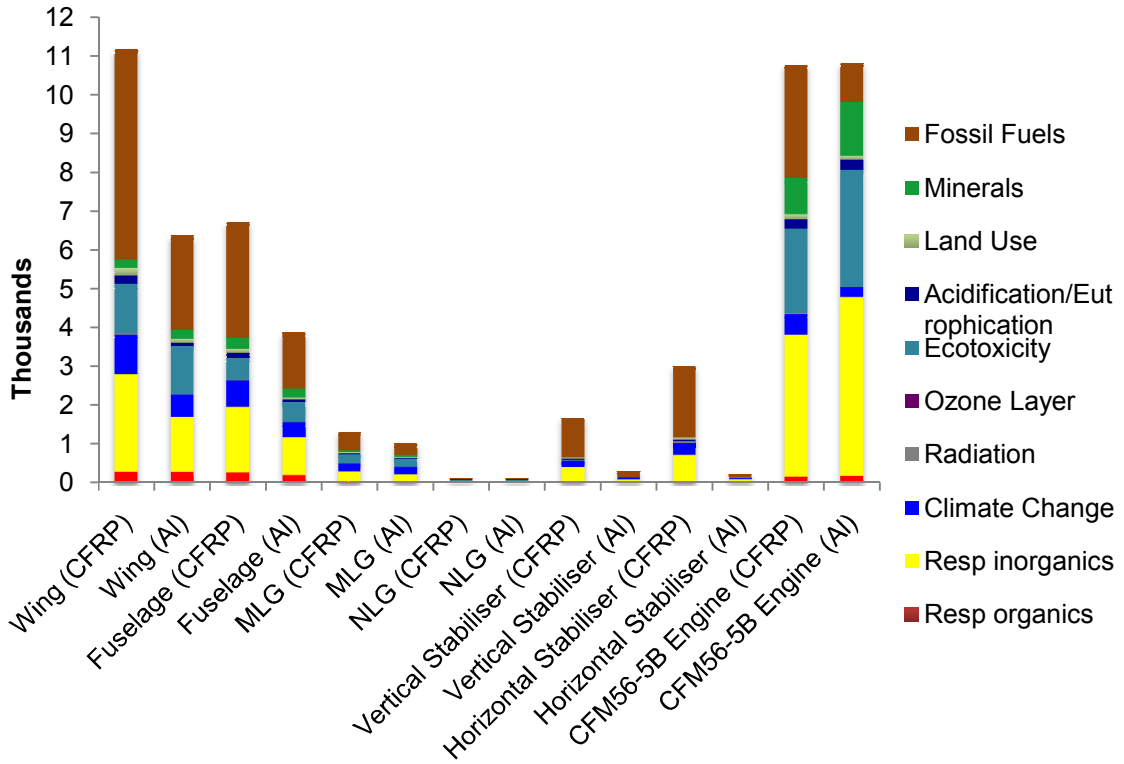


Figure 37 - Comparison between conventional A320 and A320 without CFRP (Weighting, Single Score)

5.4.2 Operation Phase Emissions

The operational phase has the most significance over the A320 life cycle, representing over 99% of the total environmental impact. This is based on the standard A320 with an average 81.5% LF over a 20 year period. However there are several variables that could have a significant impact on this phase; Changing LF, increased or decreased years of operation, reductions in JET A1 fuel consumption as a result of future technological advances or the use of alternative fuels. Changes in LF would be relatively insignificant to the manufacturing contribution over a 20 year life, with even the unlikely reduction to a 50% average LF still only representing an overall 0.15% manufacturing impact contribution over the life cycle. Similarly, reducing the aircraft lifespan to 10 years would still only result in a 0.17% total manufacturing impact contribution.

Fuel consumption reductions are certainly achievable with future advances in technology. If the fuel efficiency was improved by 50% over the 20 year life, the manufacturing contribution to the lifecycle would be increased by 32.6%. Even with this ambitious reduction in fuel, the manufacturing phase would still only represent 0.13% of the lifecycle impact. The LCA analysis of the A320 found that the manufacturing phase in the total aircraft lifecycle when operating with JET A1 represents only 4.4 Million passenger/km, equivalent to only 6.5 days of standard operation.

In recent years, significant research and testing has been carried out by manufacturers and operators into alternatives for JET A1 fuel (Rahmes, 2009), (Timko M. H.-B.-L., 2011). Alternative or biofuels as they are more commonly known, are fuels produced sustainably from a biomass (algae, jatropha) following the concept that the biomass crops will absorb the CO_2 emitted during operation and reduce the overall GHG emissions by 60-85% (Rahmes, 2009). To understand the overall impact on the aircraft lifecycle when using biofuel, the LCA study was processed using a JET-A1 substitute. No current process databases for LCA analysis contain aviation biofuel including Ecoinvent, used in

this study. Therefore a custom fuel entry was created to emulate Jatropha biofuel and estimate an approximate environmental impact of operating with alternative fuels when compared to JET A1. For the 'emissions to air' resulting from biofuel combustion, comparison data from (Stratton, 2010) and (Rahmes, 2009) was used, with the production and biomass growth stage modeled using the database entry for Rape Methyl Ester. Figure 38 shows the results of the analysis, using the standard operating utilisation of 20 years with 81.5% LF, comparing JET A1 and Jatropha Biofuel together with a 50:50 mix of the two.

Figure 38 shows some interesting comparisons between conventional and alternative fuels. Impact factors for climate change and fossil fuel depletion understandably reduce proportionately with JET A1 content, climate change indicating the absorption of CO_2 during biomass growth. However the impact of land use is significantly higher when operating with jatropha together with respiratory inorganics, described in (Tilman, 2009) as the resultant of ammonia produced from nitrogen fertilisers during biomass growth.

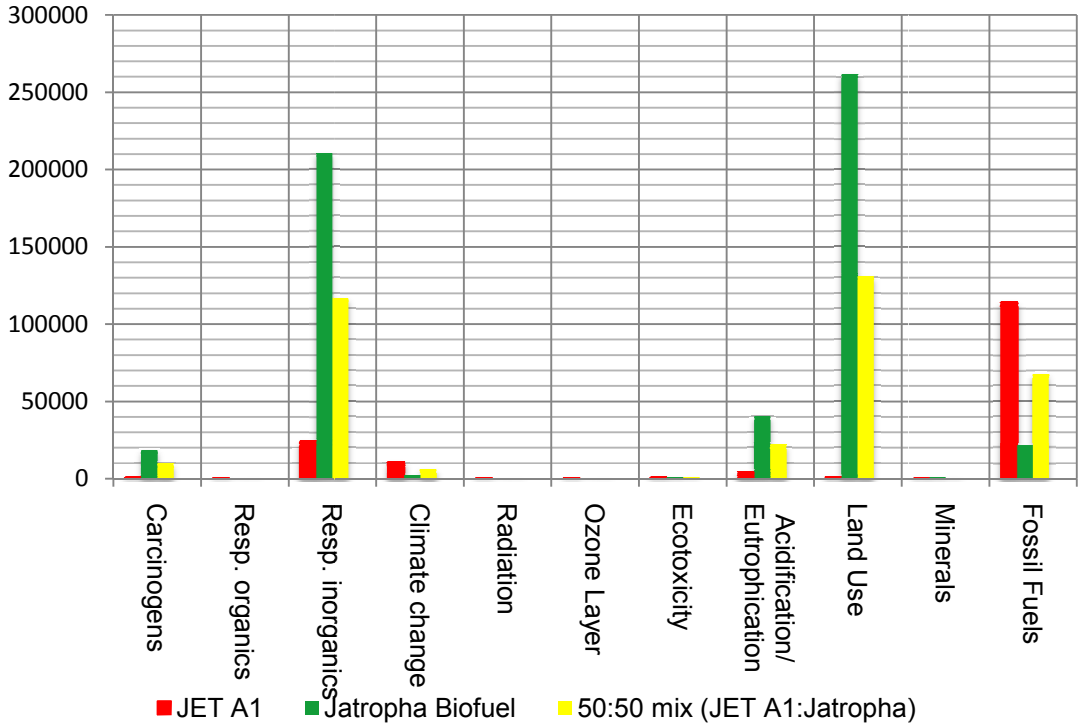


Figure 38 - Estimated Lifecycle Impact Assessment of Biofuel use (Normalisation)

5.4.3 Disposal Phase

Over the 20 year life cycle, the disposal scenario detailed in Table 13 provides only a 9.53 x 10^{-3} return over the lifecycle, approximately 10% of the overall manufacturing phase. The CFM56-5B power plant assembly dominates the emissions return due to the scenario listing them as reusable, which is condition dependent.

5.5 LCIA Results

The life cycle impact assessment (LCIA) consists of a number of key elements; Classification, characterisation, normalisation and weighting. The impact assessment will be conducted using the Eco-Indicator 99 method (PRe Consulants, 2000), which allows the analysis to be outputted in a single score resulting from a series of environmental impacts. The single scores represent a number of damage models (endpoints) including damage to Human Health, Ecosystem Quality or Resources.

The perspective used for this study is Hierarchist (PRe Consulants, 2000) and is used to 'weight' the impact categories. Three different weighting perspectives exist, however hierarchist includes all three endpoints (Goedkoop, 2001). Each of the lifecycle phases have been examined individually, so Figure 39 presents normalised results for the Eco-Indicator categories of the A320 relating to the impact categories. Fossil fuel depletion is the most significant contributor to the overall impact, resulting from the 99% operational impact using JET A1 fuel.

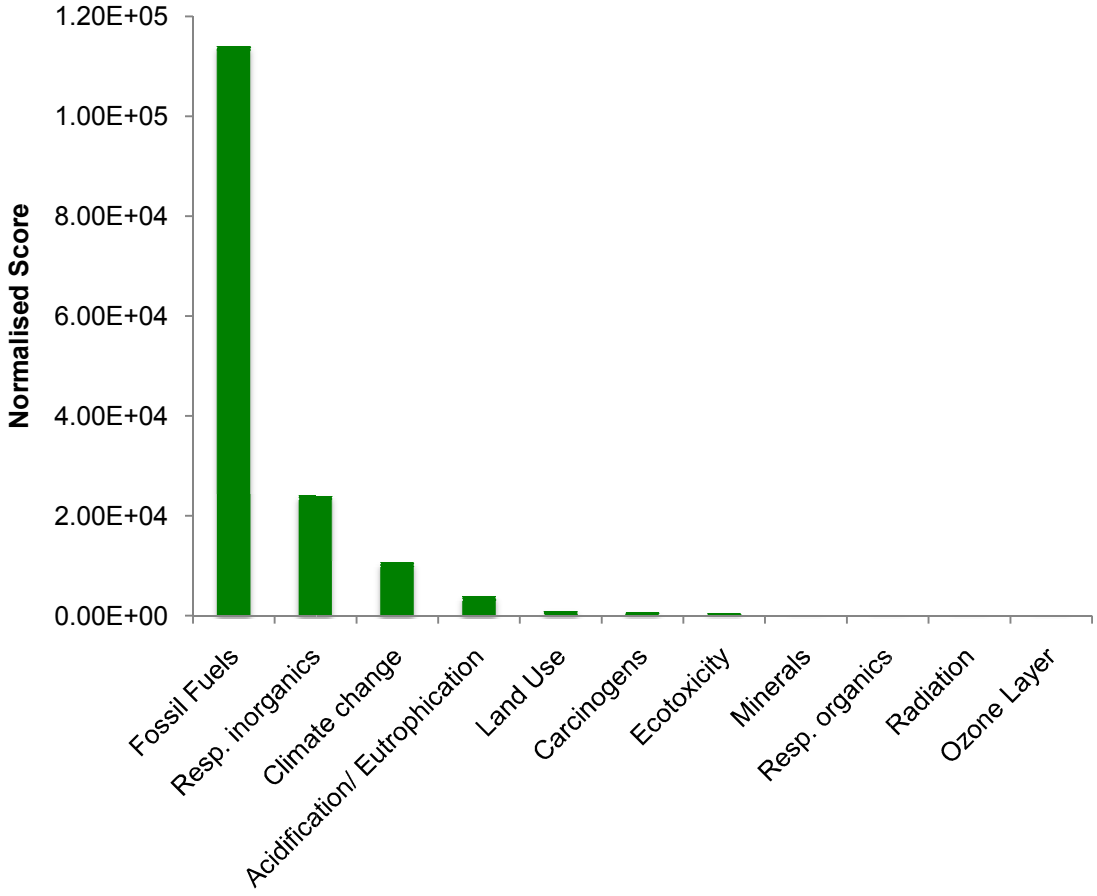


Figure 39 - Normalised results for Eco-Indicator Categories during complete A320 Aircraft Life Cycle

5.6 Chapter Conclusions

This paper has presented a holistic LCA study of an Airbus A320 aircraft over typical lifespan with average utilisation. The study has examined the three main life phases and examined the contribution of each to the overall environmental impact of the aircraft. Using normalisation and weighting of the impact factors associated with Eco-Indicator 99 (H), the following conclusions can be drawn:

- Operation is the highest contributor to the overall environmental impact of the A320 with a 99.9% impact, with kerosene combustion accounting for the majority of emissions. The impact associated with the manufacturing phase is comparable to only 6.5 days of normal (baseline) operation.
- Among the manufacturing phase of the A320, which accounts for under 0.1% of the lifecycle impact, the wing and the engine components contribute for 63% of the impact.
- CFRP material accounts for 10% of the overall material content, however contributes to 45% of the total manufacturing impact. Replacing CFRP for conventional aluminium reduces the manufacturing impact by 47%, however increases the contribution over the operational stage of life due to increased weight. Disposal for complex composite materials such as CFRP is highly impact negative, which remains a main drawback to CFRP use.
- Fuel consumption reductions will significantly reduce CO_2 emissions and fossil fuel depletion, however even a 50% reduction in JET A1 consumption would still only increase the manufacturing phase impact by 0.04%.
- Future use of alternative biofuel could significantly reduce CO_2 emissions and therefore the impact of climate change and fossil fuel depletion, however the impact of land use is shown to be significant when analysed with Eco Indicator 99 and therefore based on this study is shown not to reduce the overall lifecycle contribution.

Although manufacturing is an intensive and significant process, it appears as negligible in the overall lifecycle. Reductions in fuel consumption with traditional fuel types or biofuel operation should be explored in more detail. However, biofuel use should be treated with a degree of caution due to the fact that the land use requirements are currently considered significant and more focus should be placed on new generation alternatives that are not competing for land resources, such as algae based biofuel (Global Bioenergy Partnership, 2009) or SPK synthetic fuels.

Chapter 6

Conclusions & Future Recommendations

6 CONCLUSIONS & FUTURE RECOMMENDATIONS

6.1 SUMMARY AND CONCLUSIONS

6.1.1 Multiple Stage Routing

- Aircraft routing strategies together with improvements in air traffic efficiency are currently the most effective immediate term areas for emission reductions
- The multiple stage routing model detailed in Chapter 3, was found to reduce CO_2 emissions in six of the seven long haul routes analysed when compared to the 'non stop' alternative. Reductions varying from 2% to 13.7% were found to be achievable due to the introduction of short haul aircraft such as the A320 and 737NG for a proportion of the route.
- The proportion of the total distance covered by the 'secondary' short haul aircraft was found to be crucial in achieving optimum emission reductions. The LHR-LAX [1] route for example utilized an A320 aircraft for 42% of the total distance and subsequently resulted in the highest emission reduction of 13.7%.
- All seven routes analysed showed reductions in NO_x emission levels averaging 14.8%. The aircraft type utilized was found to be an important factor in NOx levels, with newer aircraft producing higher levels due to increased temperatures produced from the newer powerplant systems.
- The multiple stage routing model is not suitable for all currently operated long haul routes. The intermediate aircraft is of crucial importance in any potential reductions in emissions. The model was shown to increase the total flight distance over both stages and it is this additional distance that must be kept to a minimum. The LHR-LAX [2] route adds an additional 1228km to the overall journey and results in a CO_2 increase of 2%. It is recommended, based on the routes analysed in the study that any additional distance should be below 1000km.
- It is for this reason that the multiple stage routing model is not suitable for scarcely populated and developed world regions such as Russia and

Africa. Routes operating between North America and Europe are the most applicable, due to the high number of Airports within relatively short distances in both Continents.

- The introduction of EU-ETS phase 3 in 2012 will increase the relevancy of CO_2 emission reductions, with the multiple stage routing model clearly representing theoretical savings in CO_2. The challenges posed by this model are clearly related to journey times and airport congestion. Passengers will generally chose the quickest route if no cheaper alternative exists.
- The multiple stage routing model was found to result in savings of $23 per passenger per flight post EU-ETS commencement due to saved ETS credits and slight reductions in JET A1 fuel consumption.
- The seven routes were also analysed with 50% blended biofuel. Biofuel exemptions from ETS resulting in savings per flight ranging from $10-19 per passenger. The analysis does not include any cost reductions due to reduced fuel consumption, as current biofuel prices are unavailable.
- For the multiple stage routing model to represent economic and environmental sense, financial incentives have to exist for routes following the model. Cost reductions can result from ETS credits and fuel consumption which need to be subsequently passed to the consumer.

6.1.2 Alternative Fuels

- Future growth expected within the aviation industry over the coming decades combined with increasing oil prices and new policy mechanisms is intensifying the need for emission reductions within the industry.
- Alternative fuels represent the best long term solution in meeting the need for emission reductions. The two most promising ‘biofuels’ currently in development are Fischer-Tropsch (SPK) fuel and HRJ fuel.
- Fischer Tropsch fuel can be produced using natural gas, coal and biomass and results in cleaner combusting fuel that is compatible with existing fuel systems. HRJ fuel is similar and is produced from plant oils.

- Although combustion emissions are similar to those found with conventional Jet A1 aviation fuel, life cycle emissions can be significantly reduced particularly when using biomass such as algae or jatropha.

6.1.3 A320 Life Cycle Assessment

- Operation is the highest contributor to the overall environmental impact of the A320 with a 99.9% impact, with kerosene combustion accounting for the majority of emissions. The impact associated with the manufacturing phase is comparable to only 6.5 days of normal (baseline) operation.
- Among the manufacturing phase of the A320, which accounts for under 0.1% of the lifecycle impact, the wing and the engine components contribute for 63% of the impact.
- CFRP material accounts for 10% of the overall material content, however contributes to 45% of the total manufacturing impact. Replacing CFRP for conventional aluminium reduces the manufacturing impact by 47%, however increases the contribution over the operational stage of life due to increased weight. Disposal for complex composite materials such as CFRP is highly impact negative, which remains a main drawback to CFRP use.
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- Future use of alternative biofuel could significantly reduce CO_2 emissions and therefore the impact of climate change and fossil fuel depletion, however the impact of land use is shown to be significant when analysed with Eco Indicator 99 and therefore based on this study is shown not to reduce the overall lifecycle contribution.

6.2 Future Recommendations

In undertaking this thesis, it has become apparent that there are a number of issues that need to be addressed however are beyond the scope of the thesis. A list of possible recommendations in which further research could be conducted is detailed below.

a) The analysis conducted into multiple stage routing has examined 7 routes predominately between North America and Europe. It would be beneficial to expand this analysis to a wider range of destinations in all continents to determine how many traditional long haul routes could be split into multiple stages.
b) Together with theoretical emissions analysis, thought should be given to the economic and wider environmental impact of introducing such a routing model, proposing financial incentives that could be introduced for more efficient routes.
c) It is apparent that a research gap exists into the combustion emissions resulting from biofuel use. Comparing the emissions released during fuel burn would assist in understanding the real time emission savings achievable.
d) The LCA study conducted of the A320 aircraft in this thesis examines the impact of only 95 sub assemblies using mainly approximated data from secondary sources. Expanding the inventory of the LCA study to include components together with the use of more accurate industry data detailing precise mass values and material specifications would significantly improve the accuracy of the study.

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Appendix A

Aircraft Routing Emissions Data

Route emissions data detailed in Appendix A has been obtained from airline websites, airline financial reports, AMEE and EMEP/CORNAIR emissions data. Calculation Results are derived from purpose developed spreadsheets from the author.

A.1.1 LHR - JFK

Route Emissions

Departure Airport	**London Heathrow (LHR)**
Destination Airport	**John F Kennedy, New York (JFK)**

Flight Profile

Great Circle Distance (km)	**6039.76**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0117	2	Boeing 747-400	329
BA0175	1	Boeing 747-400	329
BA0113	1	Boeing 777	229
BA0115	1	Boeing 777	229
BA0179	1	Boeing 747-400	329
BA0183 (Not operated on Saturdays from Nov - Mar)	1	Boeing 747-400	329

Seats Available per Day (Excluding Saturday off peak)	**2103**
Seats Available per Day (Saturday off peak)	**1774**

No of Peak Operating Days per Year	**343**
No of Off-Peak Operating Days per Year	**22**

Number of B747-400 Flights per Year	1803
Number of B777 Flights per Year	730
Number of Flights per Year (+/- 0.5%)	2533

B747-400 Available Seats per Year	593187
B777 Available Seats per Year	167170
Number of Seats Available per year	760357

BA Average Load Factor (Americas) 2010	79.66%
BA Average Load Factor (Americas) 2009	80.23%
BA Average Americas Load Factor	79.95%

Average No of Passengers per Year B747-400		474223
Average No of Passengers per Year B777		133644
	TOTAL	607867

BOEING 747-400

Total Emissions per Flight

LTO Fuel Consumption	3402.2	kg
Cruise Fuel Consumption	61561.5933	kg
TOTAL FUEL USED	**64963.7933**	**kg**
TOTAL CO2	**204857.018**	**kg**
TOTAL NOx	**903.247004**	**kg**
TOTAL CO	**82.5655396**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	6134166.6	kg
Cruise Fuel Consumption	110995553	kg
TOTAL FUEL USED	**117129719**	**kg**
TOTAL CO2	**369357203**	**kg**
TOTAL NOx	**1628554.35**	**kg**
TOTAL CO	**148865.668**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	12.9351847	kg
Cruise Fuel Consumption	234.057546	kg
TOTAL FUEL USED	246.99273	**kg**
TOTAL CO2	778.867607	**kg**
TOTAL NOx	3.43415051	**kg**
TOTAL CO	0.31391468	**kg**

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	44316.423	kg
TOTAL FUEL USED	**46879.223**	**kg**
TOTAL CO2	**147829.319**	**kg**
TOTAL NOx	**740.523155**	**kg**
TOTAL CO	**116.332233**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1870844	kg
Cruise Fuel Consumption	32350988.8	kg
TOTAL FUEL USED	**34221832.8**	**kg**
TOTAL CO2	**107915403**	**kg**
TOTAL NOx	**540581.903**	**kg**
TOTAL CO	**84922.5299**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	13.9987071	kg
Cruise Fuel Consumption	242.068294	kg
TOTAL FUEL USED	256.067001	**kg**
TOTAL CO2	807.483742	**kg**
TOTAL NOx	4.04493785	**kg**
TOTAL CO	0.63543813	**kg**

A.1.2 LHR - ORD

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Chicago O Hare (ORD)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0295	1	Boeing 777	229
BA0297	1	Boeing 777	229

Seats Available per Day (Excluding Saturday off peak)	**458**
Seats Available per Day (Saturday off peak)	-

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	-

Number of B777 Flights per Year	730
Number of Flights per Year (+/- 0.5%)	730

B777 Available Seats per Year	167170
Number of Seats Available per year	167170

BA Average Load Factor (Americas) 2010	79.66%
BA Average Load Factor (Americas) 2009	80.23%
Jet Blue Average Load Factor	79.95%

Average No of Passengers per Year B777		133644
		0
	TOTAL	133644

Flight Profile

Great Circle Distance (km)	**6915.801**

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	51296.6695	kg
TOTAL FUEL USED	**53859.4695**	**kg**
TOTAL CO2	**169840.706**	**kg**
TOTAL NOx	**847.765426**	**kg**
TOTAL CO	**121.054052**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1870844	kg
Cruise Fuel Consumption	37446568.7	kg
TOTAL FUEL USED	**39317412.7**	**kg**
TOTAL CO2	**123983715**	**kg**
TOTAL NOx	**618868.761**	**kg**
TOTAL CO	**88369.4582**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	13.9987071	kg
Cruise Fuel Consumption	280.196289	kg
TOTAL FUEL USED	294.194996	**kg**
TOTAL CO2	927.715894	**kg**
TOTAL NOx	4.63072416	**kg**
TOTAL CO	0.66122999	**kg**

A.1.3 LHR - ATL

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Atlanta International (ATL)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0227	1	Boeing 777	229

Seats Available per Day (Excluding Saturday off peak)	**229**
Seats Available per Day (Saturday off peak)	**0**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	-

Number of B777 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	365

B777 Available Seats per Year	83585
Number of Seats Available per year	83585

BA Average Load Factor (Americas) 2010	79.66%
BA Average Load Factor (Americas) 2009	80.23%
Jet Blue Average Load Factor	79.95%

Average No of Passengers per Year B777	66822
	0
TOTAL	66822

Flight Profile

Great Circle Distance (km)	**7370.941**

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	55036.9117	kg
TOTAL FUEL USED	**57599.7117**	**kg**
TOTAL CO2	**181635.19**	**kg**
TOTAL NOx	**905.326799**	**kg**
TOTAL CO	**123.705581**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	935422	kg
Cruise Fuel Consumption	20088472.8	kg
TOTAL FUEL USED	**21023894.8**	**kg**
TOTAL CO2	**66296844.4**	**kg**
TOTAL NOx	**330444.282**	**kg**
TOTAL CO	**45152.5371**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	13.9987071	kg
Cruise Fuel Consumption	300.626504	kg
TOTAL FUEL USED	314.625211	**kg**
TOTAL CO2	992.140557	**kg**
TOTAL NOx	4.94513996	**kg**
TOTAL CO	0.67571336	**kg**

A.1.4 LHR - DEN

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Denver International (DEN)

Flight Profile

Great Circle Distance (km)	**8172.873**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA219	1	Boeing 777-200	229

Seats Available per Day (Excluding Saturday off peak)	
Seats Available per Day (Saturday off peak)	**229**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B777-200 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	365

B777-200 Available Seats per Year	83585
Number of Seats Available per year	83585

BA Average Load Factor (Americas) 2010	79.66%
BA Average Load Factor (Americas) 2009	80.23%
BA Average Americas Load Factor	79.95%

Average No of Passengers per Year B777-200		66822
		0
	TOTAL	66822

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	61833.1306	kg
TOTAL FUEL USED	**64395.9306**	**kg**
TOTAL CO2	**203066.441**	**kg**
TOTAL NOx	**1021.10569**	**kg**
TOTAL CO	**128.521686**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	935422	kg
Cruise Fuel Consumption	22569092.7	kg
TOTAL FUEL USED	23504514.7	**kg**
TOTAL CO2	74119251	**kg**
TOTAL NOx	372703.577	**kg**
TOTAL CO	46910.4154	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	13.9987071	kg
Cruise Fuel Consumption	337.749291	kg
TOTAL FUEL USED	351.747998	**kg**
TOTAL CO2	1109.20385	**kg**
TOTAL NOx	5.57755559	**kg**
TOTAL CO	0.70202023	**kg**

A.1.5 LHR - LAX

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Los Angeles Int (LAX)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0279	1	Boeing 747-400	329
BA0283	1	Boeing 747-400	329
BA0269	1	Boeing 747-400	329
		Off peak seats	*658*
		Off peak flights	*2*

Seats Available per Day (Excluding Saturday off peak)	**987**
Seats Available per Day (Saturday off peak)	**658**

No of Peak Operating Days per Year	**343**
No of Off-Peak Operating Days per Year	**22**

Number of B747-400 Flights per Year	1073
Number of Flights per Year (+/- 0.5%)	1073

B747-400 Available Seats per Year	353017
Number of Seats Available per year	353017

BA Average Load Factor (Americas) 2010	79.66%
BA Average Load Factor (Americas) 2009	80.23%
Jet Blue Average Load Factor	79.95%

Average No of Passengers per Year B747-400		282219
		0
	TOTAL	282219

Flight Profile

Great Circle Distance (km)	**9550.431**

BOEING 747-400

Total Emissions per Flight

LTO Fuel Consumption	3402.2	kg
Cruise Fuel Consumption	103954.616	kg
TOTAL FUEL USED	**107356.816**	**kg**
TOTAL CO2	**338539.171**	**kg**
TOTAL NOx	**1553.35463**	**kg**
TOTAL CO	**112.463349**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	3650560.6	kg
Cruise Fuel Consumption	111543303	kg
TOTAL FUEL USED	**115193863**	**kg**
TOTAL CO2	**363252530**	**kg**
TOTAL NOx	**1666749.52**	**kg**
TOTAL CO	**120673.174**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	12.9351847	kg
Cruise Fuel Consumption	395.236071	kg
TOTAL FUEL USED	408.171256	**kg**
TOTAL CO2	1287.12795	**kg**
TOTAL NOx	5.9058636	**kg**
TOTAL CO	0.42758633	**kg**

A.1.6 LHR - SIN

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Singapore Changi (SIN)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0011	1	Boeing 747-400	329
BA0015	1	Boeing 747-400	329

Seats Available per Day	**658**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B747-400 Flights per Year	730
Number of Flights per Year (+/- 0.5%)	730

B747-400 Available Seats per Year	240170
Number of Seats Available per year	240170

BA Average Load Factor (Asia Pacific) 2010	82.10%
BA Average Load Factor (Asia Pacific) 2009	84.80%
BA Average Load Factor	83.45%

Average No of Passengers per Year B747-400		200422
		0
	TOTAL	200422

Flight Profile

Great Circle Distance (km)	**11864.5**

BOEING 747-400

Total Emissions per Flight

LTO Fuel Consumption	3402.2	kg
Cruise Fuel Consumption	135400.709	kg
TOTAL FUEL USED	**138802.909**	**kg**
TOTAL CO2	**437701.624**	**kg**
TOTAL NOx	**2086.30115**	**kg**
TOTAL CO	**133.937239**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	2483606	kg
Cruise Fuel Consumption	98842517.6	kg
TOTAL FUEL USED	**101326124**	**kg**
TOTAL CO2	**319522186**	**kg**
TOTAL NOx	**1522999.84**	**kg**
TOTAL CO	**97774.1845**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	12.3918915	kg
Cruise Fuel Consumption	493.172327	kg
TOTAL FUEL USED	505.564219	**kg**
TOTAL CO2	1594.24814	**kg**
TOTAL NOx	7.59897051	**kg**
TOTAL CO	0.48784191	**kg**

A.1.7 LHR - BKK

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Suvarnabhumi Int, Bangkok (BKK)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0009	1	Boeing 747-400	329

Seats Available per Day	**329**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B747-400 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	365

B747-400 Available Seats per Year	120085
Number of Seats Available per year	120085

BA Average Load Factor (Asia Pacific) 2010	82.10%
BA Average Load Factor (Asia Pacific) 2009	84.80%
BA Average Load Factor	83.45%

Average No of Passengers per Year B747-400		100211
		0
	TOTAL	100211

Flight Profile

Great Circle Distance (km)	**10410.648**

BOEING 747-400

Total Emissions per Flight

LTO Fuel Consumption	3402.2	kg
Cruise Fuel Consumption	115211.944	kg
TOTAL FUEL USED	**118614.144**	**kg**
TOTAL CO2	**374038.071**	**kg**
TOTAL NOx	**1712.78494**	**kg**
TOTAL CO	**119.544103**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1241803	kg
Cruise Fuel Consumption	42052359.6	kg
TOTAL FUEL USED	**43294162.6**	**kg**
TOTAL CO2	**136523896**	**kg**
TOTAL NOx	**625166.503**	**kg**
TOTAL CO	**43633.5976**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	12.3918915	kg
Cruise Fuel Consumption	419.638442	kg
TOTAL FUEL USED	432.030334	**kg**
TOTAL CO2	1362.36529	**kg**
TOTAL NOx	6.238506	**kg**
TOTAL CO	0.43541754	**kg**

A.1.8 LHR -DXB

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Dubai International Airport (DXB)

Flight Profile

Great Circle Distance (km)	**5994.403**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0107	1	Boeing 747-400	329
BA0109	1	Boeing 777	229

Seats Available per Day (B747-400)	**329**
Seats Available per Day (B777)	**229**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B747-400 Flights per Year	365
Number of B777 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	730

B747-400 Available Seats per Year	120085
B777 Available Seats per Year	83585
Number of Seats Available per year	203670

BA Average Load Factor (Africa & Middle East) 2010	74.50%
BA Average Load Factor (Africa & Middle East) 2009	75.00%
BA Average Load Factor	74.75%

Average No of Passengers per Year B747-400		89764
Average No of Passengers per Year B777		62480
	TOTAL	152243

BOEING 747-400

Total Emissions per Flight

LTO Fuel Consumption	3402.2	kg
Cruise Fuel Consumption	61056.5238	kg
TOTAL FUEL USED	**64458.7238**	**kg**
TOTAL CO2	**203264.127**	**kg**
TOTAL NOx	**840.632017**	**kg**
TOTAL CO	**82.203606**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1241803	kg
Cruise Fuel Consumption	22285631.2	kg
TOTAL FUEL USED	**23527434.2**	**kg**
TOTAL CO2	**74191406.4**	**kg**
TOTAL NOx	**306830.686**	**kg**
TOTAL CO	**30004.3162**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	13.8341584	kg
Cruise Fuel Consumption	248.27042	kg
TOTAL FUEL USED	262.104579	**kg**
TOTAL CO2	826.520527	**kg**
TOTAL NOx	3.41821072	**kg**
TOTAL CO	0.33425951	**kg**

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	40459.2158	kg
TOTAL FUEL USED	**43022.0158**	**kg**
TOTAL CO2	**146724.584**	**kg**
TOTAL NOx	**731.236591**	**kg**
TOTAL CO	**115.686224**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	935422	kg
Cruise Fuel Consumption	14767613.8	kg
TOTAL FUEL USED	**15703035.8**	**kg**
TOTAL CO2	**53554473.2**	**kg**
TOTAL NOx	**266901.356**	**kg**
TOTAL CO	**42225.4718**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	6.14425624	kg
Cruise Fuel Consumption	97.0000739	kg
TOTAL FUEL USED	251.329853	**kg**
TOTAL CO2	857.148772	**kg**
TOTAL NOx	4.27180319	**kg**
TOTAL CO	0.67582611	**kg**

A.1.9 LHR - BOM

Route Emissions

Departure Airport	London Heathrow (LHR)
Destination Airport	Chhatrapati Shiavaji Int (BOM)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
BA0139	1	Boeing 777	229
BA0199	1	Boeing 777	229

Seats Available per Day (B777)	**458**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B777 Flights per Year	730
Number of Flights per Year (+/- 0.5%)	730

B777 Available Seats per Year	167170
Number of Seats Available per year	167170

BA Average Load Factor (Africa & Middle East) 2010	74.50%
BA Average Load Factor (Africa & Middle East) 2009	75.00%
BA Average Load Factor	74.75%

Average No of Passengers per Year B777		124960
	TOTAL	124960

Flight Profile

Great Circle Distance (km)	**7864.334**

BOEING 777

Total Emissions per Flight

LTO Fuel Consumption	2562.8	kg
Cruise Fuel Consumption	59214.4798	kg
TOTAL FUEL USED	**61777.2798**	**kg**
TOTAL CO2	**194808.773**	**kg**
TOTAL NOx	**943.153178**	**kg**
TOTAL CO	**125.293752**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1870844	kg
Cruise Fuel Consumption	43226570.3	kg
TOTAL FUEL USED	**45097414.3**	**kg**
TOTAL CO2	**142210404**	**kg**
TOTAL NOx	**688501.82**	**kg**
TOTAL CO	**91464.439**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	14.9715938	kg
Cruise Fuel Consumption	345.924434	kg
TOTAL FUEL USED	360.896028	**kg**
TOTAL CO2	1138.05128	**kg**
TOTAL NOx	5.50979643	**kg**
TOTAL CO	0.73195223	**kg**

A.1.10 JFK - ORD

Route Emissions

Departure Airport	John F Kennedy (JFK)
Destination Airport	Chicago O'Hare (ORD)

Flight Profile

Great Circle Distance (km)	**1294.577**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
AA577	1	Boeing 757-200	188

Seats Available per Day (Excluding Saturday off peak)	188
Seats Available per Day (Saturday off peak)	**0**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B757 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	365

B757 Available Seats per Year	68620
Number of Seats Available per year	68620

AA Load Factor Domestic (2010)	82.90%
AA Load Factor Domestic (2009)	82.60%
AA Domestic Average Load Factor	82.75%

Average No of Passengers per Year B757-200	56783
	0
TOTAL	56783

Airbus A320

Total Emissions per Flight

LTO Fuel Consumption	1252.9	kg
Cruise Fuel Consumption	4648.75896	kg
TOTAL FUEL USED	**5901.65896**	**kg**
TOTAL CO2	**20140.798**	**kg**
TOTAL NOx	**77.9739251**	**kg**
TOTAL CO	**20.904969**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	457308.5	kg
Cruise Fuel Consumption	1696797.02	kg
TOTAL FUEL USED	2154105.52	**kg**
TOTAL CO2	7351391.27	**kg**
TOTAL NOx	28460.4827	**kg**
TOTAL CO	7630.31368	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	8.05360931	kg
Cruise Fuel Consumption	29.8821042	kg
TOTAL FUEL USED	37.9357136	**kg**
TOTAL CO2	129.464537	**kg**
TOTAL NOx	0.50121441	**kg**
TOTAL CO	0.13437661	**kg**

A.1.11 LHR - DEN

Route Emissions

Departure Airport	John F Kennedy (JFK)
Destination Airport	Denver International (DEN)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
97	1	Airbus A320	150

Seats Available per Day (Excluding Saturday off peak)	
Seats Available per Day (Saturday off peak)	**150**

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of A320 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	365

A320 Available Seats per Year	54750
Number of Seats Available per year	54750

Jet Blue Average Load Factor (2009)	79.70%
Jet Blue Average Load Factor (2008)	80.40%
Jet Blue Average Load Factor	80.05%

Average No of Passengers per Year B777-200		43827
		0
	TOTAL	43827

Flight Profile

Great Circle Distance (km)	**2845.13**

Airbus A320

Total Emissions per Flight

LTO Fuel Consumption	802.4	kg
Cruise Fuel Consumption	7713.37312	kg
TOTAL FUEL USED	**8515.77312**	**kg**
TOTAL CO2	**26853.68**	**kg**
TOTAL NOx	**111.680192**	**kg**
TOTAL CO	**23.8815306**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	292876	kg
Cruise Fuel Consumption	2815381.19	kg
TOTAL FUEL USED	3108257.19	**kg**
TOTAL CO2	9801593.2	**kg**
TOTAL NOx	40763.2701	**kg**
TOTAL CO	8716.75866	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	6.68249011	kg
Cruise Fuel Consumption	64.2379606	kg
TOTAL FUEL USED	70.9204507	**kg**
TOTAL CO2	223.640891	**kg**
TOTAL NOx	0.93008696	**kg**
TOTAL CO	0.19888845	**kg**

A.1.12 JFK - LAX

Route Emissions

Departure Airport	John F Kennedy (JFK)
Destination Airport	Los Angeles (LAX)

Flight Profile

Great Circle Distance (km)	**4333.3**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
671	1	Airbus A320	150
675	1	Airbus A320	150
677	1	Airbus A320	150

Seats Available per Day (Excluding Saturday off peak)	450
Seats Available per Day (Saturday off peak)	**300**

No of Peak Operating Days per Year	**313**
No of Off-Peak Operating Days per Year	**52**

Number of A320 Flights per Year	1043
Number of Flights per Year (+/- 0.5%)	1043

A320 Available Seats per Year	156450
Number of Seats Available per year	156450

Jet Blue Average Load Factor (2009)	79.70%
Jet Blue Average Load Factor (2008)	80.40%
Jet Blue Average Load Factor	80.05%

Average No of Passengers per Year B777-200	125238
	0
TOTAL	125238

Airbus A320

Total Emissions per Flight

LTO Fuel Consumption	802.4	kg
Cruise Fuel Consumption	11813.7568	kg
TOTAL FUEL USED	**12616.1568**	**kg**
TOTAL CO2	**39783.844**	**kg**
TOTAL NOx	**160.64732**	**kg**
TOTAL CO	**26.5862083**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	836903.2	kg
Cruise Fuel Consumption	12321748.3	kg
TOTAL FUEL USED	13158651.5	**kg**
TOTAL CO2	41494549.3	**kg**
TOTAL NOx	167555.154	**kg**
TOTAL CO	27729.4152	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	6.68249011	kg
Cruise Fuel Consumption	98.3864816	kg
TOTAL FUEL USED	105.068972	**kg**
TOTAL CO2	331.324955	**kg**
TOTAL NOx	1.33789148	**kg**
TOTAL CO	0.22141335	**kg**

A.1.13 ATL - LAX

Route Emissions

Departure Airport	Atlanta (ATL)
Destination Airport	Los Angeles (LAX)

Flight Profile

Great Circle Distance (km)	**3408.0432**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
51	1	Boeing 737-700	137
53	1	Boeing 737-700	137
55	1	Boeing 737-700	137
61	1	Boeing 737-700	137

Seats Available per Day (Excluding Saturday off peak)	548
Seats Available per Day (Saturday off peak)	

No of Peak Operating Days per Year	**365**
No of Off-Peak Operating Days per Year	

Number of B737 Flights per Year	1460
Number of Flights per Year (+/- 0.5%)	1460

B737 Available Seats per Year	200020
Number of Seats Available per year	200020

Air Tran Average Load Factor (2010)	81.40%
Air Tran Average Load Factor (2009)	79.80%
Air Tran Average Load Factor	80.60%

Average No of Passengers per Year B737		161216
		0
	TOTAL	161216

Boeing 737

Total Emissions per Flight

LTO Fuel Consumption	825.3	kg
Cruise Fuel Consumption	10389.8246	kg
TOTAL FUEL USED	**11215.1246**	**kg**
TOTAL CO2	**35365.819**	**kg**
TOTAL NOx	**105.435555**	**kg**
TOTAL CO	**25.4265426**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	1204938	kg
Cruise Fuel Consumption	15169143.9	kg
TOTAL FUEL USED	16374081.9	**kg**
TOTAL CO2	51634095.7	**kg**
TOTAL NOx	153935.911	**kg**
TOTAL CO	37122.7521	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	7.47405408	kg
Cruise Fuel Consumption	94.0919797	kg
TOTAL FUEL USED	101.566034	**kg**
TOTAL CO2	320.27874	**kg**
TOTAL NOx	0.95484193	**kg**
TOTAL CO	0.230267	**kg**

A.1.14 ORD - LAX

Route Emissions

Departure Airport	Chicago O'Hare (ORD)
Destination Airport	Los Angeles (LAX)

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
1247	1	Boeing 737-800	160
1165	1	Boeing 737-800	160
1217	1	Boeing 737-800	160
2099	1	Boeing 737-800	160
557	1	Boeing 737-800	160
889	1	Boeing 757	188
699	1	Boeing 737-800	160
607	1	Boeing 737-800	160
455	1	Boeing 767	225

Seats Available per Day	1533
No of Peak Operating Days per Year	**365**
Number of B737-800 Flights per Year	2555
Number of B757 Flights per Year	365
Number of B767 Flights per Year	365
Number of Flights per Year (+/- 0.5%)	3285
B737-800 Available Seats per Year	408800
B757 Available Seats per Year	68620
B767 Available Seats per Year	82125
Number of Seats Available per year	559545
AA Load Factor Domestic (2010)	82.90%
AA Load Factor Domestic (2009)	82.60%
AA Average Load Factor	82.75%
Average No of Passengers per Year B737-800	338282
Average No of Passengers per Year B757	56783.05
Average No of Passengers per Year B767	67958
TOTAL	463023

Flight Profile

Great Circle Distance (km)	**3055.939**

Boeing 737

Total Emissions per Flight

LTO Fuel Consumption	825.3	kg
Cruise Fuel Consumption	9256.71916	kg
TOTAL FUEL USED	**10082.0192**	**kg**
TOTAL CO2	**31792.675**	**kg**
TOTAL NOx	**94.7424413**	**kg**
TOTAL CO	**24.2370875**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	2108641.5	kg
Cruise Fuel Consumption	23650917.5	kg
TOTAL FUEL USED	25759559	**kg**
TOTAL CO2	81230284.6	**kg**
TOTAL NOx	242066.938	**kg**
TOTAL CO	61925.7585	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	6.23338369	kg
Cruise Fuel Consumption	69.9147973	kg
TOTAL FUEL USED	76.148181	**kg**
TOTAL CO2	240.125944	**kg**
TOTAL NOx	0.71557735	**kg**
TOTAL CO	0.18305957	**kg**

BOEING 767-400

Total Emissions per Flight

LTO Fuel Consumption	1617.1	kg
Cruise Fuel Consumption	15195.5921	kg
TOTAL FUEL USED	**16812.6921**	**kg**
TOTAL CO2	**53016.899**	**kg**
TOTAL NOx	**231.039638**	**kg**
TOTAL CO	**25.6223699**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	590241.5	kg
Cruise Fuel Consumption	5546391.13	kg
TOTAL FUEL USED	**6136632.63**	**kg**
TOTAL CO2	**19351168.1**	**kg**
TOTAL NOx	**84329.4678**	**kg**
TOTAL CO	**9352.16501**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	8.68533065	kg
Cruise Fuel Consumption	81.6144593	kg
TOTAL FUEL USED	90.2997899	**kg**
TOTAL CO2	284.750045	**kg**
TOTAL NOx	1.24089768	**kg**
TOTAL CO	0.13761595	**kg**

BOEING 757

Total Emissions per Flight

LTO Fuel Consumption	1252.5	kg
Cruise Fuel Consumption	11661.6627	kg
TOTAL FUEL USED	**12914.1627**	**kg**
TOTAL CO2	**40724.842**	**kg**
TOTAL NOx	**184.967129**	**kg**
TOTAL CO	**28.812548**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	457162.5	kg
Cruise Fuel Consumption	4256506.88	kg
TOTAL FUEL USED	**4713669.38**	**kg**
TOTAL CO2	**14864567.3**	**kg**
TOTAL NOx	**67513.0019**	**kg**
TOTAL CO	**10516.58**	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	8.05103812	kg
Cruise Fuel Consumption	74.9608708	kg
TOTAL FUEL USED	83.011909	**kg**
TOTAL CO2	261.778248	**kg**
TOTAL NOx	1.18896399	**kg**
TOTAL CO	0.18520633	**kg**

A.1.15 BKK - SIN

Route Emissions

Departure Airport	Suvarnabhumi Int, Bangkok (BKK)
Destination Airport	Singapore Changi (SIN)

Flight Profile

Great Circle Distance (km)	**1574.573**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
FD3501	1	Airbus A320	180
FD3503	1	Airbus A320	180
FD3505	1	Airbus A320	180

Seats Available per Day	**540**

No of Peak Operating Days per Year	**365**

Number of A320 Flights per Year	1095
Number of Flights per Year (+/- 0.5%)	1095

A320 Available Seats per Year	197100
Number of Seats Available per year	197100

Air Asia Average Load Factor (2009)	78.00%
Air Asia Average Load Factor (2008)	75.00%
Air Asia Average Load Factor	76.50%

Average No of Passengers per Year A320	150782
	0
TOTAL	150782

Airbus A320

Total Emissions per Flight

LTO Fuel Consumption	802.4	kg
Cruise Fuel Consumption	4432.62824	kg
TOTAL FUEL USED	**5235.02824**	**kg**
TOTAL CO2	**16508.161**	**kg**
TOTAL NOx	**73.6203026**	**kg**
TOTAL CO	**21.6119721**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	878628	kg
Cruise Fuel Consumption	4853727.93	kg
TOTAL FUEL USED	5732355.93	**kg**
TOTAL CO2	18076436.3	**kg**
TOTAL NOx	80614.2314	**kg**
TOTAL CO	23665.1094	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	5.82716049	kg
Cruise Fuel Consumption	32.1904738	kg
TOTAL FUEL USED	38.0176343	**kg**
TOTAL CO2	119.884975	**kg**
TOTAL NOx	0.53464272	**kg**
TOTAL CO	0.15694969	**kg**

A.1.16 DXB - BOM

Route Emissions

Departure Airport	Dubai International (DXB)
Destination Airport	Chhatrapati Shiavaji Int (BOM)

Flight Profile

Great Circle Distance (km)	**2100.624**

Daily Flight Schedule

Flight No	FPD	Aircraft Type	Seats Available
9W541	1	Boeing 737 NG	140
9W543	1	Boeing 737 NG	140

Seats Available per Day	**280**

No of Peak Operating Days per Year	**365**

Number of B737 NG Flights per Year	730
Number of Flights per Year (+/- 0.5%)	730

B737 NG Available Seats per Year	102200
Number of Seats Available per year	102200

Jet Airways Average Load Factor (International) 2010	80.10%
Jet Airways Average Load Factor	80.10%

Average No of Passengers per Year B737 NG	81862
	0
TOTAL	81862

Airbus A320

Total Emissions per Flight

LTO Fuel Consumption	825.4	kg
Cruise Fuel Consumption	6251.80039	kg
TOTAL FUEL USED	**7077.20039**	**kg**
TOTAL CO2	**22316.96**	**kg**
TOTAL NOx	**67.212783**	**kg**
TOTAL CO	**21.1556832**	**kg**

TOTAL Emissions Over Year

LTO Fuel Consumption	602542	kg
Cruise Fuel Consumption	4563814.28	kg
TOTAL FUEL USED	5166356.28	**kg**
TOTAL CO2	16291380.8	**kg**
TOTAL NOx	49065.3316	**kg**
TOTAL CO	15443.6487	**kg**

AVERAGE Emissions per Passenger

LTO Fuel Consumption	7.3604423	kg
Cruise Fuel Consumption	55.7499589	kg
TOTAL FUEL USED	63.1104012	**kg**
TOTAL CO2	199.009809	**kg**
TOTAL NOx	0.59936493	**kg**
TOTAL CO	0.18865421	**kg**

Appendix B

LCA Inventory Data

Sources Used for Inventory Data

- Components – Airbus Aircraft Maintenance Manual (AMM)
- Material/Material Type – Airbus AMM
- Production Location – http://www.airbus.com
- Transportation – http://www.airbus.com
- Mass Values – Airbus Weight & Balance Manual + Estimation

B.1 Wing Inventory A320

Component/System	Material	Material Type	Manufactuer	Production Location	Stage 1 Transportation		Miles	Final Transportation	Final Transport Method	Miles	Per Wing (kg)	Both Wings (kg)	*% of wing*
Slat 1	Aluminium Alloy	7010-T7651	Airbus	Bremen, Germany	Broughton,UK	Sea	578	Toulouse, France	Beluga (Manchester)	600	39	**78**	*0.57*
Slat 2	Aluminium Alloy	7010-T7651	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		30	**60**	*0.44*
Slat 3	Aluminium Alloy	7010-T7651	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		28	**56**	*0.41*
Slat 4	Aluminium Alloy	7010-T7651	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		25	**50**	*0.37*
Slat 5	Aluminium Alloy	7010-T7651	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		23	**46**	*0.34*
Inner Flap	CFRP	CFRP	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		114	**228**	*1.66*
Outer Flap	CFRP	CFRP	Airbus	Bremen, Germany	Broughton,UK	Sea		Toulouse, France	Beluga (Manchester)		122	**244**	*1.78*
Spoiler 1	CFRP	CFRP	Airbus	Filton, UK	Broughton,UK	Road	180	Toulouse, France	Beluga (Manchester)		15	**30**	*0.22*
Spoiler 2	CFRP	CFRP	Airbus	Filton, UK	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		13	**26**	*0.19*
Spoiler 3	CFRP	CFRP	Airbus	Filton, UK	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		12	**24**	*0.18*
Spoiler 4	CFRP	CFRP	Airbus	Filton, UK	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		12	**24**	*0.18*
Spoiler 5	CFRP	CFRP	Airbus	Filton, UK	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		14	**28**	*0.20*
Aileron	CFRP	CFRP	Saab Aerostructures	Linköping, Sweden	Broughton,UK	Sea	800	Toulouse, France	Beluga (Manchester)		24	**48**	*0.35*
Wing Tip & Winglet	CFRP	CFRP	RUAG Aerospace	Emnen, Switzerland	Broughton,UK	Road	650	Toulouse, France	Beluga (Manchester)		26	**52**	*0.38*
Landing Gear Leg Fairing	CFRP	CFRP	Messier Dowty	Bidos, France	Toulouse, UK	Road	145	N/A	N/A		15.4	**30.8**	*0.22*
Front & Rear Spars	Aluminium Alloy	7010-T7651	Airbus	Filton, UK	Broughton,UK	Road	180	Toulouse, France	Beluga (Manchester)		2000	**4000**	*29.21*
Wing Skin	Aluminium Alloy	7075-T6	Airbus	Puerto Real, Spain	Broughton,UK	Road	1160	Toulouse, France	Beluga (Manchester)		1000	**2000**	*14.60*
Ribs	Aluminium Alloy	7010-T7651	Airbus	Filton, UK	Broughton,UK	Road	180	Toulouse, France	Beluga (Manchester)		1000	**2000**	*14.60*
Flap Track Fairings	CFRP	CFRP	Airbus	Bremen, Germany	Broughton,UK	Sea	578	Toulouse, France	Beluga (Manchester)		100	**200**	*1.46*
Outer Wing Box	Aluminium Alloy	7010-T7651	Airbus	Nantes, France	Broughton,UK	Road	560	Toulouse, France	Beluga (Manchester)		600	**1200**	*8.76*
	Titanium	Titanium Zinc Plate	Airbus	Nantes, France	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		300	**600**	*4.38*
	Steel	Reinforced Steel	Airbus	Nantes, France	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		100	**200**	*1.46*
Inner Wing Box	Aluminium Alloy	7010-T7651	Airbus	Nantes, France	Broughton,UK	Road	560	Toulouse, France	Beluga (Manchester)		600	**1200**	*8.76*
	Titanium	Titanium Zinc Plate	Airbus	Nantes, France	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		300	**600**	*4.38*
	Steel	Reinforced Steel	Airbus	Nantes, France	Broughton,UK	Road		Toulouse, France	Beluga (Manchester)		100	**200**	*1.46*
Exterior Finish	Paint		N/A	Toulouse, France	N/A	N/A	N/A	N/A	N/A	N/A	50	**100**	*0.73*
Primer & Sealant			N/A	Toulouse, France	N/A	N/A	N/A	N/A	N/A	N/A	15	**30**	*0.22*
ADDITIONAL COMPS	Aluminium Alloy	7010-T7651	Airbus	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	**100**	*0.73*
ADDITIONAL COMPS	Steel	Reinforced Steel	Airbus	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	**100**	*0.73*
ADDITIONAL COMPS	CFRP	CFRP	Airbus	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	**100**	*0.73*
ADDITIONAL COMPS	Titanium Alloy	Titanium Zinc Plate	Airbus	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20	**40**	*0.29*

Total Mass	**13694.8**	kg

Material	Total Mass	% of Structure
Aluminium	10790	78.79
Steel	540	3.94
Titanium	1200	8.76
CFRP	1034.8	7.56
Other	130	0.95
Estimated Transportation		
	Miles	
Sea	1956	
Road	3615	
Air (Beluga)	600	

B.2 Fuselage Section Inventory A320

Component/System	Material	Manufacturer	Production Location	Transportation	Destination	Miles	Weight (kg)	% of Fuselage
ADDITIONAL COMPS	Titanium	Airbus	N/A	N/A	N/A		**300**	2.80
Aft Cargo Door	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France		**121**	1.13
Aft Passenger/Crew Door	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France		**96**	0.90
APU	N/A	N/A	N/A	N/A	N/A		**136**	1.27
Belly Fairing	CFRP	Airbus	Puerto Real, Spain	Road	Toulouse, France	850	**75**	0.70
Bulk Cargo Door	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France		**37**	0.35
Cabin Floor Beams	GFRP	Airbus	Toulouse, France		Toulouse, France		**800**	7.47
Emergency Exits	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France		**30**	0.28
Flap & Slat Control Units	Steel	Airbus	Stade, Germany	Road	Toulouse, France	960	**100**	0.93
Forward Cargo Door	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France		**121**	1.13
Forward Passenger/Crew Door	Aluminium Alloy	Airbus	Puerto Real, Spain	Road	Toulouse, France	850	**98**	0.91
Frames	Aluminium Alloy	Airbus	Nantes, France	Air (Beluga)	Toulouse, France	250	**3000**	28.00
Horizontal Stabiliser Acuator	Steel	Airbus	Getafe, Spain	Road	Toulouse, France	500	**100**	0.93
Main LDG Doors	CFRP	Airbus	Puerto Real, Spain	Road	Toulouse, France	850	**300**	2.80
Nose LDG Doors	CFRP	Airbus	Puerto Real, Spain	Road	Toulouse, France		**50**	0.47
Pressure Bulkheads	Aluminium Alloy	Airbus	Toulouse, France		Toulouse, France		**1000**	9.33
Radome	AFRP	Airbus	Nantes, France	Air (Beluga)	Toulouse, France	250	**26**	0.24
Skin	Aluminium Alloy	Airbus	Nantes, France	Air (Beluga)	Toulouse, France		**2000**	18.67
Stringers	Aluminium Alloy	Airbus	Nantes, France	Air (Beluga)	Toulouse, France		**2000**	18.67
Tailcone	Aluminium Alloy	RUAG Aerospace	Oberpfallenhofen, Germany	Air (Beluga)	Toulouse, France	250	**324**	3.02

Total Mass	**10714**	kg

Material	Total Mass	% of Structure
Aluminium	4064	37.93
Steel	4000	37.33
GFRP	100	0.93
CFRP	1326	12.38
AFRP	800	7.47
Titanium	324	3.02

Estimated Transportation	
Road	850
Air (Beluga)	0

B.3 Horizontal & Vertical Stabiliser Inventory Data

Vertical Stabiliser

Component/System	Material	Manufacturer	Production Location	Transportation	Destination	Miles		Weight (kg)	% of Vertical Stabiliser
Box	CFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France	800		**185**	32.40
Box	GFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**180**	31.52
Rudder	CFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**88**	15.41
Removable Leading Edge	GFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**48**	8.41
Tip	CFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**9**	1.58
Dorsal Fin	CFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**26**	4.55
Fuselage Fairing	GFRP	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**15**	2.63
ADDITIONAL COMPS	Aluminium Alloy	Airbus	Stade, Germany	Air (Beluga)	Toulouse, France			**20**	3.50

Total Mass	**571**	kg

Material	Total Mass	% of Structure
CFRP	308	53.94
GFRP	243	42.56
Aluminium Alloy	20	3.50

Horizontal Stabiliser

Component/System	Material	Manufacturer	Production Location	Transportation	Destination	Miles		Weight (kg)	% of Horizontal Stabiliser
Box	CFRP	Airbus	Getafe, Spain	Road	Toulouse, France	500		418	68.30
Elevator	CFRP	Airbus	Getafe, Spain	Road	Toulouse, France			97	15.85
Removable Leading Edge	CFRP	Airbus	Getafe, Spain	Road	Toulouse, France			84	13.73
Tip	Aluminium Alloy	Airbus	Getafe, Spain	Road	Toulouse, France			6	0.98
Tailplane Fuselage Fairing	GFRP	Airbus	Getafe, Spain	Road	Toulouse, France			7	1.14

Total Mass	**612**	kg

Material	Total Mass	% of Structure
CFRP	599	97.88
GFRP	7	1.14
Aluminium Alloy	6	0.98
Estimate Transportation		
Road	500	
Air (Beluga)	800	

B.4 Main & Nose Landing Gear Inventory

Main Landing Gear

Component/System	Material	Manufacturer	Production Location	Transportation	Miles	Weight (kg)	% of MLG
MLG Complete Twin	Steel	Messier Dowty	Bidos, France	Road	145	**1682**	57.80
	Aluminium Alloy	Messier Dowty	Bidos, France	Road		**90**	3.09
	Titanium	Messier Dowty	Bidos, France	Road		**90**	3.09
MLG Leg Fairing	CFRP	Messier Dowty	Bidos, France	Road		**32**	1.10
Wheel with Tyre and Brake (4 of)	Steel	Messier Dowty	Bidos, France	Road		**736**	25.29
	Aluminium Alloy	Messier Dowty	Bidos, France	Road		**40**	1.37
	Titanium	Messier Dowty	Bidos, France	Road		**40**	1.37
	Rubber	Messier Dowty	Bidos, France	Road			
Downlock Actuator	Steel	Messier Dowty	Bidos, France	Road		**100**	3.44
MLG Locking Stay	Titanium	Messier Dowty	Bidos, France	Road		**100**	3.44

Total Mass	**2910**	kg

Material	Total Mass	% of Structure
Steel	2518	86.53
Aluminium Alloy	130	4.47
Titanium	230	7.90
CFRP	32	1.10

Nose Landing Gear

Component/System	Material	Manufacturer	Production Location	Transportation	Miles	Weight (kg)	% of NLG
NLG Complete	Steel	Messier Dowty	Bidos, France	Road	145	**263**	50.10
	Aluminium Alloy	Messier Dowty	Bidos, France	Road		**30**	5.71
	Titanium Alloy	Messier Dowty	Bidos, France	Road		**30**	5.71
Wheel with Tyre x2	Steel	Messier Dowty	Bidos, France	Road		**58**	11.05
	Aluminium Alloy	Messier Dowty	Bidos, France	Road		**7**	1.33
	Titanium Alloy	Messier Dowty	Bidos, France	Road		**7**	1.33
Retraction Actuator	Steel	Messier Dowty	Bidos, France	Road		**20**	3.81
Steering Actuator	Steel	Messier Dowty	Bidos, France	Road		**10**	1.90
Shock Absorber	Steel	Messier Dowty	Bidos, France	Road		**80**	15.24
	Aluminium Alloy	Messier Dowty	Bidos, France	Road		**10**	1.90
	Titanium Alloy	Messier Dowty	Bidos, France	Road		**10**	1.90

Total Mass	**525**	kg

Material	Total Mass	% of Structure
Steel	431	82.10
Aluminium Alloy	47	8.95
Titanium Alloy	47	8.95
Estimated Transportation		
Road	290	

B.5 CFM56-5B Engine & Power Plant Accessories Inventory

CFM56-5B Engine

Component/System	Material		Weight per Engine (kg)	Total Weight (kg)
CFM56-5B				
	Iron Nickel Chromium Alloy		550	**1100**
	Steel		200	**400**
	Aluminium Alloy		500	**1000**
	Nickel		700	**1400**
	Titanium Alloy		828	**1656**
		SUB TOTAL	**2778**	**5556**

Power Plant Accessories

Component/System	Material		Weight per Engine (kg)	Total Weight (kg)
Inlet Cowl	CFRP		69	**138**
	Titanium Alloy		69	**138**
Fan Cowl (LH)	CFRP		18.5	**37**
	Titanium Alloy		18.5	**37**
Fan Cowl (RH)	CFRP		21	**42**
	Titanium Alloy		21	**42**
Thurst Reverser LH	CFRP		96.5	**193**
	Titanium Alloy		96.5	**193**
Thrust Reverser RH	CFRP		106	**212**
	Titanium Alloy		106	**212**
Pylon	Steel		493	**986**
	CFRP		50	**100**
	GFRP		50	**100**
Pylon Fairings	CFRP		10	**20**
		SUB TOTAL	**1225**	**2450**
		TOTAL	**4003**	**8006**

Material	Total Mass (kg)	% of Structure
Iron Nickel Chr Alloy	550	**1100**
Steel	693	**1386**
Aluminium Alloy	500	**1000**
Nickel	700	**1400**
Titanium Alloy	1139	**2278**
CFRP	371	**742**
GFRP	50	**100**

Appendix C

Estimated Disposal Scenario for A320

Aircraft Section	Component	Quantity	Total Quantity per A320	Material Composition of Component					Total Mass	Disposal Proportions				Total Disposal Masses per Component				
				Aluminium	CFRP	STEEL	TIT	NICKEL		Landfill	Incineration	Recycle	Re-use	LANDFILL	INCINERATION	RECYCLE	REUSE	TOTAL (kg)
Engine	Fan Cowl LH	1	2		37		37		74	50	50			37	37	0	0	74
Engine	Fan Cowl RH	1	2		42		42		84	50	50			42	42	0	0	84
Engine	Powerplant	1	2	2000		600	1062	1100	4762	25			75	1190.5	0	0	3571.5	4762
Engine	Pylon	1	2		100	986			1186	25		75		296.5	0	889.5	0	1186
Engine	Pylon Fairings	1	2		20				20	50	50			10	10	0	0	20
Engine	Thrust Reverser LH	1	2		193		193		386	50	50			193	193	0	0	386
Engine	Thrust Reverser RH	1	2		212		212		424	50	50			212	212	0	0	424
Engine	Inlet Cowl	1	2		108		108		236	50	50			118	118	0	0	236
Fuselage	Cabin Door Fwd	2	2	196					196	20		80		39.2	0	156.8	0	196
Fuselage	Cargo Door Aft	1	1	121					121	20		80		24.2	0	96.8	0	121
Fuselage	Cabin Door Aft	2	2	192					192	20		80		38.4	0	153.6	0	192
Fuselage	Belly Fiaring	1	1		75				75	50	50			37.5	37.5	0	0	75
Fuselage	Bulk Cargo Door	1	1	37					37	20		80		7.4	0	29.6	0	37
Fuselage	Cabin Floor Beams	1	1		500				500	20		80		100	0	400	0	500
Fuselage	Emergency Exits	4	4	60					60	20		80		12	0	48	0	60
Fuselage	Flap & Slat Control Units	1	1			100			100	20		80		20	0	80	0	100
Fuselage	Cargo Door Fwd	1	1						121	20		80		24.2	0	96.8	0	121
Fuselage	Frames	1	1	3500					3500	20		80		700	0	2800	0	3500
Fuselage	Additional Components	1	1				300		300	50	50			150	150	0	0	300
Fuselage	Horizontal Stab Actuator	2	2			100			100	20		80		20	0	80	0	100
Fuselage	Main LDG Doors	2	2		300				300	50	50			150	150	0	0	300
Fuselage	NLG Doors	1	1		50				50	50	50			25	25	0	0	50
Fuselage	Pressure Bulkheads	2	2	2200					2200	20		80		440	0	1760	0	2200
Fuselage	Radome	1	1		26				26	50	50			13	13	0	0	26
Fuselage	Skin	1	1	1400					1400	20		80		280	0	1120	0	1400
Fuselage	Tailcone	1	1	324					324	20		80		64.8	0	259.2	0	324
Fuselage	Stringers	1	1	1600					1600	20		80		320	0	1280	0	1600
Fuselage	Seatings	54	54	1458					1944	50	50			972	972	0	0	1944
Fuselage	Galley	1	1	50					100	50	50			50	50	0	0	100
Fuselage	Interior	1	1						300	50	50			150	150	0	0	300
Horizontal Stabiliser	Box	1	1		418				418	50	50			209	209	0	0	418
Horizontal Stabiliser	Elevator	1	1		97				97	50	50			48.5	48.5	0	0	97
Horizontal Stabiliser	Removable Leading Edge	1	2		168				168	50	50			84	84	0	0	168
Horizontal Stabiliser	Tailplane FS Fairing	1	1		7				7	50	50			3.5	3.5	0	0	7
Horizontal Stabiliser	Tip	1		6					6	20		80		1.2	0	4.8	0	6
Landing Gear	Complete Twin	1	2	360		1501			1861	20			80	372.2	0	0	1488.8	1861
Landing Gear	Downlock Act	1	2			100			100	20		80		20	0	80	0	100
Landing Gear	Leg Fairing	1	2		64				64	50	50			32	32	0	0	64
Landing Gear	Lock Stay	1	2				100		100	50	50			50	50	0	0	100
Landing Gear	Wheel+Brake	4	8	272		1000			1632	50	50			816	816	0	0	1632
Landing Gear	Complete	1	1	30		263	30		323	20			80	64.6	0	0	258.4	323
Landing Gear	Retraction Act	1	1			20			20	20		80		4	0	16	0	20
Landing Gear	Shock Absorber	1	1	10		80	10		100	20		80		20	0	80	0	100
Landing Gear	Steering Act	1	1			10			10	20		80		2	0	8	0	10
Landing Gear	Wheel with Tyre	2	2	6		40	6		72	50	50			36	36	0	0	72
Vertical Stabiliser	Box	1	1		365				365	50	50			182.5	182.5	0	0	365
Vertical Stabiliser	Add Comp	1	1	20					20	20		80		4	0	16	0	20
Vertical Stabiliser	Dorsal Fin	1	1		26				26	50	50			13	13	0	0	26
Vertical Stabiliser	Fuselage Fairing	1	1		15				15	50	50			7.5	7.5	0	0	15
Vertical Stabiliser	Removable Leading Edge	1	1		48				48	50	50			24	24	0	0	48
Vertical Stabiliser	Rudder	1	1		88				88	50	50			44	44	0	0	88
Vertical Stabiliser	Tip	1	1		9				9	50	50			4.5	4.5	0	0	9
Wing	Add Comp	1	2	100	100	100	66		366	30	30	40		109.8	109.8	146.4	0	366
Wing	Aileron	1	2		48				48	50	50			24	24	0	0	48
Wing	Flap Track Fairing	1	2		200				200	50	50			100	100	0	0	200
Wing	Front + Rear Spars	1	2	3400					3400	20		80		680	0	2720	0	3400
Wing	Inner Flap	1	2		228				228	50	50			114	114	0	0	228
Wing	Inner Wing Box	1	2	1600		200	600		2400	30	30	40		720	720	960	0	2400
Wing	LDG Leg Fairin	1	2		30.8				30.8	50	50			15.4	15.4	0	0	30.8
Wing	Outer Flap	1	2		244				244	50	50			122	122	0	0	244
Wing	Outer Wing Box	1	2	1600		200	600		2400	30	30	40		720	720	960	0	2400
Wing	Paint	1	2						130	100				130	0	0	0	130
Wing	Ribs	1	2	2000					2000	20		80		400	0	1600	0	2000
Wing	Skin	1	2	1000					1000	20		80		200	0	800	0	1000
Wing	Slat 1	1	2	78					78	20		80		15.6	0	62.4	0	78
Wing	Slat 2	1	2	60					60	20		80		12	0	48	0	60
Wing	Slat 3	1	2	56					56	20		80		11.2	0	44.8	0	56
Wing	Slat 4	1	2	50					50	20		80		10	0	40	0	50
Wing	Slat 5	1	2	46					46	20		80		9.2	0	36.8	0	46
Wing	Spoiler 1	1	2		30				30	50	50			15	15	0	0	30
Wing	Spoiler 2	1	2		25				26	50	50			13	13	0	0	26
Wing	Spoiler 3	1	2		24				24	50	50			12	12	0	0	24
Wing	Spoiler 4	1	2		24				24	50	50			12	12	0	0	24
Wing	Spoiler 5	1	2		28				28	50	50			14	14	0	0	28
Wing	Wing Tip + Wiglet	1	2		52				52	50	50			26	26	0	0	52

	LANDFILL	INCINERATION	RECYCLE	REUSE	
Total Mass	11264.4	5731.2	16873.5	5318.7	39187.8
% per Disposal Method	28.74	14.62	43.06	13.57	100.00

Appendix D

SimaPro Impact Assessment Diagram of A320

142


1 p
Airbus A320
100%
2 p
Wing
12.2%
1 p
Fuselage
69.3%
2 p
Main Landing Gear
1.79%
1 p
Vertical Stabilizer
4.77%
1 p
Horizontal Stabilizer
8.65%
2 p
CFM56-5B Engine
3.1%
2 p
Wing - Additional Components
1.76%
2 p
Wing - Flap Track Fairing
0.96%
2 p
Wing - Front & Rear Spars
4.17%
2 p
Wing - Inner Flap
1.37%
2 p
Wing - Inner Wing Box
4.05%
2 p
Wing - Outer Flap
3.61%
2 p
Wing - Outer Wing Box
4.05%
2 p
Wing - Ribs
2.32%
2 p
Wing - Skin
1.65%
1 p
Fuselage - Belly Fairing
1.08%
1 p
Fuselage - Frames
1.18%
1 p
Fuselage - Additional Components
0.975%
2 p
Fuselage - Main LDG Doors
4.33%
2 p
Fuselage - Pressure Bulkheads
1.75%
1 p
Fuselage - Skin
1.4%
1 p
Fuselage - Stringers
1.55%
1 p
Fuselage - Interior Components
2.54%
2 p
Main Landing Gear Complete Train
1.13%
2 p
Main Landing Gear Leg Fairing
0.922%
8 p
Main Landing Gear - Wheel with Tyre & Brake
1.35%
1 p
Vertical Stabilizer - Box
2.87%
1 p
Vertical Stabilizer - Rudder
1.31%
1 p
Horizontal Stabilizer - Box
0.83%
1 p
Horizontal Stabilizer - Elevator
1.4%
1 p
Horizontal Stabilizer - Removable Leading Edge
1.21%
2 p
CFM56-5B Engine - Powerplant
15.5%
2 p
CFM56-5B Engine - Pylon
4.61%
2 p
CFM56-5B Engine - Thrust Reverser LH
1.41%
2 p
CFM56-5B Engine - Thrust Reverser RH
1.74%
2 p
CFM56-5B Engine - Inlet Cowl
2.08%
1.67E4 tkm
Transport, aircraft, freight, Europe/RER U
6.48%
2.38E4 kg
Aluminium alloy, AlMg3, at plant/RER U
18.4%
54 p
Fuselage - Interior Components Cowling
2.17%
4.11E3 kg
X12CrNi17 7 (301) I
1.04%
3.19E3 kg
CFRP
45.4%
500 kg
Iron-nickel-chromium alloy, at plant/RER U
2.87%
3.56E3 kg
Titanium zinc plate, without pre-weathering, at
11.6%
763 kg
Nickel, 99.5%, at plant/GLO U
9.49%
3.21E3 kg
Steel, electric, chromium steel 18/8, at plant/RER U
3.85%
1.67E4 tkm
Operation, aircraft, freight, Europe/RER U
5.5%
4.57E5 MJ
Electricity mix, aluminium industry/GLO U
4.45%
2E4 MJ
Nitrogen, liquid, at plant/RER U
0.966%
1.45E3 kg
Acrylonitrile E
1.48%
1.49E3 kg
Polymethyl methacrylate, sheet, at plant/RER U
2.32%
3.32E5 MJ
Heat, natural gas, at industrial furnace >100kW/RER S
4.37%
1.54E6 MJ
Electricity, production mix 3F/3F U
33.6%
7.56E3 kg
Casting, brass/CH U
1.57%
3.56E3 kg
Contour, brass/RER U
1.35%
3.32E3 kg
Zinc, primary, at regional storage/RER U
9.72%
502 kg
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U
2.55%
414 kg
Ferronickel, 25% Ni, at plant/GLO U
2.24%
7.6E3 kg
Kerosene, at regional storage/RER U
4.21%
8.73E4 MJ
Electricity, hard coal, at power plant/CN U
1.92%
2E4 MJ
Electricity, oil, at power plant/IT U
1.07%
3.2E4 MJ
Electricity, natural gas, at power plant/UCTE U
1.08%
4.69E3 kg
Aluminium, primary, at plant/RER U
10.6%
1.08E4 kg
Aluminium, secondary, from new scrap, at
1.41%
7.59E3 kg
Aluminium, secondary, from old scrap, at plant/RER U
2.71%
1.52E5 MJ
Natural gas, burned in industrial furnace >100kW/RER U
1.91%
2.24E5 MJ
Electricity, medium voltage, production UCTE, at grid/UCTE
3.22%
3.89E5 MJ
Hard coal, burned in power plant/RER U
10.1%
1.3E5 MJ
Electricity, oil, at power plant/FR U
6.39%
4.41E5 MJ
Electricity, natural gas, at power plant/3F U
16.7%
8.22E3 kg
Zinc concentrate, at beneficiation/GLO U
1.67%
7.6E3 kg
Kerosene, at refinery/RER U
4.17%
5.23E4 MJ
Heavy fuel oil, burned in power plant/IT U
1.07%
8.44E4 MJ
Natural gas, burned in power plant/UCTE U
1.08%
4.69E3 kg
Aluminium, primary, liquid, at plant/RER U
10.4%
253 kg
Copper, at regional storage/RER U
1.5%
1.04E5 MJ
Heat, natural gas, at boiler modulating >100kW/RER U
1.35%
1.68E5 MJ
Natural gas, high pressure, at consumer/RER U
4.19%
2.65E5 MJ
Electricity, high voltage, production UCTE, at grid/UCTE
4.27%
3E5 MJ
Heavy fuel oil, burned in power plant/FR U
6.39%
1.1E6 MJ
Natural gas, burned in power plant/3F U
16.7%
134 kg
Blasting/RER U
1.31%
9.07E3 kg
Aluminium oxide, at plant/RER U
4.89%
2.12E3 kg
Anode, aluminium electrolysis/RER U
1.21%
1.33E5 MJ
Electricity, medium voltage, aluminium industry, at grid/GLO
1.6%
1.09E5 MJ
Natural gas, burned in boiler modulating >100kW/RER U
1.35%
1.01E4 m3
Natural gas, at long-distance pipeline/RER U
4.18%
4.74E3 tkm
Transport, natural gas, pipeline, long distance/RER U
0.0599%
2.08E5 MJ
Electricity, medium voltage, production UCTE/UCTE U
4.26%
4.48E4 kg
Hard coal supply mix/RER U
4.1%
1.28E4 kg
Heavy fuel oil, at regional storage/RER U
6.82%
1.1E6 MJ
Natural gas, high pressure, at consumer/3F U
15.4%
1.39E4 kg
Aluminium hydroxide, at plant/RER U
4.53%
3.59E3 kg
Petroleum coke, at refinery/RER U
0.988%
3.18E5 MJ
Electricity, high voltage, aluminium industry, at grid/GLO
1.14%
2.28E3 m3
Natural gas, production DZ, at long-distance
0.955%
3.1E3 m3
Natural gas, production NL, at long-distance
1.14%
4.42E3 m3
Natural gas, production RU, at long-distance
2.07%
2.69E3 m3
Natural gas, at production offshore/NO U
0.986%
9.23E5 tkm
Transport, transoceanic freight ship/OCE U
1.4%
1.32E4 kg
Heavy fuel oil, at refinery/RER U
6.9%
2.59E4 m3
Natural gas, at evaporation plant/3F U
14.5%
1.95E4 kg
Bauxite, at mine/GLO U
1.9%
7.31E4 MJ
Heat, light fuel oil, at industrial furnace 1MW/CH U
1.2%
6.52E3 kg
Disposal, residual from bauxite digestion, 0% water,
0.981%
5.17E3 m3
Natural gas, at production onshore/RU U
1.98%
9.23E5 tkm
Operation, transoceanic freight ship/OCE U
3.21%
5.14E3 kg
Crude oil, production RU, at long distance transport/RER U
3.22%
7.07E3 kg
Crude oil, production RME, at long distance
1.41%
1.02E3 kg
Crude oil, production RAF, at long distance
1.49%
6.29E3 kg
Crude oil, production NO, at long distance transport/RER U
2.77%
5.03E3 kg
Crude oil, production GB, at long distance transport/RER U
2.27%
2.59E4 m3
Natural gas, liquefied, at freight ship/3F U
14.2%
7.71E4 MJ
Light fuel oil, burned in industrial furnace 1MW/
1.2%
5.14E3 kg
Crude oil, at production onshore/RU U
3.2%
7.69E3 kg
Crude oil, at production onshore/RME U
1.48%
1.85E3 kg
Crude oil, at production onshore/RAF U
1.85%
6.29E3 kg
Crude oil, at production offshore/NO U
2.76%
5.03E3 kg
Crude oil, at production offshore/GB U
2.26%
3.04E4 m3
Natural gas, liquefied, at liquefaction plant/GLO
13.3%
1.76E5 tkm
Transport, liquefied natural gas, freight ship/GLO U
1.39%
1.88E3 kg
Light fuel oil, at regional storage/CH U
1.05%
1.76E5 MJ
Natural gas, burned in gas motor, for storage/DZ U
1.99%
3.87E4 m3
Natural gas, at production onshore/DZ U
14.3%
1.49E3 kg
Diesel, at regional storage/RER U
0.819%
2.24E3 kg
Diesel, at refinery/RER U
1.22%